Environmental Footprints and Eco-design of Products and Processes

Felipe Luis Palombini
Fernanda Mayara Nogueira *Editors*

Bamboo Science and Technology

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Environmental Footprints and Eco-design of Products and Processes

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Felipe Luis Palombini · Fernanda Mayara Nogueira
Editors

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Editors
Felipe Luis Palombini
Department of Industrial Design (DDI)
Federal University of Santa Maria (UFSM)
Santa Maria, Brazil

Fernanda Mayara Nogueira
Faculty of Philosophy, Sciences and Letters
at Ribeirão Preto (FFCLRP)
University of São Paulo
Ribeirão Preto, Brazil

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About the Editors

Dr. Felipe Luis Palombini is an Assistant Professor of the Department of Industrial Design from the Federal University of Santa Maria (UFSM) in Santa Maria (Brazil), and a Post-doctoral Researcher in the Graduate Program of Design (PGDesign) at the Federal University of Rio Grande do Sul (UFRGS), in Porto Alegre (Brazil). Felipe Palombini received his M.Sc. and his Ph.D. in the Graduate Program in Design (PGDesign/UFRGS) and was a Post-doctoral Researcher at the Graduate Program of Botany (PPGBot/UFRGS). His main research topics are focused on bionics, sustainability, design, and materials selection and characterization via Finite Element Analysis and X-ray Microtomography. He is also associated with the Design and Computer Simulation Research Group (DSC/UFRGS), and the Plant Anatomy Laboratory (LAVeg/UFRGS).

Dr. Fernanda Mayara Nogueira is a Researcher at the Laboratory of Molecular Biology of Plants from the Faculty of Philosophy, Sciences, and Letters at Ribeirao Preto (FFCLRP)—University of Sao Paulo (USP). Fernanda Nogueira received her M.Sc. and her Ph.D. in the Graduate Program of Botany (PPGBot) at the Federal University of Rio Grande do Sul (UFRGS). She has experience in the area of plant anatomy and plant morphology with emphasis on reproductive morphology. She has interest in the following topics: floral development, reproductive morphology, bioimaging, 3D technologies, and X-ray microtomography.

Bamboo: A Mechanically Optimum Design in Nature

Hiroyuki Shima, Akio Inoue, and Motohiro Sato

Abstract This chapter reviews the latest research on the mechanics and morphology of bamboo. Bamboo is one of the fastest-growing plants, even under unmanaged conditions; thus, it has the potential to become a renewable natural resource. The rapid maturation of bamboo is due to its hollow structure, which requires less photosynthetic material to grow and makes its culm lightweight (which, in turn, suppresses the risk of collapse by self-weight). More noteworthy is the mechanical optimality in naturally designed bamboo culms, as can be deduced from the delicate harmony and balance between the circular crossbeam (diaphragm) at a node and the reinforcing fiber (vascular bundle sheath) inside the culm. Surprisingly, the spatial arrangement of the two attributes is finely tuned to optimally improve the mechanical performance of bamboo culm, as confirmed by state-of-the-art research. A better understanding of the optimal design for enhancing the mechanical function of bamboo culm will lead to a nature-derived optimal design of functional materials with excellent mechanical properties.

Keywords Bamboo culm · Hollow cylinder · Structural mechanics · Bending stiffness · Internode length · Diaphragm · Vascular bundle · Functionally graded materials

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H. Shima (✉)
Department of Environmental Sciences, University of Yamanashi, Kofu 400-8510, Japan
e-mail: hshima@yamanashi.ac.jp

A. Inoue
Faculty of Agriculture, Kindai University, Nara 631-8505, Japan

M. Sato
Faculty of Engineering, Hokkaido University, Sapporo 060-8628, Japan

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1 Introduction

1.1 Bamboo as a Natural Resource

Bamboo is a woody perennial plant characterized by a long and hollow culm.[1] Bamboo is grown not only in East and Southeast Asia but also in other temperate and humid regions such as Australia, Central and South America, and Africa [1]. There are approximately 1,250 species of bamboo globally [2], with 238 species in Japan [3]. There are more than 150,000 ha of bamboo forests in Japan [4], of which 99% are composed of Moso bamboo and Madake[2] at a 3:1 ratio [5]. Hachiku[3] is also a major bamboo species, along with Moso bamboo and Madake, although it occupies only approximately 0.4% of the total bamboo growing area [6]. In Japan, these three bamboo species are known to be the three most useful bamboo species [7].

Bamboo exhibits a different morphology from that of other woody plants [8]. For example, almost all bamboo species have a hollow cavity inside,[4] unlike trees with a solid cross-section [9]. The long hollow cavity is separated by "nodes", each of which comprises a circular disk embedded in the cavity and a circumferential ridge on the surface [10]. In an individual bamboo culm, dozens of nodes are arranged at gradually modulated intervals along the culm [11]. The space between adjacent nodes is called the "internode"; after the bamboo shoot sprouts on the ground, many internodes extend longitudinally in a sequential manner, causing the entire culm to grow [12]. Bamboo nodes also serve as starting points for branch growth [13], and each branch growing from the culms also has a few nodes. The anatomy of the bamboo culm is shown in Fig. 1.

Since the beginning of human history, bamboo has been recognized as a useful forest resource at each stage of its growth [14]; a few examples are displayed in Fig. 2. In the early stages of development, for instance, the bamboo shoot serves as an edible side dish [15]. Before logging, bamboo can be used to prevent landslides through the ground-holding solid effect of the rhizome [16]. Furthermore, after felling, bamboo is widely used in daily life as a structural component in buildings, in deodorants and humidity control as bamboo charcoal, and in various craft supplies owing to its excellent processability [2]. Furthermore, bamboo culms that have been dried after being felled are very strong, easy to process, and retain a lot of elasticity that wood lacks. Therefore, harvested bamboo has been widely used as a material for products

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[1] The trunk of bamboo is called "culm" instead of "stem" since it belongs to the family of grasses (*Poaceae* family).

[2] The scientific names for these species are as follows: Madake (*Phyllostachys bambusoides*) and Moso bamboo (*Phyllostachys pubescens*).

[3] The scientific name for Haticku is *Phyllostachys nigra.*

[4] An exception is Calcutta bamboo (*Dendrocalamus strictus*), also called Solid bamboo, which has a solid (not hollow) cross-section. This species of bamboo is widely found across South and Southeast Asia, particularly India.

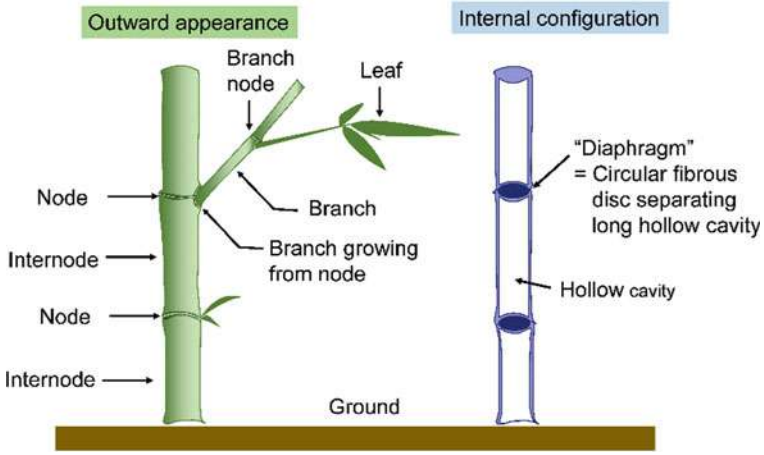

Fig. 1 Anatomy of bamboo culm. The outside of the culm (left) has nodes along the length, from which the branches extend. Inside the culm (right), a longitudinally elongated cavity is separated by circular plates called diaphragms

that require flexibility, such as bows and fishing rods [17]. This implies that if we continue to explore the fundamental understanding of the practical utility of bamboo and increase the attractiveness of bamboo to the general public, we should be able to make a significant contribution to the realization of a sustainable social system [18].

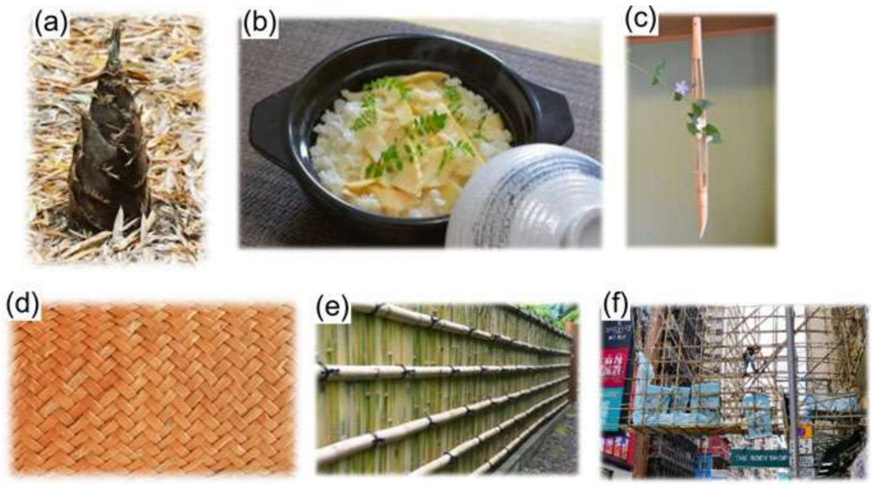

Fig. 2 Uses of bamboo in everyday life. **a**, **b** Freshly sprouted bamboo shoots are used as ingredients in dishes such as bamboo shoot rice. **c**, **d** Because the culms and branches of bamboo are easy to split, they are used to make daily necessities such as single-flower vases and basket nets. **e**, **f** Dried bamboo culms are strong and are used for fences in residential areas and scaffolding on construction sites

Fig. 3 Left: Segment of a bamboo culm. Right: Magnified view of the section near a diaphragm. Reprinted with permission from [20], Copyright 2016, American Physics Society

1.2 Structural Wisdom Hidden in Bamboo Culm

From the viewpoint of structural mechanics, a close examination of the entire bamboo culm reveals certain interesting properties. It is apparent that bamboo culms exhibit a cylindrical shell structure that is hollow, very long, and thin [19]. This hollow structure may seem insufficient for stabilizing the entire culm against mechanical disturbance because it causes flattening of the cross section of the culm and local buckling when an external bending force is applied. However, this weakness is avoided in wild bamboo through the presence of "nodes" and "reinforcing fibers" over the entire culm, as explained below.

A bamboo node refers to a combination of two attributes: an external ridge on the outer surface of the culm and an internal diaphragm embedded in the hollow cavity [9], as shown in Fig. 3. The diaphragm acts as a ring stiffener for the region near the node as it prevents the collapse of the culm under external pressure. We will see later that the sequential insertion of many diaphragms with an appropriate spacing leads to improved mechanical stiffness of the entire bamboo culm [20].

In addition to the nodes, vascular bundles embedded in the bamboo culm play the role of reinforcing fibers against bending forces [21, 22]. Vascular bundles not only perform the function of transporting water and nutrients but also serve as mechanical support to reinforce the bamboo culm—similar to how rebar is embedded in reinforced concrete [23, 24]. The fibers, which are sufficiently rigid, are aligned in the longitudinal direction to enhance the bending stiffness of the culm as a whole against crosswinds and bending caused by gravity. The elastic modulus[5] and tensile

[5] Here, the elasticity modulus (or Young's modulus) is a proportionality constant between strain and stress in the coaxial direction within the elastic deformation range where Hooke's law holds. For example, the modulus of elasticity of copper is approximately 100 GPa; if you take a wire made of copper with a cross-sectional area of 1 mm^2 and a length of 1 m, and then hang a weight of 10 kg from it, the wire will be strained by 0.1% and stretched by approximately 1 mm. Woody lumber and plastic resin show the modulus of elasticity to be on the scale of a dozen GPa and a few GPa, respectively.

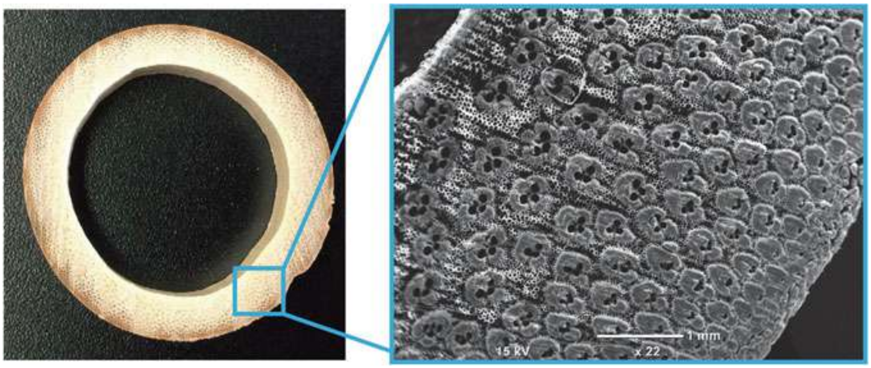

Fig. 4 (Left) Cross-section of wild Moso bamboo. (Right) Microscopic observation of the right-bottom portion. Thick fibers are sparsely distributed near the inner wall, while relatively thin fibers are densely distributed near the outer wall. Adapted from [24], License CC BY

strength[6] of the vascular bundle of Moso bamboo, for instance, were measured to be approximately 45 GPa and 700 MPa, respectively; both of which are comparable to those of industrial steel. In fact, a bamboo culm can be considered a composite material made of “hard” vascular bundles and a “soft” matrix of parenchyma cells [25], as shown in Fig. 4.

Interestingly, the excellent mechanical adaptability of bamboo culms originates from the delicate harmony and balance between the nodes and fibers. As mentioned earlier, the fibers are arranged vertically in the woody portion; therefore, the entire bamboo culm tends to split in the direction of the fibers. In other words, if a vertical crack occurs in a part of the bamboo, there is a danger that the entire culm will split vertically. The nodes of bamboo culms play a role in reducing this risk of splitting. At the node, the orientation of the fibers is intertwined; thus, any vertical cracks in the culm stop at the nearest node. Furthermore, the position of the nodes along the culm is excellently controlled from a strength perspective. The nodes are unevenly spaced along the height, which gives the bamboo sufficient strength to grow as tall as possible while keeping its weight down; thus, the "minimum weight/maximum strength" principle is achieved by regulating the node interval in the height direction.

The beautiful harmony between the nodes and fibers of bamboo, effectively functioning to enhance the mechanical stability of the entire culm, can be regarded as an example of an environmental adaptation strategy that accompanies biological evolution. From a broader perspective, it is fair to say that terrestrial plants (*Embryophyta*) have adopted different animal survival strategies. Once terrestrial plants take root, they cannot move from there; thus, they must adapt to continue to exist within the given physical environment. Thus, in line with the law of the survival of the fittest, plants have acquired the optimal form by eliminating waste in the process of evolution. In other words, plants have acquired a sophisticated structure over 500 million years of

[6] The tensile strength is the amount of maximum tensile stress that a material can be subjected to before failure.

their evolutionary history.[7,8] It should come as no surprise that the morphology and structure of plant species that have survived such fierce competition for survival harbor a dynamic rationality that surpasses human ingenuity.

As a noteworthy example of plant wisdom, this chapter focuses particularly on the morphology of bamboo—a hollow cylindrical structure masterpiece derived from nature. Section 2 briefly summarizes what we know from field observations of the characteristics of bamboo morphology and growth processes. Section 3 describes the theoretical framework necessary to explain the relationship between bamboo culm morphology and mechanical properties. Section 4 explains that the non-uniform arrangement of bamboo nodes is mechanically rational, based on the mechanic's theory presented in the previous section. Section 5 presents how the gradient distribution of the vascular sheaths embedded within the xylem of bamboo contributes to the mechanical stability of the culm. Finally, Sect. 6 summarizes the chapter and comments on certain interesting open questions.

2 Fast-Growing Wild Bamboo

2.1 Role of Nodes and Rhizome

Bamboo, an evergreen perennial plant, has excellent fertility and grows very quickly compared with other plants [26]. It has been reported that in just 24 h, Madake and Moso bamboo grew by as much as 121 cm and 119 cm, respectively [19, 27]. Why does bamboo grow rapidly? Two characteristics can explain this: the location where the bamboo grows and how it obtains nutrients.

Many plants grow by producing nutrients through photosynthesis in their leaves and supplying the nutrients to the tips of their leaves and stems. The tips of these leaves and stems are called meristematic points, where the cells actively divide and grow. Similar to other plants, bamboo has a growth point at the tip of the culm. However, in addition to that, bamboo has a belt-like structure called a "growth zone" between nodes. In this growth zone, cell division is actively carried out; therefore, the intervals between nodes become longer, similar to bellows. For instance, an individual bamboo species may have approximately 60 nodes. This implies that if one growth zone elongates by 1 cm, the entire individual grows by 60 cm. In this

[7] One typical example of manifesting the wisdom of plant forms is the morphology of tree trunks and branches. Many species of trees control their tissue geometry autonomously so that stress concentrations do not occur anywhere on the outer surface [28]. Stated differently, trees regulate their growth so that each individual segment becomes a structure with uniform strength.

[8] Another noticeable example is the optimal structure of the leaves of terrestrial plants. Despite their thinness, the leaves of land plants are strong enough to withstand wind and rain. The reason why plant leaves can cleverly meet the contradictory requirements of being "thin but strong" is owing to their extremely efficient sandwich structure [29]. This structure consists of a thin, hard surface material (epidermal tissue) and a thick, soft core material (mesophyll tissue) that is extremely useful for building a light and hard-to-bend flat surface using limited resources.

way, bamboo grows simultaneously in two places: the growth zone located between nodes, and the meristematic point located at the tip of the culm. The number of nodes is fixed during the creation of the bamboo shoot and does not increase with growth.

Another factor that determines the growth rate of bamboo is the mechanism through which it absorbs nutrients. Most plants produce nutrients through photosynthesis in their leaves, and each plant grows independently. On the contrary, a single bamboo culm does not grow independently but is connected via a "rhizome",[9] which is a stem buried underground, and shares the nutrients necessary for growth with other individuals (see Fig. 5). Therefore, if one individual bamboo becomes sick, the adjacent individual may also become sick. Bamboo shoots that emerge from different places are connected to each other through underground stems and grow by receiving nutrients from the underground stems. For example, in the case of Moso bamboo, after 50–60 days of growing the culm from the bamboo shoot, the culm stops growing, and the rhizome begins to grow. After that, it takes approximately 4 months to grow the rhizome to approximately 8 m, after which it stops growing. Furthermore, the nutrients are stored in the rhizomes and wait for spring bamboo shoots to appear. By allowing the bamboo shoots to absorb the nutrients stored in the rhizomes, bamboo culms can grow rapidly in the subsequent spring season.

2.2 Stepwise Elongation of Internodes

Figure 6a illustrates the variation in the internode length and culm diameter of mature Moso bamboo along the height direction. The horizontal axis indicates the number of nodes counted from the base to the top. As can be seen from the figure, the internode length is the longest at the center of the bamboo culm and shows monotonic variation along the culm, decreasing downward and upward from the center [12, 19]. In contrast, the culm diameter is largest near the base and gradually decreases from the bottom to the tip [31]. In more detail, for Moso bamboo, the culm diameter decreases significantly in the section from the base to the fifth or sixth node and then decreases in the upper part almost linearly concerning the number of nodes.

When the culm internodes elongate, different internodes elongate at different times. Figure 6b shows the increase in internode length after bamboo shoot germination. The figure shows that after germination, the culm completes its growth sequentially from the lower to the upper internodes. Specifically, only the internodes close to the ground elongate until 3 weeks after germination, while the other internodes remain short at the time of germination. Four to five weeks after germination, the internodes near the ground stop growing, and the internodes located at the mid-height start actively elongating. After a certain period, these intermediate internodes also stop elongating, leaving only the upper internodes to elongate. Such sequential

[9] Rhizome refers to a kind of rootstock consisting of a creeping stem, usually growing horizontally underground. In the case of bamboo, the rhizomes are woody and segmented—just like the culms.

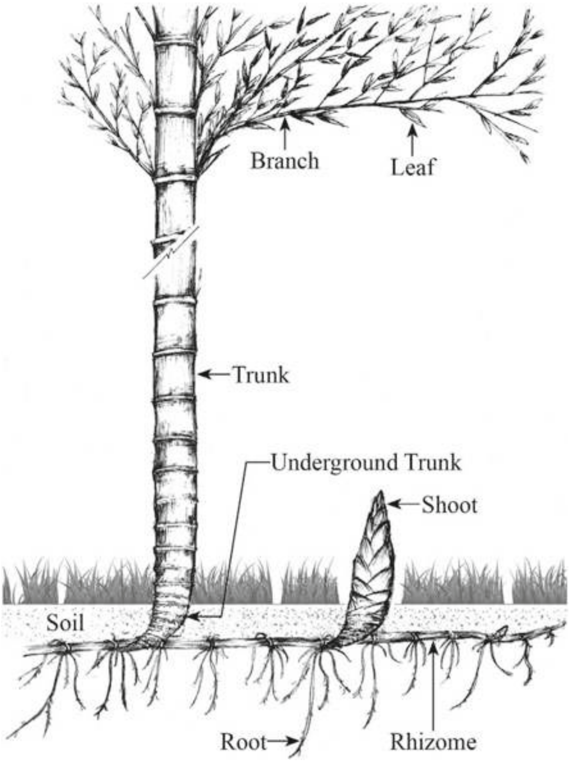

Fig. 5 Relationship between the shoot, mature Moso bamboo, and rhizome. The culms and bamboo shoots, which appear to be different individuals on the ground, are connected to each other through underground rhizomes. Adapted from [30], License CC BY

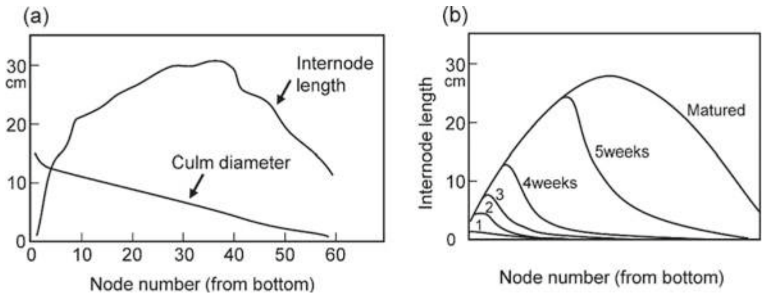

Fig. 6 **a** Variation in culm diameter and internode length in the height direction. **b** Diagram of internode elongations at different intervals as the culm grows

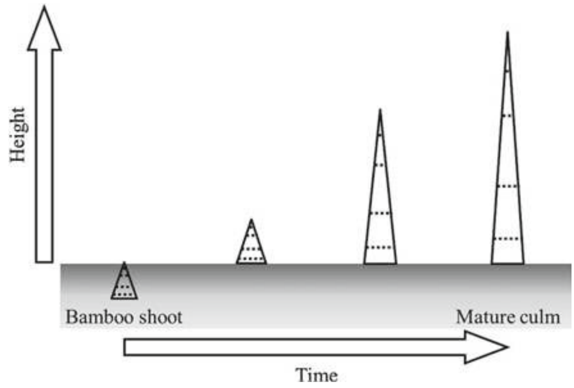

Fig. 7 Schematic diagram of the change in the internode lengths during culm elongation. The dotted lines represent the position of the nodes. Reprinted with permission from [32], Copyright 2017, Springer

growth within individuals is rarely observed in other plants and can be considered a mechanism unique to bamboo.

Preparations for such internode growth begin in winter when the bamboo shoots are buried in the ground. In winter, bamboo shoots grow from the rhizomes and underneath the ground, causing the tips of the shoots to protrude above the ground. By this time, most of the internodes seen in matured bamboo culms have already completed cell differentiation, and only a small part of the tip of the bamboo shoot remains undifferentiated. When the bamboo shoot begins to elongate above the ground, the preformed internodes are elongated sequentially from the lower internodes at different elongation rates (see Fig. 7). Simultaneously, the tip of the bamboo shoot also elongates, completing the undifferentiated internodes. Elongating bamboo shoots have meristematic tissue just above each node. Cell division is actively carried out in this tissue, and cells that divide and proliferate push up the culm above each node.

3 Basic Theory for Beam Bending

3.1 Second Moment of Inertia and Bending Stiffness

To proceed with the theoretical argument on the mechanics of bamboo culms, we suppose that a bamboo culm can be modeled by a long, straight, thin-walled hollow beam made from a homogeneous and elastic material. The mechanical stability of elastic beams has been thoroughly analyzed in the field of structural mechanics; therefore, by applying the existing theory to bamboo culms, it is possible to quantitatively describe the mechanical stability of bamboo culms against loads such as own weight and crosswinds.

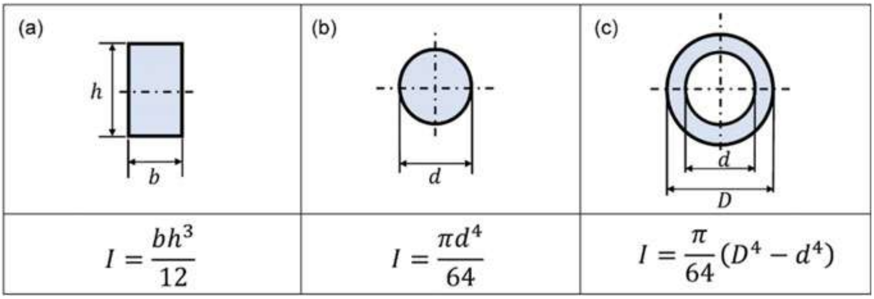

Fig. 8 Typical beam cross-sectional geometries and mathematical representations of their second moments of inertia with respect to the axes, which are presented by the dotted lines

In general, the durability of a given beam against bending (i.e., resistance to bending force) is determined by the second moment of inertia I of the beam. The value of I is evaluated only by the shape of the cross-section. More concretely, I describes the geometrical property of how the constituent volume elements are dispersed around an axis in the cross-section. For example, the cross-section of a square beam with width b and height h is a rectangle, as shown in Fig. 8a, and its second moment of inertia with respect to the dashed-line axis is equal to $bh^3/12$. Clearly, the greater the height h, the larger the value of I, implying that beam bending will be less likely.

If the shape of the cross-section changes, the value of I also changes. Figures 8b and 8c show the solid and hollow cross-sections of a circular beam, respectively, as well as the corresponding values of I. When the cross-section is a hollow concentric circle, the value of I is determined only by the inner diameter d and outer diameter D. . In particular, for a thin cylinder with a fixed thickness (i.e., $(D - d)/D \ll 1$), the larger the outer diameter D, the greater the value of I in proportion to its fourth power, making the structure more difficult to bend.

How is the second moment of inertia related to the bending resistance of a given columnar structure? Fig. 9 illustrates the solution, which describes the amount of deflection δ (the degree of deviation from the straight shape before deformation) when a concentrated load W or distributed load P is applied to beams with different boundary conditions. As shown in Fig. 9, the amount of deflection δ is inversely proportional to the product of EI in any case; here, E refers to the modulus of elasticity (Young's modulus), and I is the second moment of inertia of each beam's cross-section. In terms of terminology, the product of EI is called the bending stiffness of the beam structure. Because EI is the denominator in the mathematical expression of δ, when EI is large, the deflection decreases. Conversely, the greater the length L or load (W or P) in the numerator, the greater the deflection δ as intuitively understood.

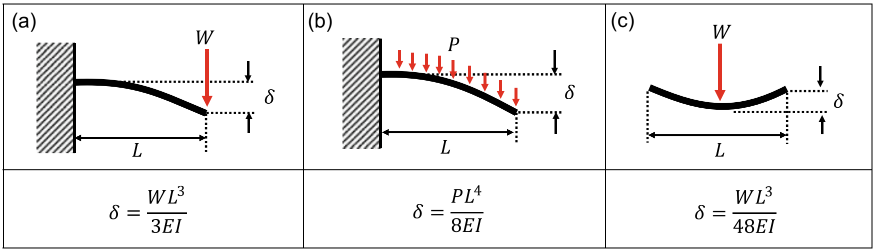

Fig. 9 Deflection δ of a beam with length L and bending stiffness EI. . Different boundary- and loading-conditions are applied. **a** Concentrated load W on a cantilever with one end fixed. **b** Distributed load P per length on the cantilever. **c** Concentrated load W on a simple beam

3.2 Mechanical Parameters of Real Bamboo Culm

Figure 10 presents the boxplot of the two mechanical characteristic quantities of bamboo culm for seven different species[10]: (a) the modulus of elasticity in gigapascal, and (b) the bending strength[11] in megapascal [33]. The number of samples measured was 55 and 36 for plots (a) and (b), respectively.

It follows from Fig. 10 that the average value of the modulus of elasticity ranges from 10 to 20 GPa, with some exceptions. These values are comparable to those of the timber used in construction. The bending strength of each species is approximately 100 MPa. These bending strength values are slightly higher than those of pine and cedar woods (ca. several tens of MPa), which are often used as building materials.

As mentioned earlier, the second moment of inertia I is responsible for the mechanical durability of the bamboo culm under bending. Based on this definition, the value of I is strongly dependent on the bamboo species since the culm diameter varies considerably depending on the species. For example, this amounts to ca. $I = 1.8 \times 10^{-6}$ [m^4], for a four-year-old *Bambusa* vulgaris ("Vittata"), which is very common in Manaus in Brazil and has been used in the construction of an ecological and sustainable village in Amazonia [34].

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[10] The suffix "spp." is an abbreviation for two or more species.

[11] The bending strength would be equivalent to the tensile strength if the material were ideally homogeneous. However, in practice, the bending strength tends to be higher than the tensile strength for the same material. This is primarily because certain imperfections (such as impurities, voids, and surface roughness) are found in real materials, leading to a local stress concentration that effectively causes a localized weakness. Another reason comes from localized strength differences in which a portion of the material determines the mechanical strength of the whole. For instance, when a material is bent, the extreme portions (the most outward or inward) are subjected to the largest stress; therefore, the bending strength of the material is determined by the strength of these extreme portions. Conversely, if the same material was subjected to only tensile force, all the constituent volume elements in the material should be subjected to the same stress. In the latter case, the material strength is determined by the mechanically weakest elements at which failure will initiate.

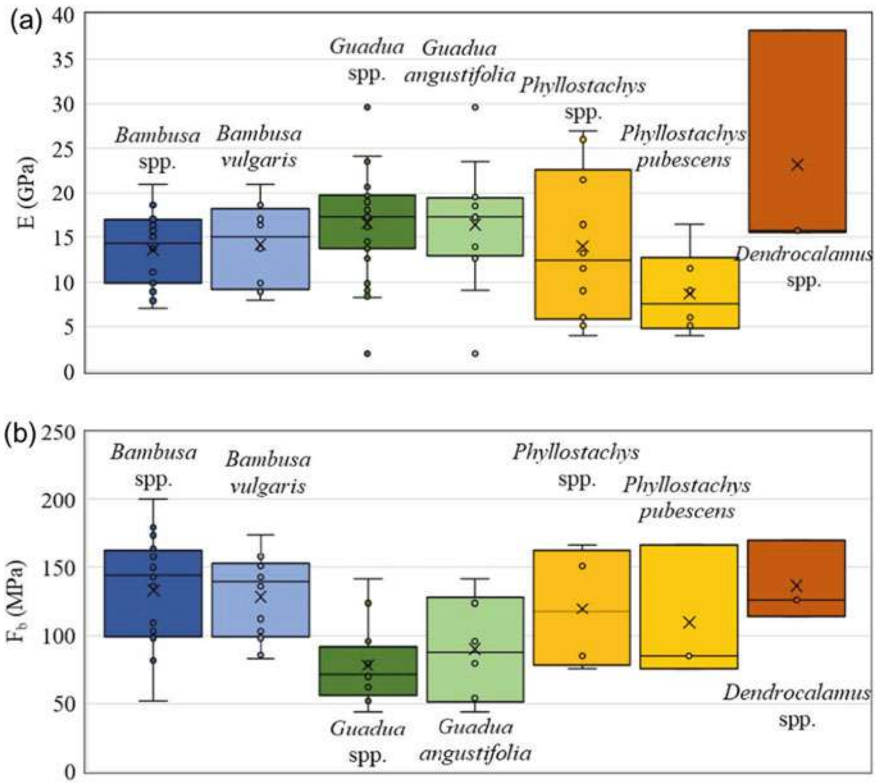

Fig. 10 Variation in the two mechanical constants of bamboo culm for different species. **a** Modulus of elasticity. **b** Bending strength. Adapted from [33], License CC BY

3.3 Brazier Phenomenon in Hollow Cylinder

The beam bending theory described in Sect. 3.1 holds true whether the beam is solid or hollow. However, if the beam is hollow, the shape of the cross-section changes owing to the bending deformation also being necessarily considered. For example, if one holds both ends of a soft rubber tube and bends it uniformly by hand, the cross-section that was originally a perfect circle deforms into an elliptical shape. The same phenomenon generally occurs when bending a hollow cylinder made of other materials; when a thin long hollow cylinder is bent uniformly, the cross-section changes from circular to elliptical as the curvature of the cylindrical axis increases. This cross-sectional deformation reduces the value of the second moment of inertia I, resulting in a decrease in the bending stiffness EI of the beam. This bending-induced reduction in the banding stiffness is called the Brazier effect. The Brazier effect also occurs when bamboo culms are subjected to bending.

Figure 11 illustrates the Brazier effect. In the initial (unloaded) state, the cylinder's axis is straight, and its cross-section is perfectly circular. Once a bending force is applied, the cylinder's axis has constant curvature, and the cross-section ovalizes. The application of bending to a hollow cylinder with a circular section gives rise to the stresses indicated by arrows; the left-pointing arrows (blue) in the upper half of the cylindrical section represent tensile stress, and the right-pointing arrows (red) in the lower half of the cylindrical section represent compressive stress. These two kinds of stresses act at a certain angle to the unrotated section, resulting in the original circular shape deforming into an oval or flattened shape. The degree of ovalization is quantified by the dimensionless parameter, called oblateness. The definition of ζ is shown in Fig. 11c; when a circular section of radius r is ovalized by bending deformation of the hollow cylinder, the product $r\zeta$ is the difference between the minor axis of the ellipse obtained and the radius r of the original circle. Based on this definition, the possible values of ζ are limited to the range of 0–1.

As intuitively understood, an increase in ζ causes an increase in the elastic energy stored in the hollow cylinder. However, this idea is correct only if the increase in ζ is small so that the cross-section deforms uniformly along the cylindrical axis. Once ζ exceeds a certain threshold, the deformation mode of the uniform flattening along the cylindrical axis becomes mechanically unstable. Instead, part of the cylinder collapses locally, forming a kink. Such kink formation in the hollow cylinder can easily be observed by bending a plastic straw in the kitchen (see Fig. 12). Interestingly, this threshold for ζ, denoted by ζ_{cr}, can be expressed as a simple integer ratio:

$$\zeta_{cr} = 0.268 \approx \frac{4}{15} \tag{1}$$

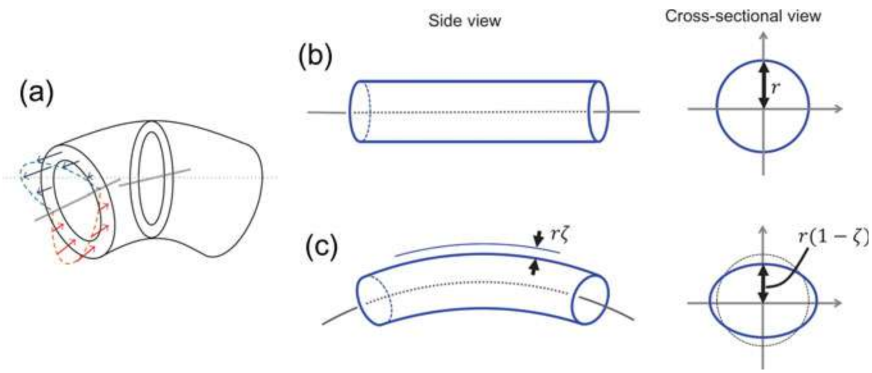

Fig. 11 **a** Schematic of the Brazier effect. The compressive (red arrow) and tensile (blue arrow) stresses caused by the application of bending result in the cross-sectional deformation from the original circular shape into a flattened shape. **b**, **c** Bending deformation process for a hollow elastic cylinder from two different viewpoints. The top panels show a straight cylinder before bending, and the bottom panels show a deformed cylinder after bending. The degree of ovalization in the cross-section is quantified by oblateness. Reprinted with permission from [20], Copyright 2016, American Physics Society

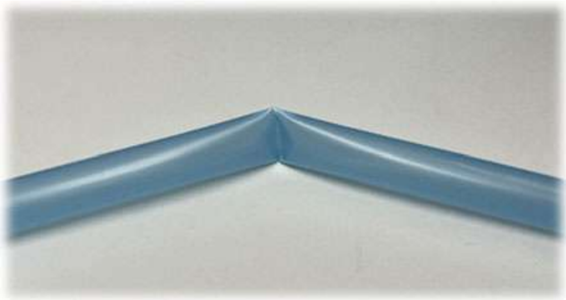

Fig. 12 A sharp fold in the form of a kink at the center of a plastic tube under bending

It should be noted that the value of ζ_{cr} is independent of the parameters defining the cylinder's elasticity and geometry. These parameters include the modulus of elasticity, the circular radius at the pre-bend state, and wall thickness. Stated differently, the deformation mode of uniform flattening along the cylindrical axis is stable only when the shorter radius of the ovalized cross-section is less than 73% of the radius of the original circular cross-section. If we apply a bending force that causes ζ to exceed the threshold, and the cylinder will collapse.

3.4 Cap-Induced Suppression of Ovalization

Note that the discussion of the Brazier phenomenon in the previous section was based on the assumption that the cylinder is sufficiently long and open at both ends. That is, we dealt with cylinders without caps at either end. However, if the length of the cylinder is relatively short and there are rigid circular caps at both ends, the overall ovalization is greatly suppressed by the boundary condition in which the cross-sections at both ends retain their initial circular shape. This circular retention effect at the ends of the cylinder propagates axially from the ends of the cylinder to the center. Therefore, the closer the cross-section is to either end, the less ovalization the cross-section will undergo.

Figure 13 shows the curved profile of a section of a long hollow cylinder subjected to uniform bending. The degree of cross-sectional deformation is such that ζ is less than $4/15$, which ensures uniform ovalization along the cylinder and, thus, the loss of local kink formation. When both ends are open (Fig. 13a), the value of ζ is constant over the entire cylinder, including both ends. However, when rigid circular caps are attached to both ends, the spatial uniformity of the flatness breaks down. The suppression of the elliptical deformation of part of the cylinder by the caps is shown schematically in Fig. 13b. At both ends, the original circle is retained, and as we move away from the ends, the value of ζ increases from 0 to the value specified in the central region.

For cylinders shorter than that depicted in Fig. 13b, the central region where ζ remains constant is also narrowed; see Fig. 13c. That is, the shorter the cylinder, the

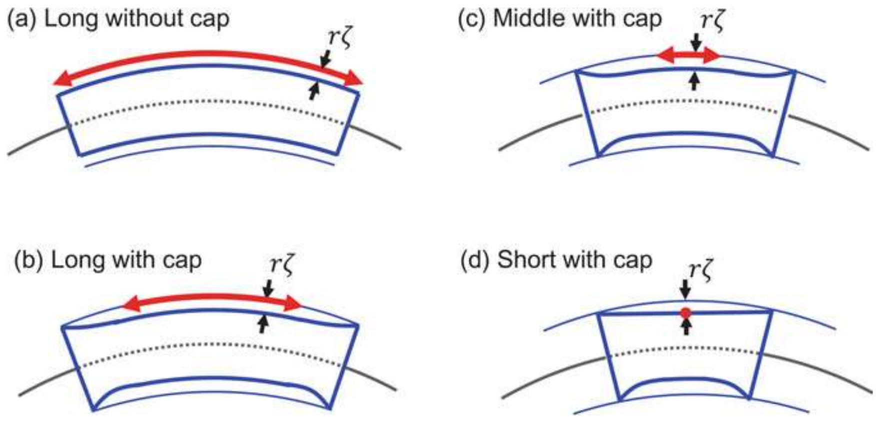

Fig. 13 **a** Curved profile of a portion of an open-ended, long, hollow cylinder. **b** A long hollow cylinder reinforced with caps with circular cross-sections at both ends. **c** A closed-ended cylinder of medium length. **d** A closed-ended cylinder of short length. Reprinted with permission from [20], Copyright 2016, American Physics Society

shorter the central zone where the value of ζ is constant. Eventually, in the case of Fig. 13d, the central zone shrinks to a point such that the generator on the upper side of the cylinder becomes almost straight. This suggests that a cylinder with this geometry should fall within the range over which the held-circular effect dominates.

It should be noted that this phenomenon of ovalization suppression by the caps on both ends is realized by bamboo culms. In bamboo, the entire culm is divided into short segments by the diaphragm located at the node, and the presence of the diaphragm suppresses cross-sectional deformation at the node. Consequently, the local suppression effect driven by the diaphragms is spread out over the entire culm.

3.5 Stiffening Parameter Ω

From the discussion thus far, we found that the cross-sectional flattening of the hollow cylinder can be suppressed by attaching caps to both ends. It was also found that, in this case, the oblateness is maximized at the position furthest from the end cap, that is, the central position of the short cylindrical segment sandwiched by the two caps.

One may consider that the more caps attached along the axis of the hollow cylinder, the less likely the cylinder will bend as a whole. However, in practice, the greater the number of caps, the greater the mass of the caps themselves, thereby reducing the stability of the overall structure. Furthermore, the formation of excessive diaphragms is detrimental to plant physiology. In the case of bamboo, to form numerous diaphragms corresponding to nodes, more photosynthetic products need to be supplied to the node positions. This could become a rate-limiting factor in bamboo growth.

Therefore, the most ideal strategy is to attach as many diaphragms as possible to increase the bending resistance of the entire culm while meeting the requirements of not hindering the growth rate and not increasing the culm's own weight significantly. How should the diaphragm be positioned to satisfy all these conditions? The answer to this question can be obtained through morphological studies of wild bamboo, as explained below.

The first significant fact is that bamboo has an anisotropic structure. More specifically, the bamboo culm is a lignin matrix reinforced by fibers aligned in the longitudinal direction. These reinforcing fibers greatly increase the stiffness and strength of the culm against mechanical loading in the axial direction. Consequently, the modulus of elasticity in the direction of the cylindrical axis, $E_{\parallel}$, becomes larger than that, in the circumferential direction, $E_{\perp}$. The second significant fact is that the effect of suppressing ovalization by inserting diaphragms at both ends is dependent on the following three geometric parameters: the length $\updownarrow$ and radius r of the internodal cylinder, and the thickness w of the culm wall. Bearing these two facts in mind, we introduce a dimensionless parameter Ω defined by

$$\Omega = \left(\frac{E_{\perp}}{E_{\parallel}}\right)^{\frac{1}{4}} \left(\frac{\updownarrow^2 w}{r^3}\right)^{\frac{1}{2}} \tag{2}$$

What occurs in the extreme case wherein the central zone shrinks to a point on the generator, as shown in Fig. 13d, should be emphasized. In this extreme situation, the oblateness at the central point, ζ^*, is related to the dimensionless parameter Ω as shown below:

$$\zeta^* = \frac{\Omega^4}{64} \tag{3}$$

Recall that for open-ended long cylinders, ζ has an upper limit for maintaining structural stability. Namely, a value of ζ that is larger than $4/15$ leads to the local collapse of the cylinder under bending. This holds true even for closed-ended short cylinders. Thus, it follows that if ζ^* is kept below $4/15$, then ζ in an arbitrary section will fall below the threshold because of the held-circular effect. In other words, when:

$$\Omega < \left(\frac{256}{15}\right)^{\frac{1}{4}} \approx 2.03 \tag{4}$$

the held-circular effect dominates the entire cylinder, such that a kink will not occur in the culm.

This is Bamboo's key takeaway. That is, positioning the diaphragm such that the value of Ω is less than 2.0, which prevents local rupture at that location. In particular, the risk of local breakage is high at the base of the culm. In other words, the bending deformation of the culm due to crosswinds and its own weight will be maximum at the base of the culm; therefore, the diaphragm should be placed such that the value of Ω at this point is 2.0 or less.

4 Optimal Node Distribution in Wild Bamboo

4.1 Measured Data of Internode Length

As previously mentioned, the diaphragms inserted at the bamboo node positions effectively suppress cross-sectional deformation of the adjacent internode. A special emphasis should be placed on the fact that the number of diaphragms in wild bamboo is exquisitely regulated to achieve a good balance between the bamboo culm weight, its lightness is obtained by extending the internode length, and mechanical stability is obtained by shortening the internode length. The latter mechanical consequence is attributed to the definition of Ω given by Eq. (2), which indicates that a small $\updownarrow$ leads to a small Ω, thus suppressing the deformation of the culm segments between nodes under bending.

Let us compare this theoretical result with field observations of wild bamboo. The nodes of a bamboo culm are usually sparsely distributed around the middle and densely distributed near the top and base. Figure 14a shows a parabolic fitting curve of the normalized internode length $\updownarrow(x)/\updownarrow_{\rm av}$ as a function of the normalized internode number $x = n/N$. Here, the original data $\updownarrow(x)$ of the internode length distribution along the bamboo culm was obtained from 50 samples of Moso bamboo in Japan; $\updownarrow_{\rm av}$ indicates the averaged value of the internode lengths for each sample, N is the total number of nodes in each sample, and n indicates the number of internodes counted from the root closest to the ground surface. It follows from Fig. 14a that the fitting curve of $\updownarrow(x)/\updownarrow_{\rm av}$ is an upward convex with its maximum at $x \approx 0.43$. This peak position corresponds almost exactly to the middle height of the culm. These observations are in good agreement with previous studies [35].

It follows from Fig. 14a that $\updownarrow(x)$ decreases rapidly as x increases and converges to 0 at $x = 1$. This decreasing behavior of $\updownarrow(x)$ indicates that nodes are far more densely populated near the tip of bamboo culms than near the base ($x = 0$). In fact, $\updownarrow(x)$ near the base remains ca. 60% of $\updownarrow_{\rm av}$. Based on these observations, the reader may mistakenly believe that the culm near the tip is substantially stiffened by a considerable number of diaphragms. That is, at a first glance, the dense population of diaphragms near the tip may appear to provide significant reinforcement. Similarly, the sparse concentration of diaphragms around the middle of the culm may appear to imply reduced reinforcement of this region. However, such an interpretation would be incorrect. The most important quantity of interest to us is the special variation in the dimensionless parameter Ω, rather than the density of diaphragms. We reiterate here that Ω is dependent on three geometric parameters: the culm wall thickness w, culm radius r, and internode length $\updownarrow$. Hence, the optimal distribution of Ω is expected to regulate these parameters. Consequently, $\updownarrow$ decreases (or increases) at the tip (middle height) of the bamboo culm, although there is seldom (significant) need for reinforcement at this position. We will see in the following discussion that this idea is supported by a measurement data analysis of Moso bamboo.

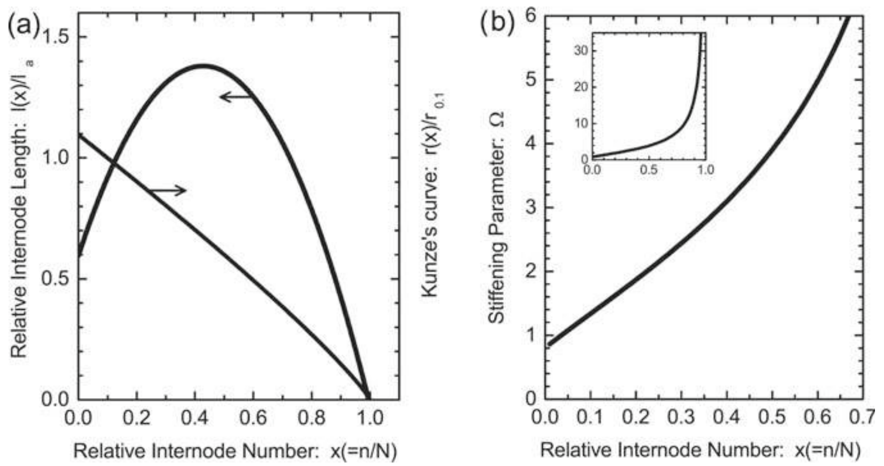

Fig. 14 (**a**) An upward parabolic curve expressing the normalized internode length $\ell(x)/\ell_{av}$ as a function of $x = n/N$. . The normalized Kunze's curve, showing the culm radius variation along the height, is also presented. (**b**) The curve of $\Omega(x)$ within a limited range of x, indicating that the criterion $\Omega < 2.033$ holds for $x < 0.59$. Inset: The entire curve of $\Omega(x)$ for $0 < x < 1$. Reprinted with permission from [20], Copyright 2016, American Physics Society

4.2 Optimal Ω Distribution

Figure 14b shows the numerical results of $\Omega(x)$ that were deduced from the measured data of $\ell(x)$. It shows a monotonic increase with x, starting from $\Omega \approx 0.86$ at $x = 0$ to $\Omega \approx 2.0$ at $x = 0.2$ and beyond. The inset shows the entire curve of $\Omega(x)$, in which an almost divergent Ω close to $x = 1$ is observed.

The most striking observation in Fig. 14b is that the criterion of $\Omega < 2.0$ holds for every $x < 0.22$. We found that, even at $x \sim 0.22$, the diaphragms remained active for reinforcement. This finding may be counterintuitive for some readers; since $\ell(x) > \ell_{\mathrm{av}}$ at $x \sim 0.22$, one might consider the diaphragms at the middle height to no longer work as ring stiffeners but allow flexible deformation of the internodes to counter crosswind. Our results show that bend-induced ovalization at the middle height is suppressed despite the large separation between the nodes.

Figure 14b also shows that the effectiveness of reinforcement is significantly enhanced near the base, where Ω becomes less than 1.0. The considerable reduction in Ω is reasonable because the bamboo segments near the base are subjected to severe external loading. Figure 15 shows a diagram of the bending moment exerted on the bamboo culms under horizontal loading. When the external load P is concentrated at the tip, the magnitude of the applied bending moment increases linearly from the tip to the base, as shown in Fig. 15a. However, if the load is uniformly scattered over the entire culm, the applied bending moment varies spatially in a parabolic manner (Fig. 15b). In both situations, the bending moment commonly observes monotonic variation, with a maximum at the base. Although the load exerted on real wild bamboo

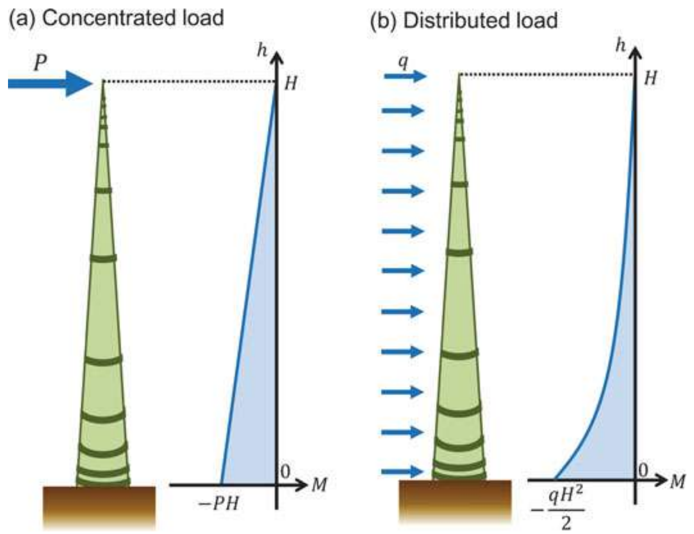

Fig. 15 Bending moment diagram of a bamboo culm under lateral loading. **a** The case of a one-point concentrated load at the top. **b** The case of a uniformly distributed load along the culm. Reprinted with permission from [20], Copyright 2016, American Physics Society

shows a more complex dependence on elevation, in general, the maximum bending moment is observed at the base. This is why $\Omega(x)$ must be significantly small near $x = 0$.

Further attention should be paid to the qualitative agreement in the profile between the $\Omega(x)$ curve (Fig. 14b) and the bending moment diagram (Fig. 15). We observed that the applied bending moment decreases monotonically from the base to the tip, which implies that the need for reinforcement decreases as the height increases. Correspondingly, $\Omega(x)$ increases monotonically with x, indicating that the degree of reinforcement gradually disappears toward the tip. The harmony between the monotonicity in the $\Omega(x)$ curve and the bending moment diagram indicates a plausible guiding principle for the morphology of wild bamboo. During the growth process, bamboos control its geometric parameters, such as $\updownarrow(x)$, $r(x)$, and $w(x)$ so that the resulting $\Omega(x)$ increases with x in a monotonic manner. In this context, the node-induced reinforcement of the culm should be almost unnecessary near the tip; therefore, it is inferred that diaphragms near the tip only support the weight of the branches and leaves that are densely distributed around the tip. In fact, it is widely observed that bamboo typically produces new branches from nodes positioned higher than the middle part of the culm. In addition, each new branch grows upward from the node, growing leaves at various positions along that branch. This implies a role for the nodes near the tip in sustaining the branches instead of reinforcing the culm.

It should be noted here that an evaluation of the spatial variation of $\Omega(x)$ is essential for a theoretical consideration of the role of nodes and internodes in the mechanical stability of bamboo. In other words, nonsensical to simply observe $\updownarrow(x)$

alone. Rather, it is important that $\Omega(x)$ monotonically increases by combining the spatial variations of $\updownarrow(x)$, $r(x)$, and $w(x)$. By observing the increasing trend of $\Omega(x)$, we can perceive that bamboo effectively resists the bending moment acting from the base to the tip as illustrated in Fig. 15. In summary, the morphology of wild bamboo culm is optimized in the sense that every internode possesses an appropriate value of Ω in response to the applied bending moment.

4.3 Sample-Dependent Fluctuation

It is important to note that the degree of gradual change in internode length can vary from culm to culm, even when our attention is limited to only a single bamboo species [35, 36]. This is also true for interspecific variation; there is a large variation in the change in internode length between different bamboo species [19]. Therefore, to draw quantitatively reliable conclusions, it is important to develop a normalization procedure that eliminates both intraspecific and interspecific variations in the change in internode length distribution for different bamboo species. This mission was successfully achieved in Ref. [32], where the intraspecific and interspecific variations in the change in internode length along the culm in three species of the genus Phyllostachys were investigated with different culm sizes in a quantitative manner. The normalization procedure was based on the cumulation and relativization of the field measurement data of the internode length distribution, confirming the validity of the universal parabolic curve of $\updownarrow(x)/\updownarrow_{\mathrm{av}}$ shown in Fig. 14a for three different species of bamboo.

5 Graded Distribution of Vascular Bundle

5.1 Functionally Graded Materials (FGMs)

In Sect. 5, we focus on how the reinforcing fibers, that is, the vascular bundles embedded in the xylem of bamboo, effectively enhance the mechanical stability of bamboo culms. In terms of structural mechanics, bamboo is a fiber-reinforced composite material that consists of two constituents: vascular bundles as reinforcing fibers and the soft tissue surrounding them. The reinforcing fibers are longitudinally aligned and have a Young's modulus in the order of several gigapascals, comparable to steel.

Figure 16 illustrates the hierarchical structure of vascular bundles, scaling it down to its building unit cell. Vascular bundles in the soft matrix are surrounded by supporting fibers responsible for bamboo's remarkable mechanical properties. In the hierarchical structure, cellulose microfibrils reinforce the intertwined hemicellulose–lignin matrix. Linear chains of glucose with orderly hydrogen bonds form the

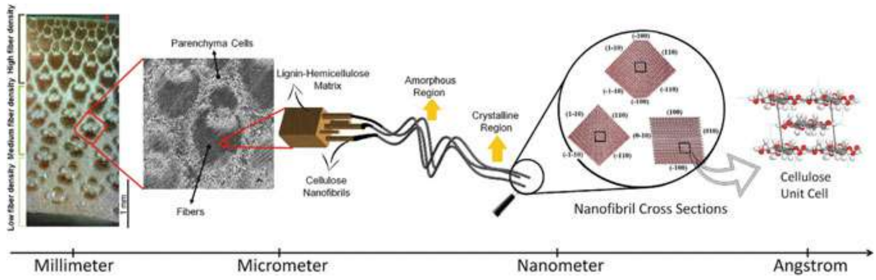

Fig. 16 Hierarchical structure of the vascular bundle embedded in bamboo culm's cross-section. Adapted from [37], License CC BY

crystalline regions of the microfibrils, whereas irregular hydrogen bonds create the amorphous regions.

The spatial distribution of the vascular bundles is of particular importance. As seen in the leftmost panel of Fig. 16, the vascular bundles are sparsely distributed on the inside near the hollow part of the culm, whereas they gradually become denser toward the outer epidermis of the culm. The biased distribution of the fibers across the wall thickness is considered to enhance the bending stiffness of the culm as a whole against crosswinds and bending owing to gravity. In this context, bamboo can be considered a functionally graded material (FGM) developed by nature. In the fields of materials science and engineering, FGM refers to functional materials obtained by spatially changing their internal physical properties and chemical composition.[12] Various types of artificial FGMs have been developed thus far. Furthermore, FGMs also exist in natural objects, for example, bones and teeth in the body, shells, and plants. One of the reasons why FGM occurs so frequently in nature is that living cells tend to adapt to external stimuli. Their self-adaptive properties are believed to have caused a natural gradient structure in the course of evolution, increasing the stiffness-to-weight ratio. In this context, we can say that bamboo is one of nature's most typical and interesting forms of FGM.

In the subsequent argument, we will unravel the intriguing fact that bamboo is an ideal naturally designed FGM in the sense that the volume fraction of the vascular bundles is optimally regulated to achieve the maximum bending stiffness of the bamboo culm. By examining the cross-sectional fiber distribution in detail, we can expect to obtain optimal design guidelines for fiber-reinforced cylindrical composite materials inspired by the morphology of bamboo.

[12] A few examples of artificial FGMs are (i) optical fibers with a continuously changing internal refractive index and (ii) heat-resistant panels for spacecraft that greatly reduce the generation of thermal stress by continuously changing the material composition.

5.2 Formulation of Fiber Distribution

To explain how the radial distribution of fibers embedded in wild bamboo is superior with regard to structural mechanics, the bamboo culm can be modeled as an elastic cylinder with a radius a and wall thickness h. In a circular cross-section, the reinforcing fibers are assumed to scatter radially from the inner hollow core towards the outer surface in a gradient manner. Further, we assume that the fiber volume fraction is represented by $V_f(r)$ obeys the parabolic equation shown below:

$$V_f(r) = c_0 + c_1 r + c_2 r^2 \left(a - \frac{h}{2} \le r \le a + \frac{h}{2}\right) \quad (5)$$

The assumption made in using Eq. (5) is consistent with existing studies that assumed the measurement data $V_f(r)$ for real bamboo can be fitted well by the curve of a gradually increasing function with respect to r. The precise form of the curve is either linear, parabolic, or forms another smooth curve, depending on the bamboo species and height of the culm section from the ground.[13]

It is expected that, in a real bamboo cross-section, many vascular bundles are optimally distributed to maximize the bending stiffness of the entire culm. To explore the optimal distribution, we first apply a virtual situation wherein a given number of reinforcing fibers are uniformly scattered with equal density throughout the wall thickness. We then impose a spatial gradient on the density of the fiber while maintaining an unchanged total number of fibers. In the initial virtual situation, $V_f(r)$ is a constant denoted by $V_f^{\rm av}$, at arbitrary positions in the cross-section. After imposing a certain gradient, $V_f(r)$ becomes r-dependent. The effect of the gradient distribution is thus evaluated by comparing the bending stiffness obtained from the r-dependent $V_f(r)$ with that from the constant $V_f^{\rm av}$. To formulate the optimal fiber distribution, we begin with a hypothetical situation in which a certain number of reinforcing fibers are distributed uniformly throughout the wall thickness. Thereafter, we consider a case where the fiber density is given a spatial gradient without altering the total number of fibers. In the former hypothetical uniform distribution condition, the value of $V_f(r)$ is equal to a constant, denoted by $V_f^{\rm av}$, at all positions in the cross-section. Conversely, in the latter condition, where a gradient is imposed on the fiber distribution, $V_f(r)$ becomes functionally dependent on r. Therefore, the effect of gradient distribution on the bending stiffness of culm can be quantitatively evaluated by comparing the bending stiffness calculated in the former and latter states.

To adjust the degree of the spatial gradient imposed on fiber density, we assumed that the total number of vascular bundles is conserved and constant. The conservation hypothesis requires $V_f(r)$ to follow the following relationship:

$$2\pi a h \cdot V_f^{\rm av} = \int_0^{2\pi} d\theta \int_{a-\frac{h}{2}}^{a+\frac{h}{2}} V_f(r) r dr \quad (6)$$

[13] Note that Eq. (5) does not rule out the possibility of a linear form of $V_f(r)$ with respect to r, as the linearity is restored by setting $c_2 \equiv 0$.

The left-hand side represents the total cross-sectional area of the vascular bundles that should be conserved. Substituting Eq. (5) into Eq. (6), followed by integration, the conservation hypothesis is expressed in terms of coefficients c_j, as follows:

$$V_f^{\text{av}} = \frac{1}{ah}\sum_{j=0}^{2}\frac{c_j}{j+2}\left[\left(a+\frac{h}{2}\right)^{j+2} - \left(a-\frac{h}{2}\right)^{j+2}\right] \tag{7}$$

Note that Eq. (7) relates three coefficients, $\{c_j\}$ $(j = 0, 1, 2)$. To satisfy Eq. (7), only two of the three coefficients can be taken as independent parameters. Hereafter, we choose c_1 and c_2, as the independent parameters and the remaining parameter, c_0, as the dependent variable determined by the other two.

Furthermore, the following three assumptions are made based on the results of actual tissue observations [24]:

1. The value of $V_f(r)$ increases monotonically with r. When $c_2 \neq 0$, it is convex downward.
2. There is an upper bound to the value of $V_f(r)$ at the outermost culm surface that is designated by V_f^{out}.
3. There is a lower bound to the value of $V_f(r)$ at the innermost culm surface, designated by V_f^{inn}.

For wild Moso bamboo, V_f^{out} and V_f^{inn} were estimated to be ca. 0.6 and 0.1, respectively. These values will be used as the typical ones in the rest of the discussion because the conclusions obtained are not overly dependent on the numerical setup details.

5.3 *Formulation of Bending Stiffness*

We can now derive the bending stiffness D_c of the fiber-reinforced cylindrical composites under bending. The bending stiffness D_c is a physical quantity that indicates the resistance to the bending deformation of a beam. For isotropic materials, the bending stiffness is expressed by the product EI; here, I is the second moment of inertia, which is determined by the cross-sectional shape and size of the beam, and E is the elastic modulus of the material. However, in the case of bamboo culm, the modulus of elasticity may vary in space, and thus, D_c is defined by

$$D_c = \int_{a-\frac{h}{2}}^{a+\frac{h}{2}} dr \int_0^{2\pi} d\theta \left[E_c(r)\cdot r^3 \sin^2\theta\right] \tag{8}$$

Here, $E_c(r)$ represents the r-dependent local modulus of the cylindrical composite. For general composite materials, the modulus of elasticity is approximated using the rule of mixtures:

$$E_c(r) = E_f V_f(r) + E_m\big[1 - V_f(r)\big] \tag{9}$$

where E_f and E_m are the elasticity moduli of the reinforcing fibers and surrounding soft matrix, respectively.[14] By substituting Eq. (9) into Eq. (8), followed by integration, D_c can be expressed in a quadratic form in terms of c_1 and c_2.

Using the above mathematical calculations, it is possible to theoretically obtain the values of constants c_1 and c_2 that maximize the bending stiffness D_c under given conditions with respect to V_f^{av}, E_f, E_m, a, and h. Hereafter, we introduce another bending stiffness D_c^0 for the virtual case of the constant fiber distribution, which is obtained by replacing $E_c(r)$ in Eq. (8) with a constant E_c^0. This is to quantitatively demonstrate the extent to which the bending stiffness of the system is improved by choosing optimal values for the constants c_1 and c_2. Thereafter, the effect of the functional gradient on the enhancement of D_c can be quantified by the improvement ratio η defined by

$$\eta = \frac{D_c - D_c^0}{D_c^0} \tag{10}$$

5.4 Optimal Fiber Distribution

Figure 17a illustrates the optimal radial distribution of reinforcing fibers for various conditions on the value of V_f^{av}; the horizontal axis indicates the normalized radius $\overline{r} = r/a$ with the outer radius a. When V_f^{av} is relatively small (less than 0.3), the optimal distribution has a parabolic function form with respect to $\overline{r}$, meaning that the fiber density needs to increase swiftly from the inside to the outside of the culm's cross-section in the radial direction. When V_f^{av} approaches 0.5, the optimal distribution alters to a linear function form.

Surprisingly, the optimal $V_f(\overline{r})$ curves, which have been theoretically estimated for various V_f^{av} values were in quantitative agreement with the measured vascular distribution of wild Moso bamboo. For wild Moso bamboo, it was experimentally observed that the base cross-section exhibited a parabolic distribution of the vascular bundles with V_f^{av} having a small value (ca. 0.2). In contrast, the cross-section close

[14] The rule of mixture can be derived by the following argument. Suppose a composite material is under uniaxial tension σ. If the material is to stay intact, the strain of the fibers ϵ_f must equal the strain of the matrix ϵ_m. Within the elasticity range, we have $\sigma_f/E_f = \epsilon_f = \epsilon_m = \sigma_m/E_m$, where σ_f and σ_m are the stress of the fibers and matrix, respectively. Noting stress to be a force per unit area, a force balance indicates that $\sigma = f\sigma_f + (1-f)\sigma_m$, where f is the fiber volume fraction in the composite. Since $\sigma = E\epsilon$ with an elastic modulus of the composite E and strain of the composite ϵ, the above two equations can be combined to yield $E\epsilon = fE_f\epsilon_f + (1-f)E_m\epsilon_m$. Finally, since $\epsilon = \epsilon_f = \epsilon_m$, the overall elastic modulus of the composite can be expressed as $E = fE_f + (1-f)E_m$, as given by Eq. (9).

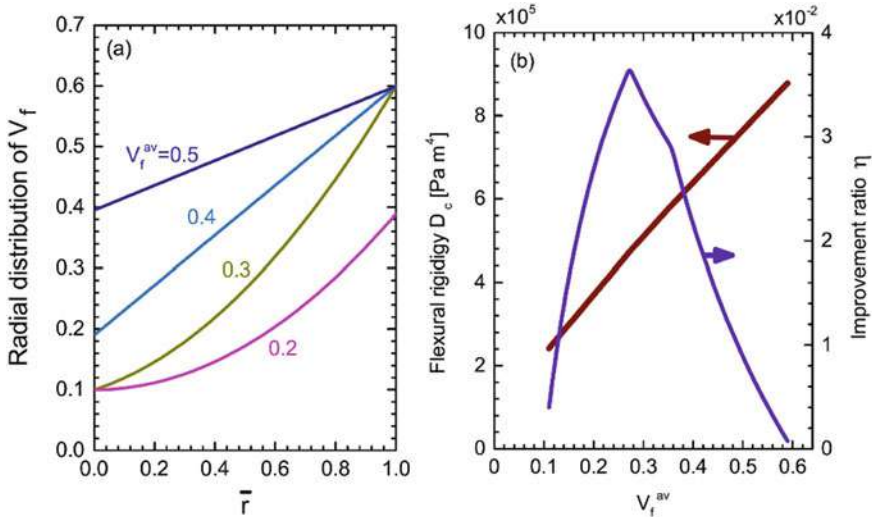

Fig. 17 **a** Optimal fiber distribution $V_f(\overline{r})$ for various conditions of V_f^{av}. **b** Maximized bending stiffness D_c and the improvement ratio in the rigidity η. Adapted from [24], License CC BY

to the top exhibited a linear distribution with a larger V_f^{av} (ca. 0.4). Consequently, the best-fitting curve for the radial distribution data of vascular bundles gradually changes from parabolic to linear with increasing internode height, as displayed in Fig. 18a. These experimental observations are well reproduced by the theory developed in Sato et al. [24], as clearly shown in Fig. 17a (also see Fig. 18b). The excellent agreement between these theoretical and experimental results supports the hypothesis that wild bamboo regulates the spatial distribution of vascular bundles using mechanical stability as a guiding principle, thereby maximizing its bending stiffness.

Another notable fact can be deduced from the Fig. 18c panel showing the monotonic increase in D_c with V_f^{av} for Moso bamboo. From base to top, the ratio of the cross-sectional area of the squeezing fibers to the total cross-sectional area of the culm increases monotonically with a doubling difference between the base (ca. 20%) and the top (ca. 40%). As derived from the theoretical consideration, within the range of V_f^{av}, the magnitude of the improvement ratio η is expected to be maximized at $V_f^{\mathrm{av}}= 0.28$ (see Fig. 17b). For this η-maximal situation, the optimal distribution curve satisfies the boundary conditions of $V_f(\overline{r}) = V_f^{inn}$ at $\overline{r} = 0$ and $V_f(\overline{r}) = V_f^{out}$ at $\overline{r} = 1$. In addition, the degree of downward convexity in the $V_f(\overline{r})$ curve is as large as possible. Beyond the η-maximal situation, the degree of convexity is allowed to degrade, while V_f^{av} increases to maximize D_c, although η itself decreases, as observed in Fig. 17b. This causes a crossover from the parabolic to the linear zone.

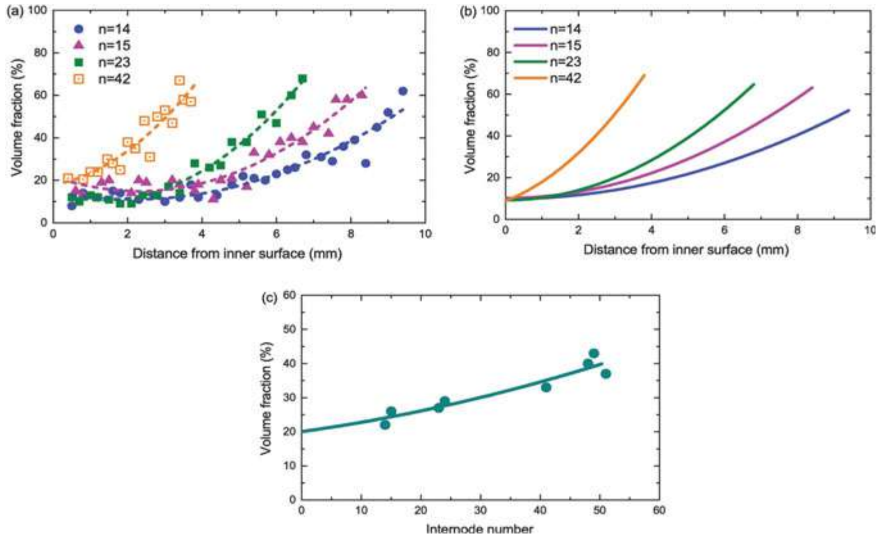

Fig. 18 Comparison between the theoretical results and field measurement data. **a** Field measurement data of the fiber's volume fraction in wild Moso bamboo in the radial direction. The index *n* represents the internode number counted from the base. **b** Theoretical curve representing the optimal fiber distribution in an elastic hollow cylinder. **c** Monotonically increasing trend of the fiber volume fraction with the internode number. Adapted from [24], License CC BY

6 Concluding Remark

In this chapter, we explained how the shape of wild bamboo is mechanically rational based on the latest research results. A specific emphasis was placed on the longitudinal arrangement of diaphragms (circular disks inserted into the culm cavity at internodes) and the radial distribution of vascular bundle sheaths embedded inside the woody portion, both of which efficiently enhanced the bending stiffness of bamboo culms. First, regarding the arrangement of the diaphragms, we saw that they are located at an appropriate position so that the dimensionless constant Ω defined by the culm thickness, radius, internode length, and Young's modulus, monotonically increases from the base to the tip of the culm. Thereafter, regarding the vascular bundle sheath, it was explained that the bending stiffness of the culm is maximized by the linear or parabolic distribution of the vascular bundle sheath, with an exquisite balance from the inside to the outside of the cross-sectional area of the culm. The most notable finding was the excellent agreement between the morphological data of the bamboo culms obtained from field measurements and the theoretically derived optimal mechanical morphology of bamboo.

Before concluding this chapter, the authors would like to introduce certain interesting (but still unresolved) problems regarding the relationship between bamboo culm morphology and their mechanical function:

1. Looking at the bamboo culm from the side, it is thick at the base and tapers toward the tip. This tapered shape is common to all species, but the rate at which the culm tapers along the length varies greatly among bamboo species [32]. The culms of certain species of bamboo may rapidly taper toward the tip. In contrast, in other species of bamboo, the culm diameter at the base and middle of the culm does not differ significantly; the taper is significant only near the tip. How do these different degrees of culm taper relate to the overall structural stability of the culm and the reduction in internal stress? Is there an optimum taper shape that reduces internal stress most effectively, depending on the total height and/or weight of the culm?
2. As mentioned in the main text, the hollowness of bamboo helps reduce the self-weight of the culms. However, to efficiently increase the height of the culm for photosynthesis, it is necessary to strike a balance between the degree of taper and hollowness of the culm. It is expected that the conditions for maintaining this balance can be theoretically derived by replacing the self-weight buckling problem of the hollow column [39]. If the theoretical solution agrees with actual bamboo measurement data, the results may lead to rational design principles for tower structures.
3. In many species, bamboo exhibits the shape of a straight, hollow cylinder. However, there are species of bamboo with completely different shapes. One example is tortoise shell bamboo (*Phyllostachys heterocycla*), a remarkable bamboo species with internodes resembling a tortoise shell. In this species, internodes are slanted and closely compressed on alternating sides of the culms, resulting in a zigzag pattern similar to a tortoise shell. Another example is square bamboo (*Chimonobambusa quadrangularis*), which has a square-shaped cross-section in the culm [40]. From a mechanical point of view, a square (or triangular) cross-sectional shape of the culm or stem results in an increase in the bending stiffness for general plants [41]. What kind of mechanical advantage is hidden in the shape of bamboo culms of these unique species? Or is it just a mutation that has no mechanical advantage and will eventually be eradicated?

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Review of the State of the Art Using μCT to Elucidate Complex Vascular Systems of Plants

Heike Beismann and Matthias Fischer

Abstract Computer tomography was introduced for medical imaging in the early 1970s but, soon after, was also applied in both the natural sciences and the materials sciences. Since then, as a non-destructive diagnostic tool, it has also provided impressive insights into the morphology and anatomy of plants and animals. A particular advantage is the examination of tissues in their natural spatial arrangement. The position and distribution of the various tissues provide information on possible biomechanical properties in addition to purely morphological insights. Biomechanical information is important for a comprehension of the structure–function relationship and the subsequent transfer to innovative biomimetic applications in technology. This chapter presents previous work on the analysis of three-dimensional structures of complex vascular systems in several plant species by means of μCT, up to the state of the art. This includes technical conditions of the CT scans and methods for the segmentation of ROIs. Special attention will be paid to the possibilities that arise from the knowledge about structure–function relationships in plant materials. Potential innovative biomimetic developments and sustainable technical developments are considered. In doing so, the possibilities of μCT analyses and the evaluation options are discussed in general and, in addition, the possibilities that arise when μCT analyses are combined with other methods like finite element analyses or three-dimensional deformation analyses (digital image correlation) are presented.

Keywords μCT · X-Ray computer tomography · Biomimetics · Bionics · Segmentation · Structure–function relationship · Finite element analysis (FEA) · Digital image correlation (DIC)

H. Beismann (✉) · M. Fischer
Westphalian Institute for Biomimetics, Westphalian University of Applied Sciences, Münsterstraße 265, 46397 Bocholt, Germany
e-mail: heike.beismann@w-hs.de

M. Fischer
e-mail: matthias.fischer@w-hs.de

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1 Introduction

The arrangement of vascular bundles in plants is of particular interest to understand the relationship between structure and function, which is directly connected to the challenge of visualising 3D structures [9]. The cross-sectional distribution of the vascular bundles is determined by the body plan (sometimes referred to as *bauplan*), a set of morphological features common to the species within a phylum [19, 39]. The general body plan for monocotyledons is an atactostele and for dicotyledons, a eustele. Deviations from the body plan are possible with respect to the specific functions [39]. The morphological descriptions of the respective structures of the vascular system help in understanding the systematics of the plant kingdom and are thus an important basis for an understanding of functions and mechanical properties in different plant groups.

To decipher the 3D structure of vascular systems, serial sections and light microscopy were necessarily followed by manual stacking and reconstruction from the perfect alignment of images, a time-consuming work. Even with the development of the optical shuttle technique [92], the manual reconstruction of vascular networks remained a problem [9], and furthermore, the techniques using cross-sections had to destroy the original structure. Recent non-destructive 3D imaging technologies have just started to overcome these problems [9, 29, 30, 75], and even go further by introducing the fourth dimension when analysing the same object at different times [20, 30].

The vascular system in plants is primarily responsible for water and assimilate transport. In this process, water is transported in most vascular plants from the root system, which is usually located in the soil, to the leaves, where the plants constantly transpire water through their stomata to the atmosphere. This ensures constant water transport via the xylem, which not only supplies all cells with the necessary water but also distributes all nutrients in the plant. However, there are also findings of reverse flow in some vessels [40]. Assimilates produced in the photosynthetically active tissues, mostly the leaves, have to be distributed from there to all other parts of the plant. This transport takes place inside the phloem in different directions. Along with water and assimilates, other substances are distributed by this transport system, e.g. hormones or electrical signals.

In addition, the vascular system fulfils a mechanical function and contributes via its three-dimensional structure to the stability of plant stems [29, 51], branching attachments, petiole–lamina connections and plant organs like fruits. Not only does the vascular system itself need to have a certain stability in order to fulfil the above-mentioned transport functions, e.g. not collapse due to strong transpiration pull [78], but the entire plant stem also benefits from the arrangement of strengthening tissues, specifically from the vascular bundle system, which contributes significantly to stability [70]. The arrangement of the strengthening tissues and the vascular bundles not only have an influence on the mechanical stability but also on the possibility to actuate a movement, as the arrangement of the vascular bundles may have a decisive influence on the opening seam and the kinematics of a movement [21].

Despite these diverse tasks the vascular tissue has to fulfil, there are still knowledge gaps about the exact functioning. For example, it has not yet been possible to understand exactly how water is transported from the roots to the tips of the tallest trees. Although the cohesion–tension theory is widely supported as the only theory consistent with the majority of data on water transport [44], recent technological advances have allowed a more careful examination of the underlying principles [11]. The maintenance of an uninterrupted water thread, or the repair mechanisms in the event of a break, are of great scientific interest and economic importance, e.g. to understand the mechanisms of drought tolerance in plant cultivars. Knowledge about the functioning of the vascular system is therefore necessary in order to be able to select the desired characteristics when breeding new varieties [90]. Since the vascular system also ensures the mechanical stability of a plant, knowledge about the arrangement of the vascular bundles or the growth of wood in tree-shaped plants is important for both agriculture and forestry. Wood and woody plants like bamboo have always played a major role in human history as raw and building materials. Understanding how this natural composite material is structured and how it can be analysed via CT techniques not only enables a more reliable quality assessment [8, 43] but also leads to more efficient and sustainable use of the material for human use.

Methodologically, early descriptions of vascular systems have in common that they emerged either from a series of cross-sections, macerations or dye staining [83]. Such methods involve the destruction of the original structures. Nevertheless, it was possible for early morphologists to create an astonishingly accurate picture of the three-dimensional relationship of the structures in this way [58].

Non-destructive analytical methods to identify the three-dimensional design of the vascular system, linked to the natural functions of conduction and mechanical stability, have only recently become possible. The latest imaging techniques, as made possible by the development of high-resolution μCT, support our understanding of the three-dimensional arrangement of the vascular bundle system and, at the same time, allow us to analyse water transport and embolism in situ [11].

In addition, it is now possible to investigate the stabilising function of the vascular bundles in their natural position without destroying them and thus to gain insights into complex vascular systems in nodes, branch connections, inverse structures, etc., which were previously difficult to decipher (Sect. 2.1).

Various methods are now available for non-destructive analyses, e.g. different CT techniques (Sect. 3) and MRI techniques [30]. New modelling options and image evaluations are currently enabling further new insights into structure–function relationships. Classical methods can also be combined with the latest image processing possibilities to reconstruct 3D images and thus complete our idea of complex 3D structures. Methods that can resolve complex structures non-destructively on the one hand and, on the other hand, can use the image material to create models via FEA that allow further statements about the mechanical behaviour appear to be particularly target-oriented (Sect. 4).

Another important point is the fact that some evaluation methods became only possible due to the increased performance of today's computers. For example, digital image correlation (DIC) can be used today to evaluate images taken in succession, e.g. to determine surface deformations. On the other hand, it can also be used to segment regions of interest (ROIs) in adjacent images, i.e. image stacks such as reconstructions based on μCT data (Sect. 4).

So far, only a few complex vascular systems have been investigated with these new methods. One cause for this situation is certainly the currently very expensive equipment and software packages that are necessary. Nevertheless, the devices are becoming financially more affordable and, therefore achievable for more working groups.

This review presents the knowledge gained so far on vascular systems of monocotyledonous and dicotyledonous plant taxa of the angiosperms, and gymnosperms using μCT. Selected taxa of economic interest, such as the monocotyledons bamboo and maize, as well as studies with a stronger scientific focus, which could only be studied in detail by a combination of different methods, are presented.

Findings from μCT analyses are also of interest for the production and use of modified natural materials, e.g. to influence the durability of natural materials. The development of fibre-reinforced polymers (FRP) can also benefit from these findings, as arrangements and length of fibres have a decisive influence on the mechanical characteristics in various load directions of a component. However, it is not only the insights from the upcoming new non-destructive technologies that can use natural materials more beneficially. Further examples are illustrated to show how the insights into the principles behind the biological models can be used to develop new biomimetic[1] products.

2 Vascular Bundle Systems in Plants Studied by μCT

2.1 Morphology and Anatomy of Selected Examples

The number of species whose vascular systems have been analysed by μCT is still quite limited; however, the methods and the appropriate equipment are currently developing rapidly [57] (Sect. 3, Fig. 1). Of course, the vascular systems of plants were studied early on and plant taxa were grouped according to the arrangement of their vascular bundles, the so-called stele. In angiosperms, atactosteles are found within the monocotyledons, while, in dicotyledonous plants, eusteles are the typical form of the vascular bundle system. So far, not only monocotyledon and dicotyledon

[1] In this text, *biomimetics* is used according to ISO 18458 [36], to describe all products and processes that use nature as a source for new inventions by abstracting the principles and applying them to innovative products. To avoid misunderstandings only this term is used, although the term *bionics* is sometimes used in literature as a synonym.

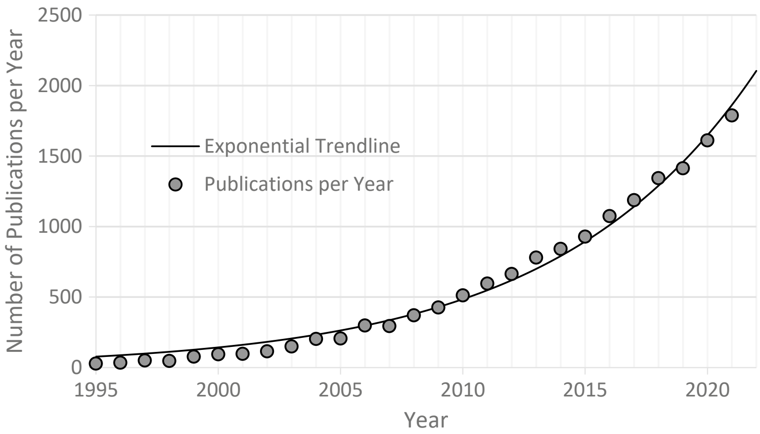

Fig. 1 X-ray microtomography publications per year between 1995 and 2021 from Web of Science "Core Collection" search from November 03, 2022; a total of 16,362 results[2]

angiosperms have been examined by μCT but also fibre bundles and wood of gymnosperms (Table 1).

Studies on vascular systems using μCT that have been published so far can be divided, depending on the goal of the research, into questions that either deal with economic challenges or are guided by scientific interests. The list of work on vascular systems in Table 1 gives an overview of essential work in which new or expanded knowledge was gained through μCT analyses of vascular systems in plants. This list does not claim to be complete, especially as this field of research is currently developing very dynamically [57] (Fig. 1). Not included is literature about the use of μCT in wood and timber analyses, hence this was not the focus of this review. The compilation in Table 1 is only intended to introduce the literature dealing with different aspects and goals of research on vascular systems studied with μCT.

Early work using analysis by μCT describes its feasibility on various objects and emphasises its potential in non-destructive analysis of delicate plant parts as no preparation is needed [75]. With the possibility to study plant structures in their

[2] Search phrase for "advanced search": (((ALL = "μCT" OR ALL = "μ-CT" OR ALL = "micro-CT" OR ALL = "mu-CT" OR ALL = "mu CT" OR ALL = "HRCT" OR ALL = "HR-CT" OR ALL = "HRXCT" OR ALL = "microtomography" OR ALL = "micro-tomography" OR ALL = "micro tomography" OR ALL = "μ-tomography" OR ALL = "μ tomography" OR (ALL = "holography" AND ALL = "micro") OR ALL = "nanoCT" OR ALL = "nano CT" OR ALL = "nano-CT" OR ALL = "nanotomography" OR ALL = "nano tomography" OR ALL = "nano-tomography") AND (ALL = "X-ray" OR ALL = "Xray" OR ALL = "X ray")) OR (ALL = "XTM" AND (ALL = "microtomography" OR ALL = "micro-tomography" OR ALL = "micro tomography" OR ALL = "μ-tomography" OR ALL = "μ tomography") AND (ALL = "X-ray" OR ALL = "Xray" OR ALL = "X ray")) OR ((ALL = "high resolution" OR ALL = "high-resolution") AND ALL = tomog* AND (ALL = "X-ray" OR ALL = "Xray" OR ALL = "X ray")) OR ((ALL = microcomp* OR ALL = micro-comp* OR ALL = "micro computed") AND ALL = tomog* AND (ALL = "X-ray" OR ALL = "Xray" OR ALL = "X ray")) OR ALL = "XμCT").

Table 1 Compilation of selected species, plant parts whose vascular system was analysed with µCT techniques, corresponding family, the field of the research, and references. Grouped in Angiospermae (Monocotyledons, Dicotyledons) and Gymnospermae

Scientific name	Common name, analysed plant part	Family	Field of research	References
Angiospermae, monocotyledons				
Qiongzhuea tumidinoda	Bamboo Nodes	Poaceae	Vascular system of bamboo nodes	[41]
Bambusa tuldoides	Bamboo Internodes and nodes, branching region	Poaceae	Vascular elements in nodal and internodal sections, arrangement of bundles that connect primarily with secondary axes	[53, 54]
Indocalamus latifolius *Shibatae chinensis*	Bamboo Nodes	Poaceae	Net-like vascular system in the nodal region. Comparison of single-branched type and multi-branched type	[87]
Phyllostachys eduli	Moso bamboo Internodes and nodes	Poaceae	Density distribution of nodes and internodes	[33]
Zea mays	Maize, several varieties Stem	Poaceae	Phenotyping different vascular bundle traits for genomics and breeding of varieties	[89, 90]
Cocos nucifera	Coconut Endocarp	Arecaceae	Biomechanics of toughening materials for biomimetic applications on various hierarchical levels	[66]
Hosta x tardiana *Caladium bicolor*	Hosta Heart of Jesus Petiole–leave-transition zone	Asparagaceae Araceae	Vascular tissue of the petiole–lamina transition zone of monocotyledons compared to dicotyledons	[39]
Dracaena marginata	Song of India Branching region	Asparagaceae	Branching patterns of the vascular system	[30]

(continued)

Table 1 (continued)

Scientific name	Common name, analysed plant part	Family	Field of research	References
Haumania danckelmanniana *H. liebrechtsiana* *Hypselodelphys hirsute* *H. scandens* *Trachyphrynium braunianum*	Nodal and internodal regions	Marantaceae	Inverted vascular bundles in nodes only appear in *Haumania* and are not connected to climbing growth form	[38]
Angiospermae, dicotyledons				
Macadamia integrifolia	Macadamia nut Seed coat	Proteaceae	Biomechanics of strengthening material for biomimetic applications on various hierarchical levels	[67]
Banksia attenuata	Candlestick banksia Fruit	Proteaceae	Biomechanics of opening fruits, bilayer structure with network-like fibres of vascular bundles	[34, 35]
Hakea salicifolia *Hakea sericea*	Willow-leaved needlewood Bushy needlewood Fruits	Proteaceae	Biomechanics of opening fruits, network-like and honeycomb structure of fibres of vascular bundles	[26]
Ibicella lutea, *Proboscidea louisianica*	Trample burrs, fruits	Martyniaceae	Biomechanics of strengthening materials and attachment mechanisms with a focus on mechanical resistance and force generation	[31]
Hemigraphis alternata *Pilea* *Peperomioides*	Red ivy Pancake plant Petiole–leave-transition zone	Acanthaceae Urticaceae	Vascular tissue of the petiole–lamina transition zone of dicotyledons compared to monocotyledons	[39]

(continued)

Table 1 (continued)

Scientific name	Common name, analysed plant part	Family	Field of research	References
Quercus robur	Common oak Wood	Fagaceae	Three-dimensional reconstruction of earlywood vessels showing their distribution and connectivity and potential of μCT technique	[75]
Acer rubrum	Red maple Roots	Sapindaceae	Three-dimensional arrangement of vessel endings within xylem networks	[83]
Vitis vinifera *Vitis arizonica*	Grapevine Wild grape Internode segments	Vitaceae	Three-dimensional xylem network organisation, including inter-vessel connections and vessel-relay connections and its resistance to embolism	[10, 82]
Cannabis sativa	Hemp Stem segments	Cannabaceae	Characterisation of phloemian primary and secondary fibres for composite materials reinforcement	[6]
Colignonia glomerate and further species	Four o'clock family, stems of 62 species	Nyctaginaceae	Comparison of the vascular system of 62 species for systematic purposes, the primary vascular system can be subdivided into the polycyclic eustele with medullary vascular bundles and the regular eustele	[15]
Gymnospermae				
Pinus sylvestris	Scots pine Cone scale	Pinaceae	Biomechanics of movement of pine cone scale for biomimetics, arrangement of fibre bundles and tissue layers	[20]

natural position even new insights arise that can expand the previous ideas of the arrangement of vascular bundle systems such as the medullary bundles in the polycyclic eustele in Nyctaginaceae [15] or the inverse vascular bundles in Marantaceae [38]. It soon became evident that μCT analyses of opaque materials, in particular, have great potential [57]. However, other methods like light microscopy of serial thin sections followed by 3D reconstruction or magnetic resonance imaging (MRI) should also be considered [30].

Within the monocotyledons, maize and bamboo are of particular scientific and economic interest. Maize is one of the most important staple food crops in the world [27], and understanding structure–function relationships of the vascular bundle system gained via μCT analyses is important knowledge, not only valuable to evaluate biomechanics and water-transport performance but also to yield micro-phenotypic growth-based traits for molecular breeding [89, 90].

Bamboo is an important resource for various products, such as paper, furniture and structural composites, especially in Asian countries [87] (see also various chapters in this book). Non-invasive imaging techniques using μCT, have been increasingly used to explore the morphology or anatomy of different bamboo species (Table 1). In 2014 the complex vascular system of bamboo nodes was first analysed by Peng et al. [62] using μCT techniques. Later, internal structures like density [33], cortex [81], the arrangement of vascular bundles in nodes [41, 54] and the vascular systems in single-branched or multi-branched species [87] were studied, leading to new insights into biomechanical stability, water and nutrient supply [41, 87]. Further studies on the vascular bundle system in stem–branch attachments of the monocotyledonous *Dracaena marginata* show comparable distribution patterns with horizontal vascular bundles to those found in bamboo [30, 87].

The transition zone from petiole to leaf lamina is a region that is susceptible to mechanical stress. In the transition zone, notch stresses occur that could lead to failure. The course of vascular bundles depends not only on the body plan but also on the geometry of the petiole–lamina geometry, thus on the loads that occur. Two different types of geometries can be distinguished in monocotyledonous and dicotyledonous plants, peltate- or umbrella-shaped leaves, with petioles attaching centrally to the abaxial side of the lamina (3D) and geometries with marginal petiole insertion (2D) [86]. A comparison of the different distribution patterns of vascular bundles in monocotyledonous and dicotyledonous plants in the transition zone from petiole to leaf lamina using μCT shows distinct differences. In the petiole, the course of vascular bundles depends on the body plan, whereas, in the transition zone, it depends on the spatial geometry of the petiole to the lamina (2D or 3D) rather than on the body plan [39].

For dicotyledonous plants, a focus of previous work on the vascular bundle system can be found in the field of biomechanics. In particular, fruits and seed coats show special mechanical properties that are influenced by various tissues, which are usually in the service of propagation and protection of the embryo [34]. Impact and puncture-resistant plant materials of the dicotyledonous Macadamia nut [67], the seed coat of its fruit, and the monocotyledonous Coconut endocarp [66], are described on several hierarchical levels and are suitable models for innovative biomimetic impact and puncture resistant products. Trample burrs, moreover, must not only have excellent strengthening tissue but also be able to attach themselves to the hooves of animals through the flexibility of their appendages. They have evolved a fascinating complex system of vascular bundles, fibres and parenchyma in the endocarp to allow epizoochory, where longitudinal bundles of lignified fibres run along the extending appendages providing the thin structures with strength and high elasticity [31]. Within the Proteaceae family, a number of species are adapted to regular bushfires. The arrangement of their vascular bundle systems and other tissues helps the fruits to open due to external factors and thus to release the seed. Typically, net-like or honeycomb-shaped vascular bundle systems are found [26, 35]. The arrangement of fibre bundles in combination with other tissues is also responsible for the reversible opening and closing movement of pine cones in gymnosperms and has already been well-studied using μCT to differentiate between the different acting tissues [20].

μCT analyses also have great potential to assess xylem network organisation. The three-dimensional network of vessels and their connections to each other have been described for *Quercus* [75] in wood and for *Acer* [83] in roots. Questions about water transport and the connection of the vessels to each other are the main focus here, with the result that vessel endings are surprisingly frequent in roots, contrary to the assumption that root vessels are longer in comparison to vessels in other tissues [83].

Uninterrupted water transport is vital for all plants, but there is also an economic benefit that can now be inferred from the analysis of gas embolisms, i.e. the interruption of water transport in situ. Results for grapevine show that the organisation of the xylem network can increase the resistance of the stem to the spread of embolism [10], and even question the idea that a single embolism can spread rapidly throughout the entire xylem network [82]. Knowledge about the formation and avoidance of embolisms can in turn help to better target breeding objectives to these traits.

2.2 Fibre-Reinforced Polymers and Altered Natural Fibre Materials

In order to better understand how fibres contribute to the mechanical properties of a natural composite, it is important to analyse the structure, distribution and orientation of fibres in biological models, like bamboo [53, 55], hemp [6] or wood [8, 84]. Furthermore, this leads to a better knowledge of how to integrate fibres into technical fibre composites. The non-destructive analysis of technical samples by μCT can also lead to a better understanding of the orientation of fibres in sample materials or FRP components. Micro-computed tomography is becoming the standard method to analyse the inner microstructure of composites using natural [23, 59] or technical fibres [3, 4, 47].

The use of fibres from plant material is of particular interest for the application in sustainable fibre composites (see also various chapters in this book). Bamboo fibres are frequently used for the production of FRP, whereby orientation, distribution and length of fibres are decisive parameters for the mechanical properties of an FRP. These parameters can better be determined by using μCT analyses than with conventional methods [23, 59]. Additionally, natural fibres can be technically altered to make them more durable. To protect bamboo from fungal attack and microbial degradation, especially during outdoor use or as fibres in FRP, impregnation of the vascular bundles with silver nanoparticles can slow down or prevent degradation. The success of impregnation and the definition of indicators for successful impregnation can be determined by using μCT analyses [60, 61].

Hemp fibres are also well suited for FRP. These are phloem fibres with distinguishable primary and secondary fibres. It was found that despite the fact that secondary fibres are shorter, similar mechanical properties could be measured and thus, both appear to be equally suitable for FRP [6].

2.3 Examples of μCT Use for Biomimetic Product Development

In biomimetics, knowledge about fibre orientation in natural models is used to derive principles that can then be used in technical implementations [36]. Particular attention is paid to mechanical features and structure–function relationships.

The rapid development of new imaging methods, e.g. SEM, TEM and AFM, as well as μCT, with new evaluation methods like FEA, DIC etc., for the characterisation of materials and thus the decoding of structure–function relationships at different scale levels has made the complex arrangements of various tissues of not only plant models but also animal models, easier to decipher [58, 91]. A deeper understanding of the fundamental relationship between structure and function is essential if a transfer to technical products is to be achieved successfully [36, 58, 80, 91]. However, a transfer can only succeed if suitable manufacturing methods, such as additive manufacturing, are available [91].

Three examples of the successful use of different analytical methods to elucidate the structure–function relationships and a subsequent transfer to initial prototypes are illustrated by bamboo, the pine cone and several different seed packages. With bamboo, a typical lightweight structure is chosen, whereas the pine cone is representative of a smart material showing repetitive movements. The illustrations of seed packages are chosen to show mechanically highly resistant materials.

Bamboo is a highly efficient natural composite structure. Only after it was possible to make the 3D arrangement of the vascular bundles in the stems visible and the overall geometry of individual vascular bundles was clarified using μCT techniques their contribution to mechanical stiffness, strength and energy absorption could be elucidated [53]. Together with the findings on the contribution of the parenchyma and gradients within the tissues to the mechanical properties, a more precise picture of the mechanical processes at the cellular and subcellular level was created [56].

The biological principles abstracted from this picture could then be applied to thin-walled structures and thus be transferred to innovative biomimetic structures with a large energy absorption capacity [55, 57] or to bamboo-inspired tubular scaffolds [88]. In addition to the arrangement of the vascular bundles in the internodes, the nodes of various bamboo species have been of particular interest from early on, as they contribute significantly to the stability of the entire plant axis. Nevertheless, until now, it has hardly been possible to clearly trace the complex branching of the vascular bundles in nodes using conventional 2D technologies such as microtome sections and subsequent microscopy. Even if early work shows that the painstaking work yielded good to astonishing results, the non-destructive analysis methods are superior and now provide a realistic picture of the complex arrangement of the vascular bundles [57]. The branching patterns of complex vascular bundle systems in the nodes of monocotyledons [38, 41, 54], the branching patterns of monocotyledons [30, 87] or the course of the vascular bundles in the transition zone of the petiole–lamina connections of monocotyledonous and dicotyledonous species [39] that have been studied so far, now make it possible to obtain a more specific picture of the distribution of stresses. This knowledge can lead to the development of biomimetic lightweight structures that consume fewer resources with the same stability as conventional construction materials and thus reduce the human impact on the environment [58].

Pine cones open in dry weather to release their airborne seeds, as the conditions for airborne dispersal are then present. They close again when the weather is unfavourable, i.e. the moisture content in the air is high. The process is reversible over years or even millennia, as has been demonstrated on fossil cones [64]. Many studies have already been carried out to analyse the pine cone scales and their kinematics depending on external factors such as dryness or moisture [2, 16]. However, the abstraction of the underlying mechanisms could only succeed after the structure–function relationships in their three-dimensional interplay of the different involved tissues could be recorded by using non-destructive analysis methods such as μCT together with simulations, force measurements, SEM, optical microscopy and digital image correlation (DIC). The mechanism goes far beyond the principle of a bilayer. Special structures for water absorption have been found in the epidermis. The internal morphology of the cone scale has further shown, through μCT images taken at different opening states, that the arrangement of the fibre bundles and the different acting layers are the major contributor to the movement [20]. Subsequently, a transfer of the mechanisms to the prototypes was possible after 4D printing methods were available that enabled the fibre structures to be designed according to the principles in the biological model [13].

Seed packages, i.e. fruit and seed encapsulations, often show materials highly resistant to mechanical forces. Distinctive packaging for the protection of seeds must essentially meet two requirements. First, it must provide protection for the seed or embryo for as long as necessary, and second, it must release the seed at the appropriate time when germination conditions are favourable [34]. The fruits of angiosperms, therefore, show manifold adaptations such as puncture resistance, break resistance, cut resistance, impact resistance, etc., often connected to highly hierarchical structures [66, 67], but at the same time, must offer the possibility of releasing the seeds. Therefore, these packages must have structures that allow opening at predestined locations (sutures). In order to release the seeds at an appropriate time, the packages must also have the ability to perceive the environmental conditions that are conducive. Since many of these packages are made of dry material, the material itself must be able to respond to environmental conditions. These mechanisms are often explained in first approximation as those of bilayer structures, however, closer examination with non-destructive methods reveals complex systems of multiple layers of tissue that work together to create an opening. Therefore, the opening sutures must be free of vascular bundles, which can clearly be seen in the μCT images of the vascular bundle systems of *Hakea* and *Banksia*, where no vascular bundles are found in the area of the opening sutures [26, 35]. The situation is different for fruits that are spread out as closed dispersal units, such as coconuts [66] or macadamia seeds [67]. Their vascular bundle systems are distributed over the entire surface of the fruit. Anisotropic properties as found in *Hakea* and *Banksia* can be of interest to the development of technical fibre composite materials. The knowledge about the arrangement of fibres could be used to generate predetermined breaking locations or to design coupling effects to achieve movements for the creation of smart components with integrated functions [26].

3 Available μCT Techniques

The first commercial X-ray computed tomography instruments for medical imaging were introduced in the 1970s, constructed similarly to Hounsfield's prototype [32] and were soon followed by industrial X-ray CT instruments that allowed for larger ranges of contrast and higher X-ray doses [72]. The latter was applied in process control, non-invasive metrology, materials performance prediction and failure analysis, while the spatial resolution of both instrument types was limited to distinguish between features that were at least several hundred μm separated [12, 72]. The wish to visualise the microstructures of materials, biological samples or fossils called for microtomography, i.e. set-ups that could resolve features smaller than 200 μm or smaller than 100 μm, respectively, depending on the author [12, 72].

The first successful X-ray microtomography using laboratory X-ray sources (X-ray tubes) was presented in 1982, showing a resolution of 15 μm [22]. A few years later followed the first X-ray microtomography systems using synchrotron X-radiation with a spatial resolution of 10 μm [5]. Since then, different instrumental set-ups have been developed using either both X-ray source types. At the beginning of this development, pencil-beams were generated with pinhole collimators. These beams passed through the object and X-ray absorption was measured directly in a small wavelength range with a zero-dimensional sensor. To get a one-dimensional view, the object was translated stepwise in the x-direction (horizontal) and one measurement had to be conducted after each step. To get a single slice, the view acquisition was repeated after each of several small rotation steps of the object, consuming a total of at least 12 h irradiation time using a laboratory X-ray source or 1 h using synchrotron radiation [37]. The next generation of instrument set-ups were fan-beam systems where a translation of the object was no longer necessary to obtain a slice but only a stepwise rotation. While the acquisition time for a slice was reduced to minutes, the detection of X-ray absorption with a one-dimensional array of photodiodes and scintillator support resulted in reconstructions of lower fidelity than pencil-beam-based images, often including ring artefacts [37, 68, 72].

Due to the development of two-dimensional sensors and high-resolution scintillator screens, parallel beam set-ups and cone-beam set-ups became accessible for synchrotron X-radiation and micro-focus X-ray sources, respectively [37]. The introduction of an appropriate algorithm for three-dimensional reconstruction instead of single-slice reconstruction was another prerequisite for the applicability of cone-beam geometry [25]. After its first implementation in an X-ray microtomography set-up [24], cone-beam geometry soon became widely used in laboratory-scale μCT systems due to its high acquisition speed and despite its initially worse resolution compared to pencil-beam systems [37]. Today, cone-beam geometry is a characteristic of laboratory-scale μCT instruments, while most X-ray tomographs for medical imaging are still (advanced) fan-beam systems [79].

To comprehend the dynamics of the increasing interest in μCT in the early 2000s, one may regard the development of commercial μCT instruments. It seems that, until the late 1990s, there was no off-the-shelf laboratory μCT instrument available [65, 72, 77]. About 10 years later, Stock listed in his second review 35 of those instruments from 15 different manufacturers and claimed the list was "almost certainly incomplete" [73].

Synchrotrons produce X-rays over a large energy range in high brilliance and in nearly parallel beams. The use of monochromators allows us to choose nearly monochromatic X-rays from this range. To achieve magnified projection images with a parallel beam, X-ray lenses or mirrors are applied, or the beam is focused, e.g. with a Fresnel zone plate to get a cone-beam with an extremely small focal spot compared to X-ray tube cone-beams, associated with less penumbral blurring [85]. Cone-beams allow magnification by varying the distances between the X-ray source, object and sensor [77]. In the early 1990s, synchrotron photon energies did not exceed 50 keV, and up to 35 keV photons were used for microtomography, limiting the sample size to a few mm. The highest obtainable spatial resolutions were 2–3 μm for synchrotron microtomography and 20–30 μm for cone-beam systems [37]. In 2004, Steppe et al. recommended to image objects of interest with dimensions less than 10 μm with synchrotron radiation, while laboratory cone-beam instruments were sufficient for dimensions larger than 10 μm [71]. Three years later, a "nano-CT" instrument was available, achieving spatial resolutions between 200 and 300 nm.

Since then, the achievable spatial resolution, in particular for laboratory X-ray tomographs, has been improving. Some of today's synchrotron set-ups as well as cone-beam set-ups are able to resolve features down to 50 nm [1, 28]. Current synchrotron X-ray set-ups allow exposure times of a few milliseconds and corresponding scan times, i.e. a temporal resolution of less than a second with a spatial resolution of a few micrometres [48]. There is a demand for high-speed imaging laboratory X-ray CT as well, allowing for high-throughput CT in industry or academic in situ testing [93]. Dewanckele et al. utilised a laboratory micro-CT system with a fixed sample stage and a horizontal rotation of source and detector, specially developed for fast imaging. At a temporal resolution of about 10 s but relatively large pixel sizes of 72–160 μm, they monitored the pore structure of decaying beer foam and the pore structure of a muffin while baking [17].

Despite all progress in the development of laboratory X-ray tomography systems, synchrotron X-ray tomography offers higher 4D resolutions (with time being the fourth dimension) and better signal-to-noise ratios. For these unique features, Toda called the latter the "flagship of X-ray tomography technology" [77]. However, accessibility of synchrotron μCT set-ups is much more limited than laboratory μCT set-ups [93].

Two techniques are predominantly used to make different sample materials distinguishable: absorption-contrast tomography and phase-contrast tomography.

Absorption-contrast tomography measures the attenuation of X-ray intensity after passing through the object for all ray paths from the source to a detection element of a sensor, for all detection elements, respectively. After collecting several of these projection images, the object rotates stepwise in relation to the linear arrangement of source and detector for at least 180°. From these projection images, a three-dimensional greyscale image is reconstructed, where the grey value of voxel represents the relative X-ray attenuation of the related space in the object.

Since the X-ray propagation speed depends on the material it passes through, there is also a phase shift of the X-ray waves happening concurrently with the attenuation processes. The phase shift is proportional to the X-ray wavelength and the real part of the complex refractive index and, thereby, the electron density of the sample material. These phase shifts are visualised by interferences between X-ray waves that pass through the sample and a reference wave. There are different methods, instrument set-ups and scan procedures to get corresponding phase shift projection images, like X-ray propagation, Zernike phase-contrast microscopy and X-ray holography or interferometry. The reconstruction process is the same as for absorption-contrast tomography [77].

Compared to absorption-contrast X-ray tomography, phase-contrast methods are more time-consuming and technically more complex [18]. Although there are several examples of laboratory set-ups, phase-contrast X-ray tomography is most often conducted in synchrotron facilities [77]. Despite these disadvantages, phase-contrast methods may allow visualising different materials that absorption-contrast methods currently do not because the difference in X-ray attenuation between the two materials is too small to be recognised by the detector. This is particularly true for light elements found in biological samples [42].

From more than 16,000 publications associated with μCT (Fig. 1), 204 are also concerned with xylem, phloem or vascular bundles and only six of those used a phase-contrast technique. All of the latter were conducted at synchrotron facilities. Two of these publications show vascular bundles but focus on other plant structures. Two other works describe the visualisation of vascular bundles in fossilised parts of trees [49, 74]. The remaining two articles deal with xylem embolism in stems of *Laurus nobilis* [50] and of seedlings of *Acer pseudoplatanus* and *Fagus sylvatica* in vivo [46], respectively. Despite the small number of studies, phase-contrast tomography remains a promising technique to visualise vascular bundles in fresh sample material by enhancing the outline of cell walls, since water-filled tissues show only small differences in X-ray attenuation. To visualise vascular bundles with absorption-contrast μCT, samples are usually dried to exploit the high difference in X-ray absorption between air and the solid constituents of the cells [8]. This is at least valid for typical photon energies of X-rays used in μCT from a few dozen keV to 100 keV [77]. In soft X-ray tomography, synchrotron X-radiation of energies in the "water window" from 284 to 543 eV is predominantly absorbed by the carbon-rich cell constituents and lesser from oxygen-rich parts (like water) [28]. Although this method works perfectly for fresh biological samples, it is limited to small sample sizes due to the generally high absorption of lower energy X-rays.

4 Segmentation Methods

The process of assigning voxels of a 3D μCT reconstruction to the corresponding structures or tissues (regions of interest—ROI) is called segmentation. In a very basic approach, this is done by a human being who maps the voxels of a slice to the different ROIs, by adding a specific marker to these voxels. Even if this work is facilitated by software that allows the marking of larger regions at the same time, it is very time-consuming and virtually impossible to segment a stack of more than 1000 slices of a 3D reconstruction by this technique.

If the greyscale contrast between the ROIs and their surrounding spaces is high enough, global greyscale thresholds can be applied to the segment automatically. Some algorithms (e.g. Otsu's method [52]) determine greyscale thresholds automatically. Alternatively, an edge-detecting filter can be used [77].

All mentioned techniques are commonly applied to segment at least a few slices of a stack. Machine learning algorithms can learn from these pre-segmented slices how to distinguish between the ROIs and their surroundings. The Biomedisa software for example exploits a weighted random walk algorithm to automatically segment the remaining slices [45]. Another method to automatically segment is to train a deep learning model with the pre-segmented slices. This technique has already been used to segment vascular bundles [26].

When it comes to the segmentation of fibres in a composite, there are often many different ROIs (individual fibres) to keep track of. In these cases, after automatic slice segmentation, an additional algorithm is applied to keep track of the individual fibres. Digital image correlation (DIC) could successfully track fibres in composites [3, 4, 47]. It is, therefore, a promising technique to track vascular bundles in plant materials.

5 Combination of μCT with Other Digital Methods

For the deduction of structure–function relationships in the μm scale, it is not sufficient just to know the changes in the spatial arrangement of the (sub-)structures while changing the environmental conditions. Determining mechanical quantities like Young's Moduli of the μm-scale substructures reveals a complete picture of a mechanism and allows to build of a mechanical model of the whole structure. It is difficult to measure these quantities directly, but it is possible to get good estimates with numerical simulations based on finite element models, i.e. finite element analysis (FEA) [76, 77].

FEA yielded good estimates for bone strength and fracture risk from structures that were derived from segmented μCT reconstructions. In these cases, the elements for FEA corresponded with the voxels of the μCT [7]. Petit et al. [63] gave an overview of FEA for cellular solids where different mesh types and elements, respectively, were derived from μCT analysis. Inferred estimations of these analyses were generally in good agreement with the macroscopic response. The feasibility of FEA for fibre-reinforced polymers has already been shown but high resolutions, as well as much computing power to predict the mechanical behaviour even of small objects, are necessary [14, 69]. Palombini et al. predicted the elastic moduli and compressive strength values for parenchyma and sclerenchyma of a bamboo node, respectively, from a combined μCT-FEA analysis [54]. To reduce the demand for computing power, they assigned all object voxels either parenchyma or sclerenchyma. The results were still difficult to assess since literature values showed large variations. A few years earlier, the same group had already predicted these quantities for the internodal part of a bamboo stem [53].

6 Conclusion

The non-destructive analyses of opaque, difficult-to-access or very fragile objects are made possible in part by the use of μCT. On the one hand, new insights can be gained, as it is now possible to look into plant materials or technical materials that were previously not possible to access. Also, in situ analyses are now upcoming with devices having bigger chambers, shorter scanning times or chambers where in situ movements in different environmental regimes (temperature and humidity) can be studied. Technical improvements like light sensors with larger dynamic ranges or new set-ups for phase-contrast μCT may render fresh biological sample material more accessible for future laboratory-scale instruments.

On the other hand, the availability of the digital data obtained from μCT techniques opens up the possibility of combining this digital data with other methods, like simulations via finite-element analyses (FEA) and digital image correlations (DIC). This results in a variety of new analysis methods to obtain new insights. The possibilities, which have only been shown in a few papers so far, will certainly become more established in the near future and further expand our understanding of structure–function relationships and create new opportunities to develop sustainable technical components.

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An Overview of the Potential Usage of Bamboo Plants in Medical Field

M. B. Noremylia, A. N. Aufa, Zarini Ismail, and Mohamad Zaki Hassan

Abstract Bamboo plants belong to the grasses family (Poaceae) and are one of the most important and valuable forest resources. This multipurpose plant contains a variety of different species. All different plant parts, such as roots, rhizomes, shoots, stems, leaves, and seeds, exhibit their own unique properties that can be used in biomedical applications. Bamboo plants have an important place in traditional Asian medicine, particularly in China and Japan. Since the 1960s, biomedical research on the toxicity and health benefits of various bamboo species and parts has been conducted worldwide. These studies have shown that bamboo has many health benefits and has been linked with the prevention of many diseases, including diabetes mellitus, hypercholesterolemia, hypertension, heart disease, and certain types of cancer. Besides that, bamboo also has antioxidant activity, antibacterial, anti-inflammatory, etc. Bamboos are known to have a diversity of constituents such as flavonoids, phenols, alkaloids, and coumarins, as determinant compounds for their bioactivity. These biodegradable materials could substitute several typical, non-biodegradable materials with comparable characteristics and performance as biomaterials. Since bamboo plant constituents are part of the physiological function of living flora, they are more compatible with the human body. This chapter reviews the potential usage of bamboo plants in medical-related fields.

Keywords Diabetes mellitus · Cholesterol · Hypertension and cardiovascular disease antioxidants · Anti-cancer · Pharmaceutical purposes · Pharmaceutical purposes · Antibacterial properties

M. B. Noremylia · Z. Ismail (✉)
Faculty of Medicine and Health Sciences, Universiti Sains Islam Malaysia, Persiaran Ilmu, Putra Nilai, 71800 Nilai, Negeri Sembilan, Malaysia
e-mail: zarini@usim.edu.my

A. N. Aufa · M. Z. Hassan
Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia

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1 Effects of Bamboo Consumption on Diabetes Mellitus

Insulin sensitivity is one of the main causes that may lead to the risk of developing diabetes mellitus [1]. Diabetes mellitus is well known as a chronic and progressive disease that has a lasting effect on the organs and tissues of the host [2]. Bamboo has been recommended as a functional food that offers health benefits in controlling the metabolic disease of the host gut microbes [3]. As shown in Fig. 1, Bamboo shoots are a potential prebiotic, which plays a significant role in gut health as well as anti-diabetic activities. This was mainly attributed to the phenolic components in bamboo leaves, such as orientin, homoorientin, isoorientin, vitexin, homovitexin, and tricin. However, the presence of cyanogenic glycosides makes them not suitable to be eaten raw.

As for usage in diabetes mellitus, various studies focus on improving the insulin sensitivity of bamboo shoots in vivo. A study by Li et al. [5] found that the bamboo shoot fiber (BSF) obtained from *D. hamiltonii* and *D. latiforus* demonstrated that the BSF had lower glucose-stimulated insulin concentration. This is due to the higher level of Akt (an enzyme of serine/threonine protein kinase) in the mice's tissue associated with a higher protein expression level of PGC-1α. The result showed that the BSF eventually improved the insulin sensitivity in the mice by activating the

Fig. 1 Bamboo shoots [4]

PGC-1α. A similar study by Zheng et al. [6] tested the bamboo shoot in both in vivo and in vitro studies to identify their hypoglycaemic properties. They found that the bamboo shoot fiber was able to reduce the oral glucose tolerance of the mice after 4 weeks of administration. Nevertheless, they demonstrated that the soluble dietary fiber of bamboo significantly increases blood insulin levels.

Bamboo is well known for its high content of carbohydrates. Some studies focus on bamboo polysaccharides, also known as polycarbohydrates. A study by Zheng et al. [7] shows extracted crude polysaccharides from the bamboo shoot shell and administered them in vivo dose-dependent on induced diabetic mice. The dose given was at ~400 mg/kg and they found that the dose eventually decreased the blood glucose level as well as serum triglycerides and total cholesterol down to 48.7, 34.8, and 26.5%, respectively. There were also decreases in weight loss of the mice, indicating that the bamboo shoot polysaccharides were able to act as an anti-diabetic agent. Li et al. [8] studied the correlation between the bamboo shoot fiber in preventing obesity as well as diabetes by modulating the gut microbiomes. The dietary fiber of the bamboo shoot reduced the obesity of high-fat mice after 6 weeks of in vivo study.

2 Bamboo Effects on Cholesterol, Hypertension, and Cardiovascular Disease

Bamboo has also been known as a herbal medicine for the treatment of hypertension due to its biological and therapeutic antioxidant properties. In addition, young bamboo shoot ingestion is said to aid in digestive improvement, hypertension relief, cancer prevention, and cardiovascular disease prevention, according to ancient Chinese medical texts.

Bamboo leaf flavonoids (BLFs) can significantly decrease the serum triglyceride level, increase high-density lipoprotein content, regulate blood lipids and reduce the risk of atherosclerosis, and have also displayed strong anti-oxidative, anti-aging, and anti-fatigue activities. A study by Fan et al. [9] demonstrated that bamboo is very effective in retarding lipid oxidation as well as preventing biogenic amine formation in pork sausage when combined with tea polyphenols. One study found that bamboo reportedly decreased the total cholesterol level in healthy young women when compared with controls on a dietary fiber-free diet [10]. A study by Jiao et al. [11] showed that bamboo shavings extract might lower serum levels of total cholesterol and total triglycerides, which are the primary contributors directly causing pathological alterations in cardiovascular illnesses. This is a result of the triterpenoid-rich bamboo shaving extract's anti-hyperlipidemic and anti-hypertensive effects as well as the vasodilator effects of friedelin on phenylephrine-induced vasoconstriction in rat thoracic aortas. Bamboo shoots contain silica, which is crucial for preserving the suppleness, permeability, and structural integrity of the arteries and controlling blood pressure. It may help lower blood lipids and cholesterol. It also improves potassium's ability to reduce hypertension and calcium's ability to help regulate heartbeat.

Bamboo contains a very high concentration of vitamin C. Vitamin C is an antioxidant, reportedly, reducing the risk of arteriosclerosis and some forms of cancer. It is capable of neutralizing reactive oxygen species in the aqueous phase before lipid peroxidation is initiated. Nirmala et al. [12] demonstrated that the fresh shoots of bamboo contain vitamin C up to 5.00 mg/100 g.

Cho et al. [13] investigated the effects of bamboo oil on lipid metabolism. They found that the total cholesterol and triglyceride concentrations in the blood decreased with the increase of bamboo oil concentrations. The total cholesterol decreased from 139.6 to 80.4 mg/dL with the increase of bamboo oil concentration up to 8.0%. It might be expected from the study that bamboo oil is believed to have possible protective or curative effects for fatty livers and arteriosclerosis induced by the high-cholesterol diet. Kang et al. [14] extracted bamboo leaves from *Sasa quelpaertensis* and administrated them to mice. The study findings not only decreased the body weight, adipose tissue weight, and serum cholesterol but also reduced the deposition of lipid droplets in the liver compared to untreated mice.

High levels of cholesterol in the blood are a crucial problem as it is one of the risk factors for various non-communicable diseases such as heart disease, hypertension, and stroke. Vitamin E is a well-known fat-soluble antioxidant and can only be obtained through diets. Vitamin E shows protective effects against coronary heart diseases due to inhibiting low-density lipoprotein (LDL) oxidation. A study by Nirmala et al. [12] and Yang et al. [15] found that the content of Vitamin E in bamboo ranges between 0.50 and 0.90%. Makatita et al. [16] found that bamboo can reduce blood cholesterol levels. The study demonstrated that blood cholesterol was reduced after consuming bamboo. They concluded that the bamboo shoot was able to be used as an alternative medicine in controlling blood cholesterol levels.

A study by Fu et al. [17] found that the compound in bamboo, orientin, can prevent apoptosis in the myocardium and cardiomyocytes of the heart in experimental animal studies. This occurred by preventing the activation of the mitochondrial apoptotic pathway, making it a potential source for cardio-protective effects. However, a study by Chuang et al. [18] demonstrated that the consumption of bamboo shoots might be associated with hyperuricemia, which is the increased uric acid content that may lead to cardiovascular disease.

Some studies focused on the bamboo culm extracts, where it was found that ethanolic from the bamboo culm showed ameliorated risk factors for cardiovascular diseases in mice treated with an of high-cholesterol diet. According to Lee et al. [19], the bamboo culm extracts significantly improved hepatic antioxidant enzyme activities while positively reducing hepatic lipid peroxidation and protein carbonylation.

3 Antioxidants

Free radicals produced in our body play an important role in the development of produced in our body and in developing many chronic diseases. Oxidative stress is a complex process characterized by the imbalanced production of free radicals and the ability of the body to eliminate reactive oxygen species through the use of antioxidants. The main antioxidants in bamboo leaves and shoots are flavonoids, phenols, and vitamins C and E [12, 20]. The flavonoids are represented mainly by the flavones C- glycosides which include homoorientin, isovitexin, orientin, and vitexin. Apart from this quercetin, luteolin, rutin, caffeic acid, p-coumaric acid, chlorogenic acid, and tricin are also present. The flavonoid content was recorded to be 3.44% in different bamboo leaf species [21]. In the case of antioxidant protection, flavonoids stand as one of the most efficient molecules in combating oxidative stress and are used for the treatment of cardiovascular illness [22].

The antioxidant of bamboo leaves was certified to be a natural antioxidant due to the presence of bioactive compounds. It has been reported to possess strong antioxidant activity and inhibit the free radical-induced deterioration of macromolecules in vitro [23]. Besides, bamboo leaves oxidants have also been identified as having therapeutic potential due to their antioxidant effects [24]. A study by Gu et al. [25] found that the bamboo leaf inhibits antioxidants and anti-inflammatory abilities due to the senescence of HaCaT cells induced by AAPH in the 10–40 μg/mL of bamboo leaf. As illustrated in Fig. 2, the recovery of mitochondrial membrane potential increases demonstrating that the bamboo leaf contains the highest antioxidants where the mitochondria acts as an oxidative phosphorylation, which generates energy by utilizing the energy released during the oxidation of the food we eat.

Bamboo shoot is considered one of the health-promoting foods due to its high content of nutrients and bioactive compounds. It holds great promise as an additive for fortifying different food products. Bamboo shoot-fortified crispy salted snacks, commonly known as namkeen lead to a reduction in bioactive compounds with better qualities, as reported by Santosh et al. [26]. In a work by Singhal et al., they reported that the fermented bamboo shoot significantly increased in phenol and flavonoid content. Besides, the antioxidant capacity was also increased, indicating their potential to protect human health [27].

Vitamin C is well known as a potent antioxidant [28]. The content of vitamin C was evaluated by Rana et al. from fresh edible shoots of *Phyllostachys mannii* and the approximate content of vitamin C was found to be around 3.23 ± 0.05 mg/100 g FW [28]. However, the vitamin C from fermented bamboo shoots was decreased to 35.77% in a study reported by Singhal et al. [27]. Soesanto discovered that the highest content of Vitamin E is found in Apus bamboo shoots extract, 0.3284%. Furthermore, the Apus bamboo extract antioxidant activity is more active than other bamboo shoot species [29].

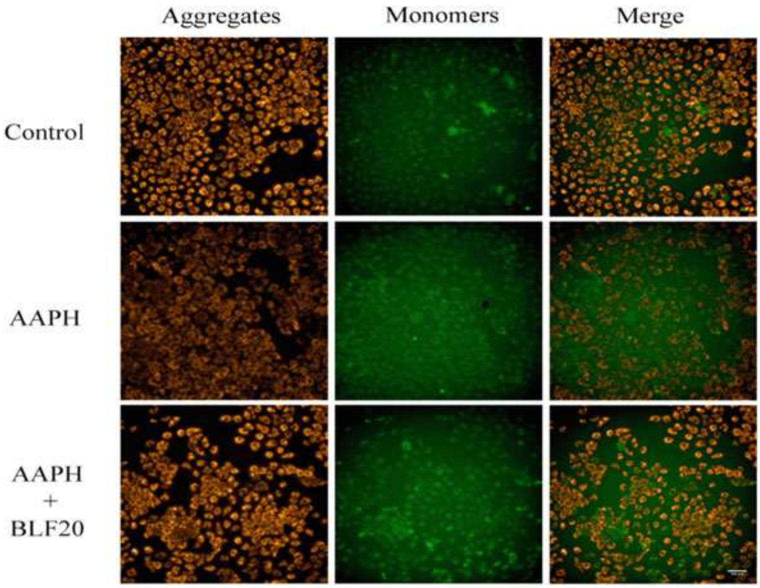

Fig. 2 Mitochondrial membrane potential of the bamboo leaf [25]

4 Anti-cancer

The consumption of bamboo shoots has been linked with the prevention of several chronic diseases, including certain types of cancer. Bamboo shoots contain several phytochemicals which have been proven to have potent anti-cancerous properties such as phytosterols, phenols, and dietary fibers [30].

Seki and Maeda found that the vigorous (multistep) extractions of bamboo leaves show more potent antitumor activity, in which they suppress tumor growth and prolong survival in mouse tumor models compared to the conventional extraction method [31]. In another work by Seki et al., similarly, they proved that Kumaiza bamboo extract had anti-cancer properties and might play an important role in cancer prevention [32]. Besides, Abdelhameed et al. clarified that methanol extract of the bamboo shoot skin *Phyllostachys heterocycle* stimulated apoptotic breast cancer cell death by 32.6-fold [33]. The bamboo salt soy sauce called Sarijang was utilized as a chemotherapeutic agent to control U937 human leukemia cells. The extract compounds triggered the apoptosis of U937 human leukemia cells through activating the intrinsic caspase pathway and the DR-mediated extrinsic pathway [34]. Kim et al. demonstrated that bamboo shavings (Bambusae Caulis in Taeniam, BCT) significantly reduced the metastatic activity of highly cancer cells by suppressing MMP-9 activity via inhibition of ROS-mediated NF-κB activation [35]. Additionally, bamboo-shaving polysaccharides (BSP) were identified as the most selective polysaccharide inhibiting the growth of six gastric cancer cell lines while having no toxic effect on normal gastric mucosal cells. Similarly, BSP had a more potent killing effect on a subset of human stomach cancer cells than on liver or lung cancer cells [36].

5 Pharmaceutical Purposes

Bamboo salt and bamboo vinegar are some important bamboo-based pharmaceutical preparations that are now gaining importance. Some pharmaceutical products are cellulose, bioethanol, bio-methane, starch, charcoal, flavors, preservatives, and bamboo leaf tea [37].

Bamboo salt (BS) is a processed salt produced according to a traditional recipe using sun-dried salt. BS is known to have therapeutic effects in treating diseases, including viral diseases, dental plaque, diabetes, circulatory organ disorders, cancer, inflammatory disorders, allergic rhinitis, and cisplatin-induced ototoxicity [38]. Bamboo salt has been added to toothpaste, and according to the manufacturer, this toothpaste can prevent cavities, reduce plaque and gingivitis, soothe sensitive teeth, fight bad breath, whiten teeth, strengthen tooth enamel, prevent receding gum line and decrease mineral loss [39].

The vapor that comes off the heated bamboo can be condensed to produce a liquid known as bamboo vinegar [40]. Bamboo vinegar has been produced in Japan for many years and is used medicinally to treat eczema, atopic dermatitis, and other skin diseases [41].

6 Antibacterial Properties of Bamboo

Bamboo, a naturally multipurpose plant, grows quickly and can survive harsh climatic conditions due to its notable antibacterial characteristics. Several studies were done to determine the bioactive compound (s) responsible for the antibacterial properties of bamboo. Afrin et al. investigated the origin of the antibacterial property of Australian-grown bamboo (*Phyllostachys pubescens*) by extraction of matured bamboo culm powder in water, dimethyl sulphoxide, and dioxane [42]. Their antibacterial activity was tested against Gram-negative bacteria, *Escherichia coli*. They identified lignin as being the main source of the antibacterial compound in *Phyllostachys pubescens.* It is assumed that the antibacterial property of lignin arises from aromatic and phenolic functional groups in lignin. Several other studies also found that lignin is the primary source of antibacterial compounds in bamboo [43, 44]. The antibacterial performance of lignin depends on its extraction and purification methods [44]. Examples of extraction methods used include ethanol fractionation, acid precipitation, nanoparticle modification, etc.

In other studies, Thanaka et al. isolated and identified active compounds, stigmasterol, and dihydrobrassicasterol from Moso bamboo shoot skins (*Phyllostachys* *pubescens*) [45]. These compounds potentially have antibacterial activity since they inhibited the growth of *Staphylococcus aureus* and *Escherichia coli*. Thus, in addition to its primary use for composting, the bamboo shoot skin can be more widely and effectively utilized. Moreover, other parts of the bamboo plant, such as leaves, also exhibit some antibacterial activity against some bacteria [46].

The antibacterial properties in natural bamboo provide the resistance of this plant to the harsh environment and self-defense against biotic and abiotic agents. So, lignin and other compounds that exhibit antibacterial activities can be advantageous factors if they can be fully exploited and retained in the final bamboo products. For example, Wang et al. retained the antibacterial trait of bamboo in a bamboo-derived product to improve resistance against microorganisms by introducing bamboo vinegar into the material [47]. Bamboo vinegar was derived from the pyrolysis of bamboo charcoal, such as acetic acid, phenolic compounds, and alcohol compounds, among others.

With the advancement of technologies, including in the textile industry, clothing manufactured from bamboo has entered the textile market. Products made from bamboo are often labeled "eco-friendly", "biodegradable", and "anti-microbial", irrespective of their method of manufacturing. However, these claims may not always portray the product's authenticity and true environmental impact [48]. There are often debates regarding the antibacterial property of bamboo textiles. Studies done by Zhou and Deng found that natural bamboo fibers do not possess any significant antibacterial effect [49], and even if they do, it is just due to a certain crude and particular microstructure of natural bamboo fibers [50]. Li and Dao investigated the antibacterial activity of bamboo and compared it with other textile fibers such as cotton, jute, flax, ramie, and bamboo viscose and reported that natural bamboo does not have the natural antibacterial property [51]. They also reported that the resistance of plant fibers might be related to their hygroscopicity, and some extraction methods could improve the ability of natural bamboo to resist microorganisms. At present bamboo-based, textiles have still not achieved their full potential, but cleaner production processes are appearing [48].

7 Effects of Bamboo Consumption on Gut Microbiota

The role of gut microbiota in health has grown tremendously in recent years. The microbiota, a collective term used for microorganisms that live in our body, plays a major role in health and disease by shaping the body's immune system and metabolism. Altered microbiota has been associated with certain conditions such as obesity and diabetes mellitus. Dietary fiber plays an important role in maintaining body weight and the overall health status of a person. Adults should consume more than 25 g of dietary fiber per day, according to the WHO [52]. Dietary fiber is a carbohydrate polymer-resistant to digestion and absorption in the human intestine, whether natural or synthetic, soluble or insoluble, fermented or nonfermented, viscous or nonviscous [53]. The fermentation of dietary fiber will produce short-chain fatty acids (SCFAs) such as acetate, propionate, butyrate, and others. Many studies have shown that SCFAs play an important role in maintaining the stability of the gastrointestinal environment; promoting colon epithelial cell proliferation, regulating inflammatory response, and inhibiting intestinal pathogenic bacterial colonization [54].

Several studies have investigated the effects of fiber from different parts of bamboo, such as bamboo shoots and culms, on the gut microbial communities. For example, Ge et al. investigated the digestive microbial communities and the production of SCFAs by in vitro human fecal fermentation [55]. They found that the insoluble fiber from bamboo promotes the production of SCFAs after 24 h of fermentation. Additionally, bamboo fiber that has been extracted by alkaline hydrogen peroxide could alter the microbial composition and diversity by increasing the relative abundance of *Bacteroides* and decreasing the ratio value of *Firmicutes* to *Bacteroidetes* [55]. Similarly, Huang et al. performed an in vitro human fecal fermentation study [56]. However, they studied the fermentation of a compound called O-acetyl-arabinoxylan obtained from bamboo shavings. The study showed O-acetyl-arabinoxylan remarkably modulates the microbial composition in the human colon, by increasing the growth of potential beneficial genera (i.e., *bifidobacterium*, *lactobacillus*, *bacteroides*, etc.) and decreasing the growth of potentially harmful genera.

Increasing evidence suggests that the development of obesity might be associated with gut microbiota, which can influence the host metabolism, digestion of nutrients, energy utilization, and storage. In an experimental animal study, researchers demonstrated that certain gut microbiota could alter the development of obese mice. Chen et al. [56] demonstrated that bamboo shaving polysaccharide could act as an anti-obesity agent in experimental mice by increasing community richness and diversity and regulating gut microbiota composition. In other experimental animal studies, mice with high-fat diets were fed different types of fiber, including bamboo shoot fiber and several other commonly consumed fibers. The study showed that mice that consumed bamboo shoot fiber had a markedly increased relative abundance of beneficial bacterial *Bacteroidetes* and strong inhibition of *Verrucomicrobia.* They conclude that bamboo shoot fiber is a potential prebiotic that can modulate gut microbiota and improve metabolism [57].

8 Conclusion

Bamboo, a multipurpose plant, could be used as a cheap and widely available resource in numerous applications, including in the pharmaceutical and biomedical industries, if carefully exploited. Previous studies have demonstrated that bamboo has many health benefits and potential due to its high content of nutrients and bioactive compounds. Various different extraction techniques were shown to exert a significant influence on their effectiveness. As evidenced by the variety of bamboo species, many parts of the plants have been used medicinally. Most of the studies have oriented toward “modern diseases”, such as heart diseases, obesity, and cancer. However, further extensive studies are needed to elucidate the effectiveness of bamboo for other diseases in the medical field.

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Novel Food Product Development Through Food-to-Food Fortification with Nutrient and Bioactive Compound-Rich Bamboo Shoot

Oinam Santosh, Harjit Kaur Bajwa, Aribam Indira, Shahar Bano, Norbu Dolma, Madho Singh Bisht, and Nirmala Chongtham

Abstract Bamboo shoot is a nutritious health food endowed with minerals, vitamins, dietary fiber, phytosterols, phenols, and various health-promoting bioactive compounds. Though a neglected food commodity and restricted to a few Asian countries, globally, bamboo shoot is being projected as a "superfood". Currently, there is a paradigm shift in the food industry due to consumer choice from healthy foods to food that prevents nutrition-related diseases and improves the physical and mental well-being of consumers. Scientific evidence and a growing awareness of the correlation between diet and health, coupled with a sedentary lifestyle and rising healthcare costs, have driven the interest of consumers to healthy food products. These products include fortified foods and nutraceuticals that confer positive health benefits to consumers. Earlier foods were incorporated with synthetic micronutrients which is now not appealing to consumers. An upcoming trend in the food industry is the demand for all-natural food ingredients that are free of chemical additives giving rise to the concept of food-to-food fortification, wherein nutrient-rich and available local resources—plant or animal is used to fortify another food. Food-to-food fortification is an emerging food-based strategy that can complement current strategies in the ongoing fight against micronutrient deficiencies. Bamboo shoots with their high content of nutrients and bioactive compounds can be used for making novel nutritious food products. Processed bamboo shoots in the form of powder, paste, or extracted bioactive compounds can be used for developing edible products which will be ready to eat or ready to cook. Bamboo shoot fortified products hold great potential as a health food. The present chapter provides state of the art in bamboo shoot fortified food products and its prospects for combating hidden hunger.

Keywords Bamboo shoot · Fortification · Processing · Preservation · Antioxidant · Bioactive compounds · Noodles · Cookies

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O. Santosh · H. K. Bajwa · A. Indira · S. Bano · N. Dolma · N. Chongtham (✉)
Department of Botany, Panjab University, Chandigarh 160014, India
e-mail: cnirmala10@gmail.com

M. S. Bisht
Department of Environmental Studies, NEHU, Shillong 793022, India

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1 Introduction

The growth and development of the human body depend heavily on food which is the source of various nutrients that nourish the human body. Several organic phytochemicals that promote good health, minerals, and organic nutrients essential for human nutrition are mostly derived from plant foods. Recent advances in the food and nutrition sciences have led to the introduction of functional foods or food-to-food fortification. Such products are a natural or processed form of food with known biologically active compounds derived from a plant that have several health benefits in terms of prevention, management, and treatment of chronic diseases of the modern age [1]. The interest in healthy eating and affordable healthcare has led the food industry to seek out plants rich in nutrients, dietary supplements, and desirable functional properties. Recently, neglected plants have been investigated and given a lot of attention for their biologically active components, including dietary fibers, amino acids, proteins, minerals, vitamins, phytochemicals, and antioxidants, which are used in the food industry to develop functional foods through fortification [2, 3]. The use of cereal brans, fenugreek, flaxseed, and white grape pomace as a source of dietary fiber has been reported for the fortification of products such as pasta, bread, biscuits, noodles, and macaroni [4–7]. Several neglected plants rich in bioactive health-promoting phytochemicals, such as buckwheat, quinoa, amaranth, and a variety of legumes, pigmented cereal grains, and nuts, are used in food industries for the development of functional foods [8]. Therefore, exploring agricultural commodities and wild plants for food-to-food fortification strategies and diet diversification are increasingly considered to potentially combat multiple micronutrient-related deficiencies. Proper choice of fortificant and processing method could ensure the stability and bioavailability of the nutrients [9]. However, for food-to-food fortification, suitable formulation strategies must be adopted as a minute difference in the mixture design and linear programming may lead to a significant impact on the sensory and physiochemical properties of the fortified food products [10]. A good and potential bio-fortificant depends on several factors such as variety and quantity of micronutrient content in foods, effect on sensory properties of food, and consumer acceptability [10]. A wide range of food-based natural fortificants has come into light that increases the micronutrient content specially the bioactive compounds, vitamins, and minerals. Bamboo is one such plant endowed with rich nutrients and bioactive compounds, which is an excellent health food and a good source for food-to-food fortification. Bamboo shoots are rich in nutrition, present a good quantity of bioactive compounds, and have the potential to prevent many chronic diseases [11].

Interest in utilizing bamboo shoots for the production of food-to-food fortification is gaining popularity in the food industries [12, 13]. Recently, several value-added products used bamboo shoots for making pickles, candies, nuggets, crackers, chutney, chips, cookies, chapatis, namkeen, tarts, and buns [13–20].

2 Bamboo Shoot Processing and Fortification

Bamboo shoot endowed with rich nutrients and bioactive compounds is an excellent health food and a good source for fortification. Fresh bamboo shoots have a very short shelf life and are available only during monsoon season. They are highly perishable due to high moisture content, vulnerable to microbial spoilage and mechanical and physical degradation. It starts browning after 2–3 days of harvesting, leading to lignification and deterioration while storing at ambient temperature [21, 22]. Due to tissue lignification, the firmness of the shoots increased rapidly after harvest and the quality of the shoot deteriorated as they are exposed to microbial spoilage, and undergo browning with various enzymatic and non-enzymatic activities [23]. Most of the bamboo shoots in the fresh form are not good for consumption without processing due to the presence of cyanogenic glycosides which cause acridity and toxicity of the shoot. It is always compulsory for proper processing and preservation technique of bamboo shoots after harvesting for long-term storage and consumption before utilization as food or additive in fortification. Harvested bamboo shoots need proper extraction of an edible portion which comprises removal of the culm sheath, washing, and chopping into desired shapes and sizes for processing treatment. In order to keep bamboo shoots in fresh form while storage, the texture properties and moisture retention are very much essential. However, without proper processing and preservation, external factors such as temperature, humidity, microbial exposure, and storage condition will affect the shelf life of shoots [24]. Processing and preservation of bamboo shoots help to reduce the deterioration of shoots and also maintain the natural color, smell, and taste. There are several methods of processing bamboo shoots both traditional and modern methods such as boiling, soaking, drying, fermentation, osmotic dehydration, solar, microwave, and freeze drying [25–27]. Anti-nutrient from bamboo shoots can be easily removed through boiling, soaking, blanching, steaming, fermentation, and stir-frying [13, 28–30].

In Southeast Asian countries, shoots are mostly harvested during the monsoon season, whereas *Phyllostachys heterocycla* var. *pubescens* and *P. nidularia* are harvested in early winter in Japan and China [31]. In France, shoots of *Sasa kurilensis* are grilled or fried for consumption without boiling, whereas in Australia and New Zealand shoots are sliced and boiled in salted water for 8–10 min [32]. In Yunnan Province of China, shoots of *Dendrocalamus semiscandens, D. hamiltonii,* and *Schizostachyum funghomii* are used for cooking by the indigenous community, while drying is considered good for bitter shoots of *D. barbatus, D. giganteus, D. membranaceus, Pseudostachyum polymorphum, Gigantochloa nigrociliata,* and *Leptocanna chinensis* [33]. In India, particularly in the northeast region, fermented bamboo shoots are a popular delicacy for a very long time. The people of West Bengal and Sikkim of India traditionally used the young shoots of *D. hamiltonii, D. sikkimensis,* and *Bambusa tulda* to prepare a non-salted fermented product *Mesu* [34]. The fermentation process takes about 7–15 days at an ambient temperature of 20–25 °C with the edible portion of the shoots chopped and filled tightly in bamboo culm covered with leaves and, after fermentation, it is pickled for long-term storage which is used in preparing curry by frying with meat. The *Kandha* tribe of Odisha, India used *D. strictus* shoots for the preparation of the semi-fermented local product *Kardi* in which bitter taste is removed by soaking sliced shoots in water for a day before consumption. The local tribe also stored bamboo shoots in the form of *Handua* which is a sun-dried form of pounded shoot paste. It is used for making curry and is considered effective against digestive problems [35]. The tribes of Arunachal Pradesh *Adi* and *Galo* process shoots of *D. hamiltonii, D. hookeri, D. giganteus, D. longispathus, Bambusa balcooa, B. pallida,* and *Melocanna baccifera* through fermentation and sun drying for the preparation of products such as *kupe, eepe, eeku,* and *eep* [36, 37]. *Kupe* is a fermented bamboo shoot form that is prepared from the soft and tender edible portion of the shoots either as a whole or slices placed in an air-tight bamboo basket wrapped with leaves of locally available herbs preferably *Phrynium* sp. During the 15–30-day fermentation process excess exudates from the basket were removed by placing a heavy weight on top of the basket. In Manipur, India fermented bamboo shoots, namely, *soibum, soidon,* and *soijin* are very much popular among the *Meitei* community. For the preparation of these indigenous fermented products, shoots of *D. hamiltonii, D. sikkimensis, D. giganteus, Melocana bambusoides, Bambusa tulda, B. vulgaris, B. balcooa,* and *B. pallida* are commonly used [38]. In the northeast region of India, traditional processing techniques such as fermentation and sun-drying of shoots are commonly followed for several products such as *Poka khorisa, Khorisa, Khorisa tenga, Miya mikhri, Miya mecheng, Jim tenga, Tuaithur, Tuairoi* of Assam, *Hirring, Hitch, Hitak, Iku, Heecha, Hikku, Ekung, Kupe, Eeku, Eup, Hi, Nogom, Ipe, Hithyi, Eepe, Eep* of Arunachal Pradesh, *Soibum, Soidon, Soijin* of Manipur, *Lungseij, Pdam* of Meghalaya, *Rawtuai rep* of Mizoram, *Bastanga, Rhujuk* of Nagaland, *Kardi*, and *Moiya koshak, Midukeye, Mellye amiley, and Moiya pangsung* of Tripura [35, 37–44]. Shoots in fermented and sun-dried forms are a very popular product with longer shelf life and are also available during the off-season.

The effects of the processing of bamboo shoots on its nutritional profiles were well documented in various reports [12, 13, 16, 26, 30, 32, 45, 46]. The depletion of nutrients from fresh to fermented and canned shoots in terms of amino acids, proteins, carbohydrates, starch, fat, vitamin, and minerals was observed in the various processed shoots, whereas there was an increase in phenols, phytosterols, and dietary fiber content [25, 47]. The increase in the phytosterols after fermentation is reported to be due to anaerobic digestion and organic matter degradation by the microorganism [48]. The effect of processing on the mineral retention of *Bambusa balcooa* and *B. bambos* was studied by Saini et al. [49] in boiling, soaking, fermentation, water preserved, and brine preserved. In all the processed forms, the results showed a decrease in the potassium, phosphorus, magnesium, calcium, silicon, sodium, and chlorine except an increase in sodium and chlorine content in water-preserved and brine-preserved shoots, whereas mineral elements such as potassium, phosphorus, and magnesium were retained in soaking. A good profile of nutrient retention and maximum removal of anti-nutrients was reported in the 20-min boiled freeze-dried bamboo shoot of *D. hamiltonii* [50]. A rich content of macro-elements, including potassium, phosphorus, calcium, sulfur, magnesium, silicon, sodium, and micro-elements zinc, iron, manganese, bromine, copper, and nickel, was also recorded.

Several processing methods have been investigated in which the nutritional value of fresh shoots is decreased after processing; however, an increase in dietary fiber and bioactive compounds is reported which is of pharmaceutical importance [26, 30].

For generations, the delicacies of bamboo shoots have remained one of the highly delectable foods, referring to both the rich man's and the poor man's delicacies [12, 51]. The edible portion of a bamboo shoot with a crisp and crunchy texture is used to make soups, stir-fries, snacks, salads, fried rice, spring rolls, and a variety of other fried foods [12]. As urbanization and lifestyles change, the need for food fortification is becoming increasingly important for the prevention of several diseases linked to poor nutrition.

The food industries are becoming increasingly interested in using bamboo shoot, which is abundant in nutrients, bioactive chemicals, and minerals, to produce natural functional food [12, 13]. Various bamboo shoot processing methods are documented for use in the development of food items with added value [13, 15]. For the development of products such as nuggets, pickles, and crackers, shoots are boiled in different percent of brine solution ranging from 1 to 5% for about 10–15 min according to the species of bamboo [16]. For the formulation of bamboo shoot fortified chicken nuggets, Das et al. [52] used fermented shoots of *Bambusa auriculata* processed in covered glass jars under normal temperature for 2 months. Similarly, Thomas et al. [53] used bamboo shoots of *Bambusa polymorpha* for fermentation in tightly packed traditional earthen pots for 6 months which was later used for the development of pork nuggets. Shoots of *Dendrocalamus hamiltonii* were boiled in normal water for 20–30 min to remove bitter compounds before the preparation of fortified products such as candy, chutney, chuk, nuggets, and crackers [17]. Choudhury et al. [54] utilized the shoots of *Bambusa balcooa* for the preparation of biscuits. Shoots were boiled for 30 min by changing the water every 10 min which was then dried at 70 °C and the dried powder was grounded to powder for use in the fortification of biscuits. Bamboo shoots fortified cookies developed by Mustafa et al. [18] utilized bamboo shoot powder which was boiled for 3–4 h, dried in a hot air oven, and ground. Processing of bamboo shoots, such as freeze-drying technique, oven-dried powder methods, or paste form after boiling and soaking, was also reported for the development of fortified biscuits, namkeen [13, 19, 50].

3 Products Fortified with Bamboo Shoots

Fortified bamboo shoot products have enormous potential as a health food and a good source for nutraceutical and pharmaceutical products. Various food-to-food fortified products have been reported to utilize bamboo shoots in the development of products such as cookies, nuggets, crackers, pickles, candy, yogurt, biscuits, chips, and many more (Table 1). The use of bamboo fiber in the preparation of the well-known Italian food "Amaretti" cookies shows more shelf life, improved texture, and an improved mouth feel [55]. Choudhury et al. [54] analyzed the effects of physicochemical, texture, and organoleptic properties of cookies fortified with shoots of *Bambusa* *balcooa*. With increasing levels of fortification, the content of gluten-reduced, while moisture, fiber, protein, fat, ash, phenolic, and antioxidant qualities increased. Incorporating 10% of bamboo shoots was recommended for sensory without affecting the overall quality. The physical features and sensory acceptance of cookies fortified with dried bamboo shoot powder were also examined by Mustafa et al. [18] and recommended at a 6% level of fortification. Santosh et al. [50] utilized shoots of *D. hamiltonii* to compare the enhancement of nutritional and organoleptic properties of biscuits fortified with the freeze-dried shoot powder through various processed forms of shoot samples including fresh, boiled, and soaked. The antinutrient in the freeze-dried shoot powder with a maximum content (99.45%) was removed in fresh shoot powder fortified biscuit, 97.28% in boiled shoot powder fortified biscuit, and 98.98% in soaked shoot powder fortified biscuit, which is safe for consumption. An increase in the nutritional, bioactive compounds, and mineral content in all the freeze-dried bamboo shoot powder fortified biscuits was observed and sensory acceptability for aroma, texture, taste, and overall quality in the boiled shoot powder fortified biscuits was maximum. Bamboo shoot in paste form after different processing forms such as boiling and soaking was used for the preparation of biscuits and investigated for the nutritional, bioactive compounds, minerals, and sensory properties [13]. The fortified biscuits showed significantly improved proteins, phenols, phytosterol, vitamin C, and dietary fiber content compared with the control products. The biscuit fortified with the paste of fresh and boiled shoots was observed to have better sensory acceptability compared to the control and the biscuit fortified with soaked shoots [56]. Felisberto et al. analyzed the physical characteristics and proximate composition of cookies fortified with flour obtained from dried bamboo culm in relation to sugar and fat substitute formulation. While the width and thickness of the product decreased in the sugar-substituted products but increased in the fat-substituted product, the mass of the cookies increased in the fortified products with higher crispness. The culm flour obtained from *Bambusa tuldoides* was also studied for its characteristics in the formulations of cookies replacing wheat flour by 15% and 30% [111]. The fortified cookies showed good acceptability at 15% incorporation of culm flour and the crude fiber increased from 5.92 g/100 g to 11.64 g/100 g compared to the control. Curammeng et al. [112] analyzed the consumer acceptability and commercialization of bamboo shoot tart utilizing the juvenile shoots of *Bambusa vulgaris*. The fortification of bamboo shoots in the shortcrust tart showed a widely acceptable sensory among the different types of consumers. Bamboo shoot chips are also developed from shoots of *Bambusa vulgaris* and studied for the microbiological and sensory properties of the products [57]. The results showed bamboo shoot chips were microbiologically safe for consumption and a has good sensory acceptability for aroma, flavor, texture, and audible crispness. Bamboo shoot powder and bamboo shoot extract of *Bambusa balcooa* were used for investigating the reduction of acrylamide levels in fried potato chips [58]. Reduction in acrylamide level of potato chips was reported with 50% in 1 g/L bamboo extract treatment and 25% in 50 g/L bamboo shoot powder treatment. Bamboo shoot candy flavored with pineapple and ginger was analyzed for shelf life, sensory and nutritional profile [53]. Bamboo shoot candy flavored with pineapple recorded a shelf life of 6 months under normal conditions without any microbial contamination during storage. Shoots are a good source of dietary fiber and are used for fortifying bakery products, meat, sausage, beverages, spices, pasta, and ketchup which has several health benefits [12]. Several value-added products such as nuggets, crackers, and pickles from different bamboo species, viz*., D. asper, D. strictus, Bambusa bambos, and B. tulda* were evaluated for nutritional profile and the fortified products showed improved texture and better acceptability in terms of flavor, odor, appearance, and taste [16]. The products also showed a good profile in carbohydrates, proteins, phenols, ascorbic acid, and minerals such as potassium, sodium, phosphorus, calcium, and magnesium. Further analysis confirming the shelf life of the products is good to consume within 6 months of preparation. Sood et al. [17] analyzed nutritional and sensory attributes in the *Dendrocalamus hamiltonii* shoots fortified products such as candy, chutney, nuggets, crackers, and chukh. The products had good sensory acceptability in terms of color, flavor, aroma, taste, and texture. In shoot fortified nuggets and crackers, a good profile of moisture content, protein, ash, fiber, and total carbohydrate was also reported. Das et al. [52] investigated nuggets fortified with fermented bamboo shoots for the quality and shelf life of the products. The nuggets showed a better physicochemical and increased shelf life with the incorporation of 10%(w/w) fermented bamboo shoot into the nugget emulsion. Pork nuggets fortified with fermented bamboo shoots of *Bambusa polymorpha* were developed and evaluated for their physicochemical, microbiological, and sensory characteristics [53]. Improved sensory and microbial qualities were observed which also increased the shelf life of pork nuggets for 2 weeks. Similar results were observed for the pork nuggets fortified with boiled bamboo shoot extract and *Averrhoa carambola* extract [59]. In order to preserve pork pickles, Chavhan et al. [60] used fermented bamboo shoots and examined the products' physical–chemical, microbiological, and shelf-life characteristics. Various formulations of bamboo shoot fortified pork pickles were examined utilizing fermented bamboo shoot extract, fermented bamboo shoot paste, and dried powder of fermented bamboo shoots. The products recorded maximum (up to 90 days) without any physicochemical and microbial effects except for the formulation of pork pickle with dried fermented powder for 30 days.

Dietary fiber from bamboo shoots has a positive impact on cholesterol profile reduction and healthy digestion [61]. Dietary fiber fortification reduces the amount of fat in deep-fried foods, which also tackles the problems of obesity and other cardiovascular ailments caused by consuming high-fat food items [62]. Zeng et al. [63] incorporated dried bamboo shoot dietary fiber at different proportions during the preparation of deep-fried fish balls. Bamboo shoot fiber-fortified deep-fried fish balls showed improved sensory acceptability and a decrease in fat content. The dairy industries are becoming more interested in the value of dietary fiber for enhancing rheological and textural qualities. Zheng et al. [64] extracted fiber from the shoots of *Dendrocalamus latiflorus* through the compound enzyme method of cellulase and papain and investigated the rheological behavior and texture properties of bamboo shoot fiber-fortified milk pudding at a different fortification level. Due to the improved elasticity of bamboo fiber, milk pudding fortified with 2 g/100 g of bamboo fiber was observed to have better rheological and texture properties. The hemicellulose

Table 1 Bamboo shoot food-to-food fortified products and their nutritional benefits

Bamboo species	Fortified products	Enhancement benefits	References
Not mentioned	Amaretti cookies	Cookies with more shelf life, improved texture and improved mouth feel	[55]
Bambusa bambos, B. tulda, D. asper, D. strictus	Crackers, nuggets, pickle	Improved texture, better acceptability and a shelf life of 6 months with a good nutritional profile of the fortified products	[16]
B. auriculata	Chicken nuggets	Nuggets showed a better physicochemical and shelf life	[52]
B. balcooa	Biscuit	Increased level of water absorption capacity whereas decreased in the gluten content with the increased fortification level in the dough sample	[54]
B. polymorpha	Pork nuggets	Improved sensory and microbial qualities which also increased the shelf life of pork nuggets for 2 weeks	[53]
B. vulgaris	Chips	Safe for consumption in terms of microbiological analysis and good sensory acceptability	[57]
B. balcooa	Fried potato chips	Reduction in acrylamide level of potato chips was reported with 50% in 1 g/L bamboo extract treatment and 25% in 50 g/L bamboo shoot powder treatment	[58]
Dendrocalamus hamiltonii	Candy, chutney, chukh, crackers, nuggets	Good sensory acceptability of all the products in terms of color, flavor, aroma, taste, and texture	[17]
Commercial bamboo fiber (JustFiber BFC 40)	Yoghurt	Enriching yogurt with bamboo offered a scaffold that strengthened the yogurt's structure and increased stability during storage	[68]

(continued)

Table 1 (continued)

Bamboo species	Fortified products	Enhancement benefits	References
Not mentioned	Pork pickles	Increased shelf life of the products without any physicochemical and microbial effects	[60]
Not mentioned	Candies	A stable storage period of 6 months was recorded under the normal condition without any microbial contamination during storage	[59]
Not mentioned	Cookies	Recommended for 6% level of dried bamboo shoot powder fortification in cookies	[18]
B. polymorpha	Pork nuggets	Improved sensory and increased shelf life of pork nuggets with a 6% level of the extract incorporated from 21 to 35 days compared to control samples	[53]
Not mentioned	Battered and breaded fish balls	Sensory acceptability was improved and a decrease in the fat content was observed in the deep-fried fish balls	[63]
Not mentioned	Frozen dough	Improvement in the mechanical properties, freezable water content, and thermal stability of the dough	[69]
Dendrocalamus latiflorus	Milk pudding	Milk pudding fortified with 2 g/100 g of bamboo fiber was observed to have better rheological and texture properties due to the improved elasticity where the system stability was attained	[64]
D. hamiltonii	Biscuit	Biscuits fortified with bamboo shoot paste were richer in nutrients and bioactive compounds compared to the control biscuits	[13, 50]

(continued)

Table 1 (continued)

Bamboo species	Fortified products	Enhancement benefits	References
D. asper	Cookies	The mass of the cookies increased in the fortified products with a better crispness	[56]
D. hamiltonii	Yogurt	Yogurt enriched with bamboo shoots showed high protein with improved functional properties, including higher appearance, texture, aroma, and taste	[70]
Bambusa tulda	Pasta	Incorporation rate (>5 BSP) has the potential to improve nutritional quality, especially carbohydrate, fiber, and protein	[71]
B. vulgaris	Tart	Improved sensory and widely accepted among the different types of consumers	[112]
D. asper	Biscuit	Enhanced the dietary fiber in products as well as its functional properties	[72]
B. tulda	Soup cube	Soup cubes simulated with bamboo are rich in minerals such as calcium, copper, potassium, and insoluble fiber, low in fat and moderate carbohydrate content, and can be recommended to reduce weight, PCOS patient, calcium-deficient patients	[73]
D. hamiltonii	Crispy salted snacks (Namkeen)	Significant improvement in the antioxidant activity of fortified crispy salted snacks	[19]
B. tuldoides	Cookies	Enhanced fiber and improved sensory acceptability	[111]

components of bamboo isolated from *Sasa senanensis* by steaming and subsequent water extraction which is a mixture of xylose and xylo-oligosaccharides (XOS) are reported to be a potential raw material in the fields of functional food and pharmaceutical industries [65]. Setiawati et al. [72] investigated the potential of bamboo fiber in the modified local flour to reduce the dependence on wheat flour and used it to prepare chemical-free functional food. The study reported the best modified flour formulation was in the combination of flour derived from *Ipomoea batatas L.* and *Dendrocalamus asper* in a ratio of 90:10 which was good for making bakery products and coating fried products. The hemicelluloses compounds, xylitol, have several health benefits such as anti-caries, anti-inflammatory, and sweetening properties [66]. Such health-benefit compounds are of great interest in the food industries and are reported to be present in *Phyllostachys pubescens* [67]. The presence of various health-benefit compounds in bamboo shoots has led to the development of various food-to-food fortified products.

4 Bioactive Compounds of Bamboo Shoot Fortified Products

Secondary plant metabolites, known as bioactive compounds, are very abundant in plants and serve a variety of purposes in humans, including lowering the risk of many chronic diseases [74]. Bamboo shoots are a rich source of bioactive compounds, including phytosterols, which are precursors to many pharmaceutical steroids and phenols, metal chelators, singlet oxygen quenchers, and free radical terminators [12, 75–77]. Bioactive compounds, which mostly consist of phenolics, phytosterols, and dietary fibers, act as natural antioxidants, protect and strengthen key organs, including the brain, neurological systems, and others, as well as enhance cardiovascular health [78, 79]. Phytosterols provide a number of health advantages, including anti-cancer, cholesterol-lowering, anti-inflammatory, and anti-atherogenic effects [80, 81]. Bamboo shoots being rich in phytosterol can be used as a natural source to make steroids, in the pharmaceutical and nutraceutical industries [12]. Srivastava [75] estimated the phytosterol concentration in fresh and fermented edible bamboo species, *Bambusa tulda* and *Dendrocalamus giganteus,* and reported a higher phytosterol content in fermented shoots (1.6–2.8%) than the fresh shoot (0.21–0.39%). Lachance and He [80] studied the phytosterol composition from the crude extract of various bamboo species, *Bambusa oldhami, B. edulis, Pseudosasa usawai, Dendrocalamus latiflorus, Phyllostachys edulis, P. pubescens,* and *P. makinoi* using gas chromatography-mass spectrometry (GC–MS) and liquid chromatography-mass spectrometry (LC–MS). The study reported several mixtures of phytosterol, including sitosterol, sitostanol, stigmasterol, beta-sitosterol, campesterol, and derivatives. Analysis of phytosterol composition in the bamboo shoot extract from *Phyllostachys pubescens* using gas chromatography-mass spectrometry (GC/MS) identified 17 compounds with main components of 26% α-sitosterol, 10.5% of 9,12-Octadecadienoic acid, and 9.83% of 9,12,15-Octadecatrienoic acid [82]. The total phytosterol content in bamboo shoot species of *Bambusa balcooa* and *Dendrocalamus strictus* was also studied in fresh and fermented shoots [48]. Phytosterol concentration was higher in fermented bamboo shoots of *B. balcooa* (0.61%) and *D. strictus* (0.42%) as compared to the fresh shoot, which ranges from about 0.14 to 0.18%. Lu et al. [83] analyzed the phytosterol composition of bamboo species *Pleioblastus amarus, Dendrocalamus latiflorus, Phyllostachys pubescens,* and *P. praecox* using a UPLC-APCI-MS method and identified the presence of phytosterol compounds, 6-ketocholestanol, desmosterol, ergosterol, cholesterol, lanosterol, cholestanol, stigmasterol, campesterol, α-sitosterol, and stigmasterol. The total phytosterol content of fresh juvenile shoots of *Bambusa balcooa, B. tulda, B. nutans, Dendrocalamus giganteus, D. hamiltonii, D. membranaceus,* and *D. strictus* was analyzed and reported in the range from 0.19 g/100 g to 0.13 g/100 g with maximum content in *B. balcooa* and *D. hamiltonii* [46]. Ingudam and Sarangthem [84] also reported maximum content of phytosterol with 0.29 g/100 g dry weight in *Dendrocalamus hamiltonii* during analysis in 12 bamboo species *Dendrocalamus brandisii, D. strictus, D. giganteus, D. flagellifer, D. hamiltonii, D. sericeus, Bambusa tulda, B. balcooa. B. nutans, B. kingiana, B. khasiana,* and *Cephalostachyum pergracile.* Santosh et al. [13] analyzed the total phytosterol content in *D. hamiltonii* shoot paste to be used for fortification and reported a maximum content of 0.47 g/100 g dry weight, which was higher than previously reported 0.19 g/100 g dry weight [46] and 0.29 g/100 g dry weight [84].

Due to the numerous health benefits of phenol, including its antioxidant and antibacterial activity, bamboo shoots, which are high in phenol content, are becoming increasingly popular in the food sector [85, 86]. Total phenol content of four bamboo species, *Bambusa balcooa, B. tulda, B. vulgaris,* and *Dendrocalamus hamiltonii,* ranges from 153.91 to 222.81 GAE (gallic acid equivalents)/100 g dry weight [87]. Eight phenolic compounds were identified from the shoot extracts of *P. pubescens* and *P. nigra* which include protocatechuic acid, p-hydroxybenzoic acid, catechin, caffeic acid, chlorogenic acid, syringic acid, p-coumaric acid, and ferulic acid [85]. Total phenol content in the fresh shoots of *Bambusa balcooa, B. tulda, B. nutans, Dendrocalamus giganteus, D. hamiltonii, D. membranaceus,* and *D. strictus* ranged from 191.37 mg/100 g to 443.97 mg/100 g fresh weight which was highest in *B. tulda* and minimum in *B. balcooa* [46]. Pandey and Ojha [88] studied total phenol content in the shoots of *Bambusa tulda, Dendrocalamus asper,* and *D. strictus* at different optimum harvesting ages of fresh shoots which ranged from 0.57 to 2.97 g/100 g with maximum content in *D. strictus,* whereas total phenol content in fresh shoots of *B. bambos, B. tulda, D. asper,* and *D. strictus* was reported within the range from 0.36 to 0.63 g/100 g [29]. Bajwa et al. [89] analyzed the physicochemical and nutritional qualities of *Dendrocalamus hamiltonii* shoots in which the phenol content was reported to be 0.59 g/100 g fresh weight, whereas Santosh et al. [13] also reported the total phenol content of the same species with 0.61 g/100 g fresh weight. Nuzul et al. [113] determined the total phenolic content, total flavonoid content, and free radical scavenging activity, as well as identified phenolic compounds in the shoots of *Bambusa beecheyana*. The study reported a significant content of total phenolics, flavonoids, and potential antioxidant activity. It also identified a total of five phenolic compounds including p-coumaric acid and 4-methoxycinnamic acid. Dietary fiber from bamboo shoots has also been linked to a number of health advantages, including the treatment and prevention of obesity and diabetes, a decrease in cardiovascular illnesses, and a lower incidence of several cancers [90–95]. By administering a fiber-free diet and a diet containing bamboo shoot fiber, Park and Jhon [61] evaluated the health advantages of bamboo shoot dietary fiber on humans. The experiment reported that fiber had positive effects on gastrointestinal function and blood cholesterol levels. Lignans, a significant fiber present in bamboo shoots, are reported to have anti-viral, anti-cancer, and anti-bacterial properties [96, 97]. A high content of dietary fiber was also reported from fresh bamboo shoots of *Bambusa bambos, B. kingiana, B. nutans, B. polymorpha, B. tulda, B. vulgaris, Dendrocalamus asper, D. brandisii, D. giganteus, D. hamiltonii, D. membranaceus, D. strictus, Gigantochloa albociliata,* and *G. rostrate,* ranging from 2.26 to 4.49 g/100 g fresh weight with the maximum in the shoots of *B. kingiana* [12].

Fortification of food products with bamboo shoots has been shown to enhance the contents of bioactive compounds in namkeens, biscuits, and nuggets. Pandey et al. [16] analyzed the phenol content in the bamboo shoot fortified nuggets, papad, and pickle. The products were fortified with the processed shoots of *D. strictus, B. tulda, D. asper, and B. bamboos*. The phenol content in the fortified products ranges from 0.48 g/100 g to 2.43 g/100 g. Choudhury et al. [54] reported an increase in the polyphenol content in biscuits by the incorporation of bamboo shoot powder prepared from the edible shoots of *B. balcooa* from 0.45 mg/100 g to 4.19 mg/100 g. Santosh et al. [50] studied various parameters, including phenol and phytosterols, in the freeze-dried bamboo shoot powder fortified biscuits. The study reported an increase of bioactive compounds and minerals in bamboo shoot fortified biscuits as compared to control biscuits. Similarly, biscuits fortified with different processed forms of bamboo shoots in paste form also showed improvement in the bioactive compound content as compared with the control products [13]. The total phenol and phytosterol contents decreased during the processing of shoots, but namkeen products fortified with bamboo shoots significantly showed an increase in phenolic (0.20 g/100 g) and phytosterol (0.22 g/100 g) content than the phenol content of control (0.08 g/100 g, 0.12 g/100 g, respectively) [20]. The development of food products with enhanced bioactive compounds has several health benefits due to which different processed bamboo shoots are being used to fortify food products.

5 Antioxidant Properties of Bamboo Shoot Fortified Products

Antioxidants are substances or compounds that prevent the formation of free radicals in our body by scavenging or inhibiting the oxidation of molecules. The majority of health advantages of antioxidants come from the body's natural ability to reduce inflammation. The important role of antioxidants is to promote cardiovascular health, inhibit the growth of cancerous tumors, prevent diabetes, slow the aging process in the brain and nervous system, and lessen the risk and severity of neurodegenerative diseases including Alzheimer's disease and Parkinson's disease [98]. In addition, antioxidants play a crucial role in the petrochemical, culinary, cosmetic, and pharmaceutical industries, where they stabilize polymeric products [99]. In the food and pharmaceutical industries, antioxidants are used to prevent deterioration, rancidity, and discoloration caused by oxidation during processing and storage [100]. There are several known natural compounds with antioxidant properties that can be extracted from plants, which are mainly phenols, polyphenols, vitamin C, vitamin E, beta-carotene, flavonoids, amino acids, and amines that are known to have the potential to reduce disease risk. However, due to a lack of natural antioxidants, nowadays most food and pharmaceutical products contain synthetic antioxidants that cause concerns about their adverse effect on health. Various synthetic antioxidants, such as butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), and tert-butyl hydroquinone (TBHQ), have been commonly used to reduce reactive oxygen species (ROS) damage in food and pharmaceutical industry but have toxic side effects thereby causing concern to the consumers. Hence, more emphasis is given to the use of natural antioxidants [78, 100]. The antioxidant properties in food become very important in the present day, as they not only extend the shelf life and sensory properties of food products but it also has several health benefits [101]. The presence of rich antioxidant activity influences the beneficial properties of several foodstuffs and beverages including fruits, vegetables, tea, coffee, and cacao on human health [102]. The utilization of antioxidant-rich plant sources for the development of bakery products was reported which inhibited the monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA) decomposition [103]. Biscuits fortified with the peel powder and juice of fresh pomegranate (*Punica granatum*) showed improvement in antioxidant activity and longer shelf life without affecting sensory properties [104]. Alashi et al. [105] fortified bread by incorporating 1, 2, and 3% (w/w) dried leafy vegetable powders from *Amaranthus viridis, Solanum macrocarpon,* and *Telfairia occidentalis* to enhance polyphenol consumption. Fortification of bread especially at a 3% level resulted in significantly higher concentrations of other polyphenols (myricetin, catechin, quercetin, and rutin) compared to the control bread. More effective DPPH radical scavenging ability was recorded in the fortified bread compared to the regular bread which indicates that vegetable leaf fortification could serve as a suitable means of enhancing the shelf life of wheat bread.

At present, natural antioxidants are in great demand as synthetic antioxidants being used in food and pharmaceuticals are showing various deleterious effects on health. Hence, bamboo is one such fast-growing plant with huge biomass which can serve as an alternative for the production of natural antioxidants. Bamboo is a versatile plant that has been used in folk medicine to treat different diseases as diaphoretic, carminative, anti-inflammatory, tonic, antimicrobial, and antioxidant properties. The main antioxidants in bamboo leaves and shoots are phenols, vitamins C and E, and mineral elements such as selenium, copper, zinc, iron, and manganese [78]. Several identified antioxidants from bamboo shoots and leaves display certain biological roles, including antioxidative, anti-cancer, anti-hypertensive, and anti-bacterial functions [96, 97, 106, 107]. Research on bamboo shoot antioxidants began in the 1990s with a study by Ishii and Hiroi [108] who identified a compound, namely, diferuloyl arabinoxylan hexasaccharide containing 5–5-linked diferulic acid from bamboo shoots and reported that ferulic acid is a naturally occurring antioxidant present in the plant-based products [109]. Choudhury et al. [54] investigated DPPH radical scavenging activity in the biscuit fortified with bamboo shoot powder (BSP). The result showed an increase in the DPPH radical scavenging activity, highest antioxidant activity at 15% (17.88%) incorporation followed by 10% (14.31%), 5% (8.57%), and control biscuit value was 3.50% only. Giri [110] studied five different shoot fortified biscuit formulations of wheat flour: bamboo shoot powder ratio, namely, A-100:0, B-95:5, C-90:10, D-85:15, and E-80:20 and subjected to sensory evaluation. The result confirmed that product B showed the best results and the antioxidant activity of the control and optimized biscuit (5%) were found to be 5.03% and 9.43%, respectively. The increase in antioxidant activity is due to the presence of a higher amount of antioxidants in bamboo shoot powder biscuits. Santosh et al. [19] evaluated the antioxidant property of bamboo shoot fortified namkeen using three different processed bamboo shoots (unprocessed bamboo shoots-US, 20-min-boiled bamboo shoots-BS, and 24-h-soaked shoot-SS) of *Dendrocalamus hamiltonii*. The antioxidant activity in the processed shoots is reported as the highest IC_{50} value of 584.621 μg/ml in the US followed by BS (1240.87 μg/ml) and SS (1295.01 μg/ml). Similarly, in fortified namkeen, the highest antioxidant activity (2100.95 μg/ml) was observed in namkeen fortified with the unprocessed bamboo shoot (UN) followed by namkeen fortified with 20-min-boiled shoots (2387.92 μg/ml) and 24-h-soaked shoots fortified namkeen (2402.87 μg/ml). It is confirmed that the incorporation of bamboo shoots enhanced the antioxidant activity of ready-to-eat namkeen products.

6 Conclusion

Malnutrition and disorders linked to diet have increased in recent years as a result of the decline in the variety of bioactive compounds, micronutrients, and mineral elements and more emphasis is given to high-energy human diets. New research suggests that bamboo is a rich source of various micronutrients, elements, vitamins, dietary fiber and low fat and carbohydrates. Adding bamboo shoots to common food products could help feed the undernourished population while also addressing hidden hunger and other health problems. With appropriate methods for the preservation of bamboo shoots in various forms, food-to-food fortification is a recent trend to utilize the maximum benefit of this highly nutritive and healthy vegetable. Bamboo shoots fortified products enriched with the nutrients and bioactive compounds from the shoot showed improvement in the organoleptic properties as well as the rich potential of antioxidants. Scientists and nutritionists are interested in food fortification and the creation of functional foods as one of the most effective ways to treat micronutrient deficiencies or hidden hunger. Bamboo shoot with high nutrient content and health-promoting bioactive components has the potential to be utilized as a healthy food or as a natural source of fortificants for food-to-food fortification to address the micronutrient inadequacy issues that the twenty-first century is currently experiencing.

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Potential of Bamboo in the Prevention of Diabetes-Related Disorders: Possible Mechanisms for Prevention

Aribam Indira, Babita Joshi, Santosh Oinam, Ashwani Koul, and Nirmala Chongtham

Abstract The therapeutic potentials of bamboo have long been recognized and have been documented in pharmacopeias around the world since 10,000 BCE. Recent scientific studies have revealed their medicinal properties that include relieving hypertension, and preventing cardiovascular diseases, cancer, diabetes, and many more. Diabetes is the most persistent and prevailing health problem today that is on the rise globally. It is a metabolic disorder characterized by pancreatic insulin resistance and β-cell dysfunction that leads to many associated complications. Bamboo extract of *Bambusa arundinacea*, *B. balcooa*, *B. tulda*, *B. vulgaris*, *Phyllostachys bambusoides*, *P. nigra*, *Sasa borealis*, *S. quelpaertensis,* etc. has proven to be a good anti-hyperglycemic agent. This chapter discusses the potential role of bamboo in controlling hyperglycemia giving insight into the related active bioactive compounds and acting mechanism for anti-diabetic activity. Several studies on animal models have proven the reduction in blood sugar levels, lactate dehydrogenase, serum glutamic pyruvic transaminase, serum glutamic oxaloacetic transaminase, triglyceride, and total cholesterol levels in animals. The extract inhibits adipogenesis, aldose reductase, and advanced glycation end products which in turn improve insulin signaling. Moreover, the extract activates 5'Adenosine monophosphate-activated protein kinase that increases glucose uptake. The rich natural antioxidant of bamboo neutralizes the reactive oxygen species produced and oxidative stress and maintains body homeostasis preventing the body from diabetic complications. The antioxidant properties of bamboo are mainly attributed to the presence of bioactive compounds mainly phenolic compounds, flavonoids and flavone glycosides, phytosterols, and polysaccharides. Bamboo, being a potent source of these bioactive compounds, can be used as a preventive nutraceutical for controlling hyperglycemia and related complications. Further, this natural resource can be utilized in the production of value-added functional food products and pharmaceutical products to prevent hyperglycemia.

A. Indira · B. Joshi · S. Oinam · N. Chongtham (✉)
Department of Botany, Panjab University, Chandigarh 160014, India
e-mail: cnirmala10@gmail.com

A. Koul
Department of Biophysics, Panjab University, Chandigarh 160025, India

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1 Introduction

Diabetes mellitus (DM) is one of the most persistent and prevalent health problems worldwide. It is related to the metabolic disorders of fats and proteins affecting various organs like the heart, blood vessels, kidneys, nerves, and eyes. Production of inadequate or no amount of insulin by the pancreatic β-cells leads to improper metabolism of glucose, thus elevating its amount. With genetic reasons being inevitable, the factors that cause DM are age, overweight, obesity, and physical inactivity [1]. The problem of DM affecting human health and development is rapidly increasing throughout the world. The number of people with DM has increased from 180 million in 1980 to 422 million in 2014 with the disorder being common among low- and middle-income people and is the fourth leading cause of mortality throughout the world [2]. In 2019, the estimated number of people affected with DM was 463 million worldwide which is expected to reach 690 million individuals in 2040 and may increase by 51% in 2045 [3, 4]. Recently, the disease has emerged as a distinct comorbidity that is closely related to acute respiratory distress syndrome and a cause of increased mortality rates during the pandemic caused by novel coronaviruses that are linked to acute respiratory distress syndrome [5].

Management of DM is still challenging because various synthetic oral treatment drugs like sulfonylureas, biguanides, α-glucosidase, and glinides have a number of serious adverse effects and none of these have yet proven to completely eradicate DM [6, 7]. Natural products with anti-diabetic properties and fewer side effects are an alternative solution to this problem and WHO has warranted further evaluation of traditional plants for their toxicity and treatment of DM [8]. Herbal- and plant-based treatment of various ailments especially DM has been practiced since ancient times and from the ethnobotanical and folklore point of view, about 800 plants may have anti-diabetic properties [9]. Various common vegetables, fruits, beverages, and spices mentioned in folklore, such as *Camellia sinensis*, *Phaseolus vulgaris, Tamarindus indica*, *Taraxacum officinale*, *Annona squamosa*, *Brassica juncea*, *Ocimum sanctum*, *Cinnamomum cassia*, *Ficus religiosa*, *Allium sativum*, *and Psidium guajava,* have been proven to have anti-diabetic effects [10–14]. The anti-diabetic properties of plants have been projected to be due to the presence of various compounds such as alkaloids, carbohydrates, glycosides, glycans, flavonoids, mucilages, steroids, terpenoids, pectins, peptides, phenols, phytosterols, polysaccharides, amino acids, lipid, glycopeptides, and iridoids [9, 15]. The presence of all these phytochemicals helps in the prevention of DM through different mechanisms in a holistic manner, indicating that consumption of plants and plant-derived food products that contain such phytochemicals will help in the alleviation of DM and its related complications.

Bamboo is one such plant that has proven to be a novel health-promoting plant [16]. It is a renewable, fast, and easy-growing resource. Besides the use of bamboo as a wood substitute for its mechanical strength, industrial raw material, and alternate to fossil fuels, it has always been an integral part of the ancient traditional medicinal system in many southeast Asian countries like India, China, Japan, Korea, Indonesia, Sri Lanka, and many more since thousands of years ago [17]. All parts of bamboo, such as rhizome, culm shavings, leaves, sheaths, roots, seeds, culm, and shoot skin, have utilization in some or the other way [18]. Scientific studies have reported bamboo to contain various nutrients and phytochemicals such as amino acids, proteins, carbohydrates, starch, vitamins, and minerals and have also proven to be a huge reservoir for phytochemicals such as dietary fibers, phytosterols, phenolic compounds, and several types of flavones. The extracts of bamboo are a potent health-benefiting agent protecting the body from various illnesses such as cardiovascular diseases, diabetes, cancer, and organ disorders, to name a few [14, 19–21]. Its rich antioxidant content neutralizes reactive oxygen species and oxidative stress and maintains body homeostasis. This article discusses the anti-diabetic and hypoglycemic effects of bamboo, highlighting its traditional medicinal uses, phytochemical constituents, and their probable mechanism of action.

2 Traditional Medicinal Uses of Bamboo

The earliest use of bamboo in traditional medicine dates back to 10,000 BCE [22]. Various ancient medicinal systems and documents have mentioned the curative properties of bamboo for many ailments like leprosy; wounds; swellings; improving digestion; and preventing respiratory diseases, cold, cardiovascular diseases, gastrointestinal problems, and cancer (Table 1). Bamboo is among the most valued herbs of traditional Chinese medicinal systems. Medicinal pharmacopeias like *Compendium of material medica* mention many beneficial effects of bamboo [22]. Parts of bamboo are either taken alone or as a formulation with other herbs. Ayurvedic remedies that contain *tabasheer* as a primary ingredient include *sitopaladi churna*, *talisadi churna*, *dadimashtaka churna*, *drakshavaleha*, *puga khanda*, *maha tarunark rasa*, etc. These are frequently employed to treat cough, the common cold, tuberculosis, acidity, and diarrhea [23]. The Sushruta Samhita, an ancient Ayurvedic treatise, listed multiple medical applications for various bamboo elements, including juvenile culms, rhizomes, culm-sheaths, and seeds [24]. *Chyawanprash* is a herbal tonic used as an energizer and immune booster in India, which was formulated in the early first millennium BCE. In the Unani medicinal system, burned bamboo rhizome powder is a common treatment for ringworm-related skin infections, joint pain, premature hair loss, and gum bleeding, and young bamboo sprouts and leaves are employed in the treatment of leprosy as a birth control method, and as a blood purifier [25, 26].

Dai medicine and *Sasa* health are traditional medicinal formulations from bamboo for the treatment of ailments popular in southeastern China and eastern Asia [20]. *Dai* medicine uses the stems of *Dendrocalamus hamiltonii*, *Thyrsostachys siamensis*, *Pseudostachyum polymorphum,* and *Dendrocalamus spp.* to prevent kidney dysfunction and related problems [27]. Leaf decoction of *Phyllostachys glauca* has been

Table 1 Ethnomedicinal and traditional medicine use of bamboo around the world

Sl. no	Country	Name	Constituents	Treatment	References
1	China	*Chenjin wan Quighuo ditan tang*	Bamboo shaving, tabasheer, cobra lily, citrus, hoelen, sage, silkworm, chrysanthemum, apricot seed, lilyturf, biota, fritillaria, ginger	Phlegm, insomnia, restlessness, blurred vision	[22]
2	China	*Gualou zhishi tang*	Bamboo shaving and sap, fritillaria, balloon flower, gourd seed, citrus, costus, licorice, Chinese skullcap, gardenia	Thick phlegm	[22]
3	China	*Jupi zhuru tang*	Bamboo shaving, licorice, citrus, crow-dipper, hoelen	Phlegm	[22]
4	China	*Qinggong tang*	Bamboo leaf, lilyturf, figwort, rhino horn, forsythia, lotus plumule	Fever with dryness	[22]
5	China	*Qingluo yin*	Bamboo leaf, lotus leaf, gourd, mirabilite, lablab bean flower, Japanese honeysuckle flower	Fever, blurry vision, headache, arthritis	[22, 44]
6	China	*Xiaoer qizhen*	Tabasheer, cobra lily, cinnabar, realgar, scorpion, croton seed	Phlegm, wheezing, coughing	[22]
7	China	*Zhuye shigao tang*	Bamboo leaf, gypsum, pinellia, lilyturf, ginseng, licorice, rice	Fever with dryness, irritability, insomnia	[22]
8	China	ND	Bamboo culm extract	Fever, cough, unconsciousness	[17]
9	China	ND	The dried leaf of *Pleioblastus amarus*	Fever, nervousness, lung disorders	[17]
10	Egypt	*Suffof-e-Suzak Qawi*	Tabasheer, Chinese date, palash, guduchi, asphaltum, Chinese rhubarb	Gonorrhea, diuretic	[143, 144]

(continued)

Table 1 (continued)

Sl. no	Country	Name	Constituents	Treatment	References
11	Egypt	*Zuroor-e-Quala*	Tabasheer, white-barked acacia, camphor tree, cardamom, pomegranate, winged prickly ash	Inflammation, microbial infection stomatitis, gastric ulcer	[145]
12	Ghana	ND	Extract of *Bambusa vulgaris* leaves	Malaria, diabetes	[31]
13	India	*Sitopaladi churna*	Tabasheer, pepper, cardamom, and cinnamon in a base of sugar	Common cold, bronchitis, sore throat, sinus, chest congestion, neuralgia, tuberculosis, cough, lung diseases	[22, 146]
14	India	*Tabasheer/Banslochan*	Intermodal siliceous exudate; contains 1% organic matter and 96.9% silicic acid	Spasmodic asthma, cough, fever	[22]
15	India	*Chyawanprash*	Tabasheer, gooseberry, red sandalwood, shatavari, cardamom, myrobalan, lotus seed, bindii, and ghee of Indian cow	Immune-related problems, vigor, vitality, and brain functions	[147]
16	India	*Talisadi churna*	Banslochan, silver fig, cardamom, cinnamon, sugar, pepper, ginger	Fever, body ache, abdominal pain, loss of taste and smell	[148]
17	India	*Dadimashtaka churna*	Banslochan, arrowroot powder, pomegranate, pepper, coriander, celery	Cough, respiratory infection, gastrointestinal tract infection	[149]
18	India	*Drakshavaleha*	Banslochan, grapes, pepper, satawar, gooseberry	Gastritis	[150]
19	India	*Puga Khanda*	Banslochan, areca nut, cow milk, cow ghee, cinnamon, cardamom, ginger, sandalwood, lotus seed	Vomiting, gastritis, dizziness, abdominal pain	[151]

(continued)

Table 1 (continued)

Sl. no	Country	Name	Constituents	Treatment	References
20	India	*Maha tarunark rasa*	Bamboo silica and other minerals, lemon juice	Fever	[152]
21	India	ND	Dried shoot with a caterpillar on leaves of the cassia tree	Weakness	[153]
22	India	ND	Fresh leaves	Fertility and reproductive ability	[33]
23	India	ND	Fermented shoots	Constipation	[34]
24	India	ND	Fermented bamboo shoots with pepper and leaves of *Allium porrum*	Influenza	[154]
25	India	ND	Shoot extract	Wounds caused by swords or arrows for flake-free hair	[116]
26	India	ND	Decoction of fermented shoots	Ringworms, tumors, meningitis	[116]
27	India	ND	*B. tulda* leaf paste	Dog bites	[116]
28	India	ND	*B. nutans, B. tulda* shoot paste/decoction	Heal skin diseases, wounds, and deadly bites	[153]
29	India	ND	*B. vulgaris* root	Burning sensation, arthralgia, debility, dysuria	[155]
30	India	ND	*B. vulgaris* roots decoction	Arka poisoning	[156]
31	India	ND	Bamboo shoot with pepper/decoction with palm jaggery	Abortion, labor pain, excessive bleeding	[157]
32	India	ND	Burnt roots of *B. arundinacea*	Ringworm, bleeding gum, painful joint	[158]
33	India	ND	Seed of *B. arundinacea*	Strangury, urinary discharges	[158]
34	India	ND	Bark of *B. arundinacea*	Skin eruption	[158]

(continued)

Table 1 (continued)

Sl. no	Country	Name	Constituents	Treatment	References
35	India	ND	Leaf of *B. arundinacea*	Haemoptysis	[158]
36	India	ND	Root of *B. arundinacea*	Cirrhosis, tumor of the abdomen, liver, spleen, and stomach	[159]
37	India	ND	*B. vulgaris* leaf	Paralysis, ulcers, diabetes, inflammatory complaints, skin disorders	[160]
38	India	ND	*B. bambos* leaf extract with black pepper and common salt infusion	Eye irritation, halitosis, anthelmintic, astringent, febrifuge	[161]
39	India	ND	Burnt roots, bark, stem, and leaves of *B. bambos*	Ringworm, bleeding gum, painful joints, skin eruption, blood purification	[161]
40	Indonesia	*Rebung*	Bamboo sprouts	Abdominal pain, jaundice	[162]
41	Indonesia	*Gulei rebung*	Decoction of bamboo sprouts with coconut palm tree	Insomnia	[163]
42	Japan	*Chikusaku*	Bamboo vinegar	Skin sensitivity, high blood pressure	[23]
43	Japan	*Chikusaku-eki*	Bamboo extract from burnt bamboo charcoal	Skin sensitivity, scabies, eczema, atopic dermatitis	[164]
44	Korea	*Jugyeom*	Bamboo salt	Aging, cancer	[30]
45	Sri Lanka	ND	Extract of *B. vulgaris* leaves	Dengue fever	[17]
46	Sri Lanka, Nigeria	ND	Extract of *B. vulgaris* leaves	Typhoid fever, gonorrhea, diarrhea, fever, inflammation, wounds, diabetes, and malaria	[91]

ND: Not defined

traditionally used by the inhabitants of Yunnan Province, China for the treatment of lung-inflammation-related disorders, *P. heterocycla* for throat-related inflammations, and *Indosasa pingbianensis* for headache and common cold [28]. Leaf extract of *Sasa sinensis* is used as a traditional medicine in Japan to control inflammation [29]. Bamboo salt (sea salt baked in bamboo culm) is an integral part of Korean medicinal practice that solves problems related to inflammation and cancer [30]. *Bambusa vulgaris* stem boiled with palm sugar is consumed twice daily by the *karo* people of north Sumatra, Indonesia to cure diabetes [30]. Dilip and Bonoranjan [32] have reported the use of a decoction of the tender young leaves of *B. balcooa* for treatment of DM by the *Moran* tribe of Tinsukia District of Assam, India. *Kani* tribe of Kanyakumari District from Tamil Nadu, India consumes seeds of bamboo (mostly of *B. arundinacea*) with the belief that it enhances their fertility and reproductive ability [33]. *Kandha* tribe of Kalahandi District, Odisha, India uses fermented shoots of *D. strictus* to cure constipation [34]. Also, leaf extracts of *B. arundinacea* have been used in the treatment of diabetes traditionally [35]. In traditional medicinal systems of Northeastern India, bamboo plant, either alone or in a mixture with other herbs, is used to treat various ailments such as toothache, hypertension, chickenpox, smallpox, diabetes, to heal cut wounds, sinusitis, headache, etc. *Adi* tribe of Arunachal Pradesh, India uses *B. tulda*, *D. giganteus*, *D. strictus*, and *Schizostachyum capitatum* for various treatments like tetanus, abortifacient, stomach pain, and in the production of steroidal drugs [36]. Young bamboo sprouts and leaves are used as blood purifiers, birth control agents, and for the treatment of leprosy [37]. Bamboo leaves have long been used for the treatment of inflammation, leprosy, eczema, eye infection, osteoarthritis, and various other diseases [38].

3 Bioactive Compounds in Bamboo and Their Potential Health Benefits

In addition to the subsequent applications of bamboo in traditional medical practices, the leaves and shoots of bamboo have been used for centuries in Asian countries [22]. The young tender shoots are consumed as a vegetable, and the leaves are used as a beverage, and these parts are regarded as functional food as they impart various phytochemicals having health-benefiting properties [106, 175]. However, the scientific validation for many of these health benefits has only recently been revealed, correlating them with the presence of bioactive components [16, 39–43]. Several major groups of bioactive compounds have been identified in bamboos, such as phenols and their derivatives, phenolic glycosides, phenolic acids and their derivatives, flavonoid and flavone glycosides, phytosterols and terpenoids, polysaccharides, saponins, general glycosides, anthraquinones, and coumarins [44, 45] (Table 2). The predominant bioactive compounds in the leaves of bamboo are flavonoids, phenolic acids, and coumaric acid which are mainly C-glycosyl flavones, O-glycosyl flavones, and poly-methoxylated flavones, namely, vitexin, isovitexin, orientin, isoorientin, naringin, quercetin, luteolin, rutin, tricin, caffeic acid, chlorogenic acid, and hydroxyl coumaric acid [46]. The seeds of *B. arundinacea* have been reported to consist of phenols, flavonoids, steroids, and tannins [47].

A major group of bioactive compounds occurring naturally in bamboo in significantly higher quantities is phenolic compounds [48–50]. Phenolic compounds are the most potent natural antioxidant compounds available through a plant-based diet that protect cellular and sub-cellular components from oxidative damage. Their superior free radical scavenging activity helps to reduce cellular oxidative stress significantly. Apart from antioxidant behavior, phenolic compounds also possess anti-diabetic, anti-hypertension, anti-inflammatory, anti-allergic, and anti-microbial properties, thereby helping in the prevention of several chronic diseases including cardiovascular diseases and cancers [51–53, 173, 174]. HPTLC analysis of the phenolic content of ethanolic extract of *B. arundinacea*, *B. vulgaris*, and *D. strictus* revealed the presence of gallic acid, chlorogenic acid, caffeic acid, and ferulic acid in all samples [54]. Other phenolic compounds like orientin, homoorientin, isoorientin, vitexin, homovitexin, tricin, apigenin, luteolin, hesperidin, coumarin, syringic acid, caffeic acid, and chlorogenic acid are the main phenolic compounds reported in bamboo and presence of these compounds has been associated with health benefits like anti-microbial, anti-inflammatory, anti-helminthic, anti-ulcer, and anti-diabetic [42, 55–57]. Antioxidative flavonoid C-glycoside derivatives, isoorientin, isoorientin 2″-O-α-L-rhamnoside, tricin 7-O-β-D-glucopyranoside, and apigenin 6-C-β-D-xylopyranosyl-8-C-β-D-glucopyranoside were isolated [58]. These flavone C-glycoside derivatives possess potent free radical scavenging activity against t-BOOH-induced oxidative damage in HepG2 cells [58]. Gomez et al. [59] reported the presence of a higher quantity of mequinol in the pyrolyzed culm of *Guadua angustifolia* which is used to treat hyperpigmented skin problems.

Phytosterols are plant-derived sterols that improve cardiovascular health by lowering the cholesterol level in the body and have immunomodulatory, anti-inflammatory, and anti-carcinogenic activities [60]. The main phytosterols found in bamboo are β-sitosterol, campesterol, friedelin, glutinol, ergosterol, cholesterol, stigmasterol, stigmasta-3,5-dien-7-one, stigmast-4-en-3-one, stigmastanol, dihydrobrassicasterol, and lupenol [19, 61–63]. Lachance and He [64] prepared a hypocholesterolemic formulation from bamboo shoot extracts, which was rich in many phytosterols such as β-sitosterol, campesterol, and stigmasterol that showed potent cholesterol-lowering activity. The phytosterols of bamboo have also been shown to inhibit or reduce cholesterol absorption, hypolipidemic, and anti-inflammatory effects against non-bacterial prostatitis and anti-microbial activity [61, 65].

Polysaccharides are important bioactive macromolecules with various activities like immunomodulatory, anti-carcinogenic, and antioxidant activity [66]. Bamboo polysaccharides with higher uronic acid content, smaller molecular weight, and lower monosaccharide content have higher antioxidant activity [67]. Polysaccharides isolated from *P. praecox* have potent prebioactive activity by significantly increasing the number of *Bifidobacterium adolescentis* and *B. bifidum* that contribute to organic acid production [66]. Moreover, β-pyran polysaccharide isolated from *Leleba oldhami* shoot shells has shown to have hypoglycemic activity [68]. A

Table 2 Potential health benefits of the bioactive compounds present in bamboo

Sl. no	Potential medicinal use	Species	Compound	References
1	Anti-adipogenesis	*Bambusa textilis*, *P. nigra*, *S. borealis*	Orientin	[56]
2	Anti-aging	*B. textilis*, *P. nigra*, *S. borealis*	Orientin	[105]
3	Anti-allergic	*P. nigra*	Trans-coniferyl alcohol	[165]
4	Anti-angiogenic	*P. nigra*	Tricin	[165]
5	Anti-bacterial	*Guadua angustifolia*, *P. pubescens*	Dihydrobrassicasterol, 4-ethyl-2-methoxyphenol	[63]
6	Anti-biotic	*P. pubescens*, *S. veitchii*, *S. albomarginata*	Xylose	[166]
7	Anti-carcinogenic	*B. textilis, D. latiflorus*, *P. amarus*, *P. bambusoides, P. nigra*, *P. praecox*, *P. pubescens*, *S. albomarginata, S. coreana, S. veitchii*	Luteolin-7-O-glucoside, stigmastanol, palmitic acid, lignin, catechin, trans-coniferyl alcohol, vitexin, isovitexin, caffeic acid, apigenin, coumarin, glucan	[57]
8	Anti-depressant	*B. textilis*, *P. nigra*, *S. borealis*	Orientin	[105]
9	Anti-diabetic	*B. textilis*, *P. edulis*, *P. nigra*, *P. prominens*, *P. pubescens*, *S. coreana*, *S. veitchii*	Isovitexin, lupenol, glucose, ferulic acid, lyoniresinol, syringic acid, benzyl-O-β-D-glucopyranoside, stigmast-4-ene-3,6-dione	[55]
10	Anti-fatigue	*S. albomarginata*	Ribose	[167]
11	Anti-fungal	*D. latiflorus*, *Pleioblastus amarus*, *P. edulis*, *P. praecox, P. pubescens*	Ergosterol, p-coumaric acid methyl ester	[55]
12	Anti-hypercholesterolemia	*D. latiflorus*, *P. amarus*, *P. praecox, P. pubescens*	Campesterol	[168]
13	Anti-hyperlipidemic	*P. nigra*	Lupenone	[168]
14	Anti-hypertensive	*S. coreana*	Hesperidin	[56]
15	Anti-hyperuricemia	*G. angustifolia*	Phenol	[59]

(continued)

Table 2 (continued)

Sl. no	Potential medicinal use	Species	Compound	References
16	Anti-inflammatory	*B. textilis*, *B. tuldoides*, *P. bambusoides*, *P. edulis*, *P. nigra*, *P. pubescens, S. albomarginata*, *S. borealis*, *S. coreana*, *S. veitchii*	Vitexin, isoorientin, apigenin luteolin-7-O-glucoside, lup-20(29)-en-3-ol, olean-12-ene, n-feruloyl serotonin, p-coumaric acid ethyl ether, p-coumaryl alcohol mannose, sinapaldehyde, 4-hydroxybenzaldehyde, trans-coniferyl alcohol	[55, 105, 167]
17	Anti-microbial	*B. textilis*, *B. tuldoides*, *D. latiflorus*, *P. edulis P. nigra P. pubescens, S. albomarginata*, *S. coreana*, *S. veitchii,*	Friedelane-3-one, arabinose, ferulic acid, coumarin, p-coumaric acid, β-sitosterol, syringic acid, 1,3-b-glucan	[105]
18	Anti-mutagenic	*P. edulis*, *P. pubescens*	Lyoniresinol	[55]
19	Anti-nociceptive	*B. textilis*, *P. nigra*, *S. borealis*	Orientin	[57]
20	Anti-osteoarthritis	*D. latiflorus*, *P. amarus*, *P. praecox, P. pubescens*	Stigmasterol	[63, 168]
21	Antioxidant	*B. textilis*, *D. latiflorus*, *G. angustifolia*, *P. amarus*, *P. praecox*, *P. edulis*, *P. prominens*, *S. coreana*	Phenol, apigenin, luteolin, β-sitosterol, ergosterol, friedelin, stigmasterol, tricin-7-O-β-D glucoside, lup-20(29)-en-3-one, phyllostadimers A, B	[55–57]
22	Anti-plasmodial	*P. edulis*	4-hydroxy-3-methoxypropiophenone	[55]
23	Anti-proliferative	*B. textilis*, *D. latiflorus*, *P. amarus*, *P. praecox, P. pubescens*	Ergosterol, apigenin	[63]
24	Anti-pyretic	*P. edulis, P. nigra*	Friedelin	[55]
25	Anti-tubercular activity	*P. pubescens*	Linoleic acid	[168]
26	Anti-viral	*P. edulis*, *P. prominens*, *P. pubescens*	Sinapaldehyde, catechin	[55]
27	Apoptosis-inducing	*S. coreana*	Luteolin	[56]
28	Attenuates plaque, amyloid, dementia	*S. borealis*	Isoorientin 2″-O-α-L-rhamnoside	[58]

(continued)

Table 2 (continued)

Sl. no	Potential medicinal use	Species	Compound	References
29	Brainprotective	*S. borealis*	Tricin 7-O-β-D-glucopyranoside	[58]
30	Cardioprotective	*P. edulis*, *P. pubescens*, *S. albomarginata*, *S. coreana*, *S. veitchii*,	Hesperidin, syringic acid, glucan, ribose, 3-(4-hydroxy-3-methoxyphenyl)-2-propenoic acid; Coniferaldehyde	[42, 56]
31	Chemoprotective	*S. coreana*	Luteolin	[56]
32	Cytoprotective	*P. edulis*, *P. pubescens*	3-O-caffeoyl-1- methylquinic acid, p-hydroxybenzoic acid	[42, 110]
33	Gastroprotective	*B. textilis*, *P. bambusoides*, *P. prominens*, *S. borealis*, *S. coreana*	Isoorientin	[169, 170]
34	Hepatoprotective	*B. textilis*, *G. angustifolia*, *P. bambusoides*, *P. edulis, P. nigra*, *P. prominens*, *S. borealis*, *S. coreana P. edulis, P. nigra*	Isoorientin, friedelin, phenol, chlorogenic acid, syringic acid	[39, 42, 110]
35	Hyperalgesic	*B. textilis*, *P. edulis*, *P. nigra*, *P. pubescens*, *S. coreana*	Vitexin, friedelin, p-coumaric acid	[105]
36	Immunomodulatory	*D. latiflorus*, *P. amarus*, *P. praecox*, *P. edulis*, *P. nigra*, *P.pubescens*, *S. coreana*	β-sitosterol, caffeic acid	[56, 110]
37	Inhibits anaerobic glycolysis	*P. heterocycla*	2,6-dimethoxy-p benzoquinone	[171]
38	Inhibits platelets aggregation	*B. textilis*, *P. nigra*, *S. coreana*	Vitexin	[56]
39	Insecticide	*P. nigra*	Friedelane-3-ol	[56]
40	Lung surfactant	*P. pubescens*	Palmitic acid	[168]
41	Melanogenesis	*B. tuldoides*, *P. nigra*	Lup-20(29)-en-3-one	[56]
42	Melisma	*G. angustifolia*	Mequinol	[59]
43	Nematicidal activity	*P. pubescens*	Linoleic acid	[168]
44	Neuroprotection	*B. textilis*, *P. bambusoides, P. edulis*, *P. nigra*, *P. pubescens*, *S. coreana*	Ferulic acid ethyl ether, coniferaldehyde, luteolin-7-O-glucoside, Vitexin, protocatechuic acid, syringic acid	[39, 55]
45	Non-narcotic analgesic	*P. edulis, P. nigra*	Friedelin	[55]

(continued)

Table 2 (continued)

Sl. no	Potential medicinal use	Species	Compound	References
46	Parkinson's disease	*P. pubescens*	Protocatechuic acid	[42]
47	Radioprotective	*B. textilis P. nigra*, *S. borealis*	Orientin	[56]
48	Regulation of cell motility	*P. pubescens*	Catechin	[42]
49	Renal protective	*B. textilis*, *P. bambusoides*, *P. prominens*, *S. borealis*, *S. coreana*	Isoorientin	[169]
50	Skin lightening	*G. angustifolia*	Mequinol	[59]
51	Treatment of chronic myeloid leukemia	*P. edulis*	5-O-caffeoyl4-methylquinic acid	[110]
52	Tumor suppression	*D. latiflorus*, *P. amarus*, *P. praecox*, *P. pubescens*	Ergosterol	[168]
53	Wound healing	*P. edulis*	4-hydroxybenzaldehyde	[55]

polysaccharide component of plants, dietary fiber is non-digestible and acts as roughage in the human diet, thereby improving the digestive system. It is not digested in the small intestine and has many associated health benefits [69]. Dietary fiber from bamboo shoots has shown therapeutic benefits for acquired intestinal diverticula [70]. Many components of dietary fiber are reported in bamboo such as neutral detergent fiber (NDF) which is the indigestible component comprising hemicellulose, cellulose, and lignin, and acid detergent fiber (ADF) comprising cellulose and lignin [22]. Studies indicate that bamboo shoots' high cellulose content might mitigate intestinal cancer by enhancing the microbial flora in the gut, lowering lipid products, and enhancing the intestine's peristalsis [71]. Consuming bamboo shoots had a favorable impact on lipid profiles, bowel movement, and the management of intestinal microbial flora [72–74]. Thus, bamboo polysaccharides have significant implications for consumers' health in terms of their direct positive impacts on lipid profiles, blood sugar levels, and bowel functions.

Apart from these major groups of bioactive compounds, several other bioactive compounds with strong antioxidant potential having valuable health benefits have been extracted and characterized from bamboos such as tricin, taxifolin and heteropolysaccharides, anti-fungal protein dendrocin, and anti-microbial compounds such as novel chitin-binding peptides Pp-AMP1 and Pp-AMP-2 and chitosanase isoforms [40, 75–79].

4 Experimental Models for Hypoglycemic and Anti-diabetic Studies

The anti-diabetic studies and experiments have been carried out both in vivo and in vitro. In vitro models for detailed diabetic studies have been reported in primary cultures of dorsal root ganglia, Schwann cells and neural tissue and cell lines. The in vivo studies are carried out either in animals by feeding or by clinical studies with diabetic models. The most common models are rodents like rats and mice of different strains by inducing diabetes with commonly commercially available chemicals like alloxan or streptozotocin (STZ). These drugs are administered parenterally through intraperitoneal, intravenous, or subcutaneous, and the doses of their administration depend on the strain of rodent and route of administration. Both alloxan and STZ enter the pancreas via GLUT2 glucose transporter mediate by generating reactive oxygen species [80, 81].

Alloxan is similar to glucose and its accumulation leads to the decreased oxidation of glucose and further leads to downstream effects like the generation of reactive species such as superoxide dismutase and accumulation of intracellular calcium that results in the destruction of pancreatic β-cells [82]. STZ releases nitric oxide (NO) and causes the alkylation of DNA, which ultimately leads to the destruction of β-cells by necrosis [83].

5 Hypoglycemic and Anti-diabetic Properties of Bamboo

Glucose or blood sugar is one of the major sources of energy of the body derived from our diet which serves as a precursor for the synthesis of many carbohydrates that are required for energy production [84]. The mechanism of adenosine triphosphate (ATP) production by glucose is depicted in Fig. 1. Glucose in the cell phosphorylates to glucose-6-phosphate which captures glucose inside the cell. This glucose either releases energy through glycolysis immediately or is stored as glycogen. A higher level of glucose leads to insulin secretion, which lowers the blood glucose level by controlling the rate of glucose utilization by the cell [85]. Impaired or insufficient insulin secretion by pancreatic cells leads to diabetes and its related complications.

Different extracts of various bamboo species have been studied for their hypoglycemic and anti-diabetic activities (Table 3). The leaves *of B. arundinacea,* when treated in euglycemic and hyperglycemic rats, showed hypoglycemic effects [35]. The leaves *B. arundinacea*, when administered at a dose of 200, 500, and 600 mg/kg in alloxan-induced diabetic rats, showed a decrease in blood sugar levels in bamboo extract administered to diabetic mice in a dose-dependent manner [86]. Zinc oxide (ZnO) nanoparticles synthesized using *B. arundinacea* have been shown to enhance the anti-diabetic potential compared to the crude extract. Histological study of liver tissue administered with ZnO nanoparticles of *B. arundinacea* showed a normal histoarchitecture with normal hepatocyte cells and central vein. Moreover, insulin secretion from the β-cells of the islet of Langerhans was improved thereby decreasing the glucose level by *B. arundinacea* ZnO nanoparticles [4]. Similarly, a dose-dependent significant reduction in blood glucose level, serum triglycerides, and total

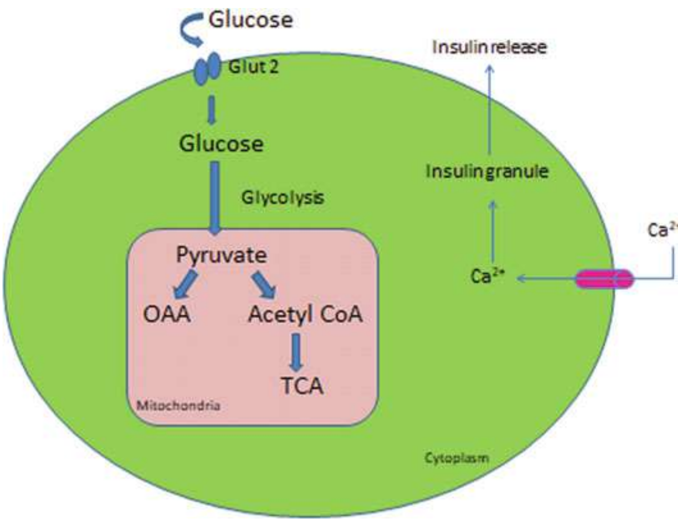

Fig. 1 Pathway of energy (Adenosine triphosphate) production by glucose [OAA: oxaloacetic acid, TCA: tricarboxylic acid cycle, Ca: calcium ion]

cholesterol level was reported in the *B. tulda* leaves extract-treated alloxan-induced diabetic rats [87]. The experiment revealed that the higher dose, i.e., 400 mg/kg b.w. reduced the blood sugar level by 48.7%, total triglyceride by 34.8%, and total cholesterol by 26.5%, and improvement in the body weight of diabetic mice was also observed. Further reduction in blood sugar level was observed in the 6th week of 100 mg/kg b.w. supplied group. This hyperglycemic activity may be due to the presence of p-hydroxybenzoic acid, salicylic acid, and many more compounds, as revealed by LC–MS analysis. Similar results of the anti-diabetic effect of leaf extract were reported in diabetic rats and the possible mechanism of this anti-diabetic effect may be due to flavonoids, phenols, and proanthocyanidin components of the leaves that help in the promotion of the glucose uptake or inhibition in the process of gluconeogenesis in liver [88, 89]. Further, it was also reported that the plasma insulin level was elevated and glycated hemoglobin was reduced in the bamboo-extract-treated groups in a dose-dependent manner compared to the diabetic mice. The hypoglycemic activity of extract has been proposed due to the intensification of the metabolism of glucose in peripheral cells and enhancement in insulin secretion [89]. A decrease in lipid peroxidation and an increase in antioxidant activities also reduced diabetic disorders [90]. Senthilkumar et al. [88] also reported the anti-diabetic properties of petroleum ether extract of *B. vulgaris*. The extract was non-toxic up to a dose of 2000 mg/kg body weight and significantly reduced the fasting blood sugar levels of hyperglycemic mice in a dose-dependent manner that was comparable to standard glibenclamide drugs. The methanol extract of *B. vulgaris* at doses of 100, 200, and 400 mg/kg also significantly reduced blood glucose levels in mice, respectively, by 32.8, 45.8, and 55.3% compared to control mice. The standard anti-hyperglycemic drug, glibenclamide, when given at a dose of 10 mg/kg reduces blood glucose levels by 50.8%. Overall, the results show that the aerial part of *B. vulgaris* has considerable anti-hyperglycemic potential due to the presence of alkaloids and saponins in the extract [91]. Middha and Usha [92] studied the in vitro hypoglycemic activity of bamboo leaf extract at different pHs and reported *B. vulgaris* to possess a varying degree of hypoglycemic activity, *D. hamiltonii*, *and D. sikkimensis* showed higher hypoglycemic activity in neutral and basic medium, whereas *B. balcooa* and *B. pallida* showed the maximum hypoglycemic activity in acidic media.

S. borealis extract increased insulin secretion and stimulated glucose uptake in in vivo cultured adipocytes and Min6 cells [93]. This improvement in insulin resistance is by secreting inflammatory cytokines [94]. Extract of *P. edulis* relieved the symptoms of type-2 diabetes [18]. In vivo studies of bamboo leaf extract of *P. edulis* also revealed the anti-hyperglycemic property of bamboo extract by lowering the hepatic fat content, reducing circulating levels of tumor necrosis alpha, inhibiting the hyper-insulinemia and improving glucose tolerance in high-fat-induced obese C57Bl/6 J mice [95]. Effervescent granules prepared from *Eucommia ulmoides* and *P. pubescens* exhibit good potential as an anti-diabetic drug as a significant amount of glucose utilization was observed which was similar to the activity of metformin [96]. Choi et al. [97] evaluated the anti-hyperglycemic activity of *S. borealis* water extract on chronic hyperglycemic-induced oxidative stress in human umbilical endothelial cells cultured in different groups of 5.5 mM low glucose, 5.5 mM glucose + 27.5 mM

Table 3 Anti-diabetic potential of bamboo

Sl. no	Species	Part used	Model used	Effect	References
1	*Bambusa arundinacea*	Leaf extract	Alloxan-induced diabetic Albino rats	Anti-hyperglycemic activity	[86]
2	*B. arundinacea*	Leaf extract	Streptozotocin-induced diabetic Wistar rats	Anti-hyperglycemic activity	[35]
3	*B. arundinacea*	Leaf extract	Streptozotocin-induced diabetic rats	Lowers glucose level, reduces lipid peroxidation and glutathione levels, elevates antioxidant activity	[172]
4	*B. arundinacea*	ZnO nanoparticles by leaf extract	Streptozotocin-induced diabetic Wistar rats	Anti-hyperglycemic activity restores insulin levels	[4]
	B. arundinacea	Seed	In vitro GOD/POD method	Anti-hyperglycemic activity through inhibition of α-amylase activity	[5]
5	*B. balcooa*	Leaf extract	Alloxan-induced diabetic rats	Reduced blood glucose and glycated hemoglobin levels, elevated plasma insulin level	[89]
6	*B. balcooa*	Leaf extract	In vitro glucose oxidase method	Anti-hyperglycemic activity in acidic pH	[92]
7	*B. pallida*	Leaf extract	In vitro glucose oxidase method	Anti-hyperglycemic control in basic and neutral pH	[92]
8	*B. tulda*	Leaf extract	Alloxan-induced diabetic rats	Regained body weight loss, reduced blood glucose level	[87]
9	*B. vulgaris*	Leaf extract	Streptozotocin-induced diabetic rats	A lowered blood glucose level	[88]
10	*B. vulgaris*	Leaf extract	In vitro glucose oxidase method	Anti-hyperglycemic control in basic and neutral pH	[92]
11	*B. vulgaris*	Aerial part extract	Acetic-acid-induced Swiss albino mice	A reduced blood glucose level	[91]

(continued)

Table 3 (continued)

Sl. no	Species	Part used	Model used	Effect	References
12	*Dendrocalamus hamiltonii*	Leaf extract	In vitro glucose oxidase method	Anti-hyperglycemic activity	[92]
13	*D. sikkimensis*	Leaf extract	In vitro glucose oxidase method	Anti-hyperglycemic activity	[92]
14	*Leleba oldhami*	β pyran from shoot shell	High-fat and streptozotocin-induced diabetic mice	Decrease blood glucose level, and cholesterol level, improve insulin level	[68]
15	*Phyllostachys bambusoides*	Stem extract	Mouse 3T3-L1 cells	The anti-diabetic effect through the promotion of adipogenesis and adipocytes function	[133]
16	*P. edulis*	Leaf extract	Mouse myoblast C2C12 cell line	Protects against lipotoxicity, decreased apoptotic rate	[18]
17	*P. edulis*	Leaf extract	High-fat diet-induced obese C57/BL6J mice	Improved glucose tolerance, decreased insulin and TNF-α levels, fat content in liver	[18]
18	*P. edulis*	Leaf extract	High-fat diet-induced obese C57/BL6J mice	Relieves symptoms of type-2 diabetes	[95]
19	*P. nigra*	Leaf extract	Rat lens aldose reductase and advanced glycation end products	Luteolin 6-C-(6″-O-trans-caffeoylglucoside) inhibits aldose reductase and advanced glycation end products	[122]
20	*P. pubescens*	Effervescent granules of leaf extract	HepG2 cells cultured in high glucose medium	Inhibits α-glucosidase and glucose-6-phosphate displacement enzymes indicating anti-diabetic potential	[96]
21	*S. borealis*	Leaf extract	High-fat diet-fed obese C57/BL6J mice	Decrease in glucose, insulin, and inflammatory cytokines levels	[94]

(continued)

Table 3 (continued)

Sl. no	Species	Part used	Model used	Effect	References
22	*S. borealis*	Leaf extract	Hyperglycemia-induced human umbilical endothelial cells	Reversed hyperglycemia-induced oxidative stress	[97]
23	*S. borealis*	Leaf extract	C2C12 skeletal myoblasts and HepG2 hepatocytes cell lines	Increased insulin signaling, phosphorylation of AMPK-activated protein kinases	[124]
24	*S. borealis*	Leaf extract	3T3-L1adipocytes and Min6 cells	Improved insulin-stimulated glucose uptake	[93]
25	*S. borealis*	Stem extract	High-fat-induced hepatic steatosis in rats	Increase PPARγ gene expression in liver cells	[134]
26	*S. quelpaertensis*	Leaf extract	High-fat diet-induced obese C57/BL6J mice and 3T3-L1 cells	Induce phosphorylation of AMP-activated protein kinase and acetyl CoA carboxylase	[130]
27	*S. quelpaertensis*	Leaf extract	3T3-L1 cells	Inhibit adipocyte differentiation via AMP-activated protein kinase	[130]

mannitol, and 33 mM glucose. The groups were cultured in the absence or presence of water extracted from bamboo. In the groups without bamboo extract supplementation, oxidants were generated with chronic glucose-induced endothelial toxicity, whereas this effect was reversed in the bamboo-extract-treated groups. NO synthase and peroxynitrite radicals expressed by high glucose were reduced by the bamboo extract. This suppressive effect of the bamboo extract was mediated by decreasing activation of PKCβ2 and NADPH suggesting the therapeutic effect of the bamboo extract on diabetic endothelial dysfunction and its related complications [97].

6 Anti-diabetic Properties of Bamboo Antioxidants

Antioxidants or free radical scavengers are substances that prevent the oxidation process, thereby slowing down or preventing the damage caused by reactive oxygen species (ROS). Increase in ROS is the main causal agent of several diseases like atherosclerosis, diabetes, cancer, Alzheimer's disease, and various neurological diseases [98]. An increase in glucose levels in the blood is the main symptom associated with diabetes. Prolonged hyperglycemia leads to an increase in the generation of ROS and alteration of the antioxidant status of the body resulting in various complications [99]. A large number of evidences also suggest a possible role of oxidative stress in the pathogenesis of diabetic complications (Fig. 2). Hyperglycemia leads to glycolytic flux thus producing ROS, and production of advanced glycation end product enhances the protein kinase C and hexamine pathway that leads to oxidative stress and decreases the antioxidant capacity [100]. Biological mechanisms can combat the ROS with various enzymatic and non-enzymatic endogenous antioxidants present in our body, but if the amount of ROS exceeds, exogenous antioxidants help in the process leading to great interest in antioxidant therapy for the treatment of diabetic patients. The use of antioxidants for the therapy of DM has been reported in many studies which may act at different levels in the management of diabetes and related complications. Antioxidants can be used as a drug substrate or as a combined drug in the treatment. The destruction of the β-cells due to oxidative stress can be curtailed with an adequate supply of antioxidants. The exact way by which the glucose level is reduced using antioxidants is not so clear but it reduces the plasma glucose level while increasing the metabolic glucose in peripheral tissues [101]. The antioxidant defense system combats overall oxidative stress. It scavenges the free radicals and maintains redox homeostasis like superoxide dismutase, glutathione reductase, glutathione peroxidase, and catalase which are otherwise decreased by the diabetic condition. Besides the enzymatic antioxidants, non-enzymatic antioxidants (vitamin C, vitamin E, and β-carotene) also decreased during oxidative stress in a hyperglycemic state [102]. Supplementation with antioxidants improves endothelial dysfunction, and mitochondrial function decreases vascular NAD(P)H oxidase activity and manages dyslipidemia and optical glucose control and blood pressure, thereby reducing the complications of diabetes like retinopathy, nephropathy, and neuropathy [102].

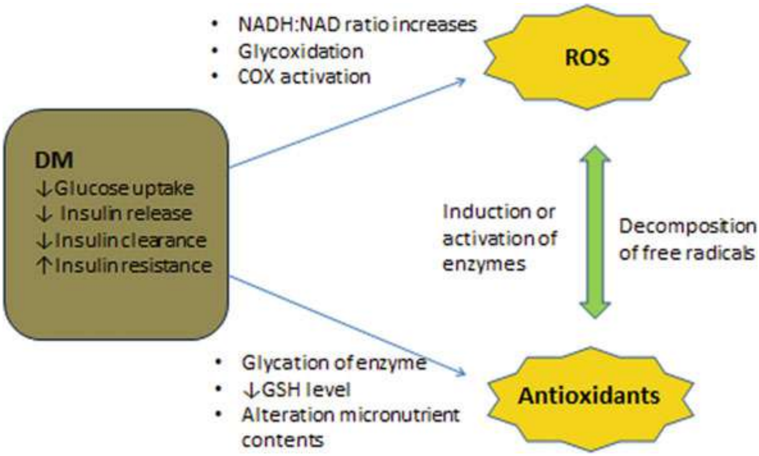

Fig. 2 Interrelation between antioxidants, reactive oxygen species (ROS), and diabetes mellitus

Among various antioxidants supplied through food and nutrition, the important ones are phenolic compounds, carotenoids, vitamin C, and minerals like selenium and zinc [103]. Antioxidant activities of several parts of bamboo have been studied extensively in many different species such as *B. nutans*, *B. pallida, B. vulgaris*, *B. ventricosa*, *D. hamiltonii*, *D. latiflorus*, *Herba lophatheri*, *Oxynthera abyssinica*, *Phyllostachys spp*., *S. argenteastriatus*, *S. borealis*. The toxicity test for the antioxidants present in antioxidants of bamboo leaves has been done by Lu et al. [104] and reported to be non-toxic. An antioxidant in leaves has been approved by the Ministry of Health, the People's Republic of China as a novel antioxidant that can be used as food additives in the preparation of food products [105]. Bamboo leaf antioxidant is furnished by various bioactive components of flavones; lactones; and phenolic acids that mainly comprise chlorogenic acid, caffeic acid, coumaroylquinic acid, dihydroxybenzoic acid, 5-feruloyquinic acid, ferulic acid, p-coumaric acid, orientin, quercitrin, rutin, apigenin, tricin, homoorientin, sinapic acid, vitexin, isovitexin, 5-O-caffeoyl-4-methylquinic acid, 3-O-caffeoyl-methylquinic acid, ferulic acids; vitamins E and C; and trace mineral elements like selenium, copper, zinc, iron, and manganese [106–110]. These compounds have important properties in the inhibition of key enzymes that are responsible for the conversion of dietary carbohydrates to glucose such as α-glucosidase and α-amylase, which in turn reduces diabetic symptoms. Polyphenols play a major role in the attenuation of insulin resistance, improve β-cells function, and stimulate insulin secretion, hence preventing diabetes and its related complications like cardiovascular diseases, neuropathy, nephropathy, and retinopathy [111]. The phenolic content in the fresh shoots of several bamboo species ranges from 191.37 to 630 mg/100 g [16]. Bamboo contains an adequate amount of vitamins E and C. The vitamin C content in fresh shoots of bamboo species has been reported to range from 1 to 4.8 mg/100 g and the vitamin E content has been reported highest in *D. asper* with 0.91 mg/100 g [16].

The phenolic and flavonoid content of fresh shoots of *D. hamiltonii* is reported to be 67.5 mg of GAE/g and 7.92 mg of QUE/g, respectively. Trace elements are a major cofactor of various antioxidant enzymes and metabolic processes. Selenium content in shoots of *B. tulda* and *D. hamiltonii* was reported to be 0.4 μg/100 g and 0.8 μg/100 g by Chongtham et al. [112]. Other trace elements like iron, copper, zinc, and manganese were also reported to be present in higher amount with 16 mg/100 g of iron content in *D. hamiltonii* and *D. manipureana* [113]. Zinc content in shoots of *Arundinaria alpine* was reported to be 21 mg/100 g by Sisay [114]. *T. rubro-marginata* shoots contained 14 mg/100 g of copper [115]. Devi [116] reported the highest amount of manganese in fresh shoots of *D. latiflorus* and *C. capitatum*, i.e., 12 mg/100 g. In vitro antioxidant activity of bamboo has been carried out using 2,2′-axino-bis(3-ethylbenzothioazoline-6-sulfonic acid (ABTS) radical cation scavenging activity and 2,2-diphenyl-1-picryl-hydrazyl-hydrate (DPPH) method. The half maximal inhibitory concentration (IC_{50}) value using ABTS scavenging method for *D. hamiltonii* shoots was reported to be 66 μg/ml whereas in the case of DPPH free radical scavenging activity of the same shoot the IC_{50} value was reported to be 568 μg/ml [117]. The in vitro antioxidant activities of three extracts, viz, aqueous, methanolic, and butanolic extracts were carried out in leaves of *B. arundinacea* wherein the methanolic extract was seen to have the most powerful antioxidant activity in the case of DPPH, ferric ion reducing antioxidant power (FRAP), and NO radical scavenging activity [118]. Bamboo oil has proven to be an excellent source of antioxidants. When bamboo shoot extracts and oil were compared, the effect on glutathione in liver cells was reported as 13.5 mM/g liver and 59.0 mM/g liver, respectively. Also, enzymatic activities of catalase and glutathione peroxidase were higher for oil compared to extract. DPPH free radical scavenging activities of 7 bamboo species were also evaluated by Choi et al. [119] and reported to range from 73.9 to 100%.

7 Scientific Evidence of Probable Anti-diabetic Mechanism with Specific Targets

7.1 Aldose Reductase (ALR) and Advanced Glycation End Products (AGE)

Aldose reductase (ALR), is a key enzyme in the polyol pathway that catalyzes the NADPH-dependent reduction of glucose to sorbitol, leading to excessive accumulation of intracellular ROS in various tissues of the heart, kidney, eye, and neurons in diabetic complications such as neuropathy, nephropathy, and retinopathy [120]. Also, advanced glycation end products (AGE), which are the products formed by the glycation process during the Millard reaction, are also a main causal factor of diabetic complications (Fig. 3). Inhibition of ALR and AGE will prevent diabetic complications [121]. The effect of *P. nigra* leaf extract in the inhibition of ALR

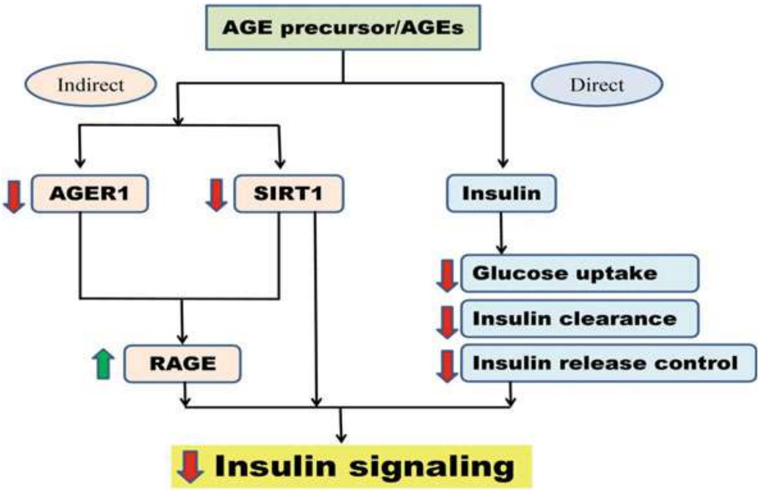

Fig. 3 Mechanism of AGEs leading to insulin resistance in insulin-sensitive tissues. AGEs participate in insulin resistance in both direct and indirect ways. In the direct mechanism, AGEs directly modify the insulin which results in the impaired and inhibition of glucose uptake, insulin clearance, and insulin release control. Whereas, in the other mechanism, AGEs cause elevation in RAGE (receptor of advanced glycation end product) expression and reduction in AGER1 (advanced glycosylation end product-specific receptor-1) and SIRT1 (sirtuin) expression that cause changes in insulin signaling

and AGE was reported by Jung et al. [122]. This inhibitory effect of the bamboo extract is due to the presence of various flavones and phenolic compounds. Isolation of different compounds and study of their inhibitory effects show that luteolin 6-C-(6-O-trans-caffeoylglucoside), which is a quercetin-like flavone, has the maximum inhibitory effect against ALR. The inhibition against AGEs formation was found to be highest for orientin and luteolin 6-C-(6-O-trans-caffeoylglucoside) with their IC_{50} values of 87.3 and 87.7 μg/ml, respectively.

7.2 Adenosine Monophosphate-Activated Protein Kinase (AMPK)

Another mechanism by which the anti-diabetic effect of bamboo extract has been proven is through the activation of AMP-activated protein kinase. AMPK is generated to maintain cellular homeostasis in conditions of an increased level of ROS, glucose deprivation, hypoxia, ischemia, etc. In diabetes, AMPK is one of the key molecules that enhance the sensitivity of insulin by increasing glucose uptake and lipid peroxidation in skeletal muscles and inhibition of hepatic glucose and lipid synthesis [123]. HepG2 hepatocytes and C2C12 skeletal myoblast were cultured in vitro to investigate the effect of *S. borealis* leaf extract on the expression and activation of AMPK and their target genes [124]. The pAMPK and its target genes showed a significant rise in both C2C12 and HepG2 cells. Further investigation proved that the ability of *S. borealis* to stimulate insulin signaling is through the activation of AMPK which increases the uptake of glucose as AMPK suppresses the expression of glucose-6-phosphatase, phosphoenolpyruvate and inhibits hepatic glucose production by gluconeogenesis. Also, activation of AMPK also reduced the phosphoenolpyruvate carboxykinase (PEPCK) gene expression which may be the reason for the depletion in blood glucose levels. The effect of the extract on insulin action in insulin-sensitive cells showed improved insulin signaling as the level of phosphorylated IRS-1 and serine phosphorylation of protein kinase B (Akt) increased significantly in both cells. Increased activation of pAMPK levels was proportional to the expression of GLUT4 gene expressions in skeletal muscles in *S. borealis*-treated mice [124].

7.3 Pro-inflammatory Cytokines

Cause of DM and its complications are also related to various inflammations like obesity. And these complications can be attenuated to a large extent by antioxidants. Insulin resistance is one of the earliest factors to be detected in diabetic conditions. As it is evident from various studies in animals and humans, obesity is one of the main causal factors of insulin resistance as gain or loss in body weight results in the improvement or deterioration of insulin resistance [125]. Obesity is a mild inflammation that causes the expansion of adipose tissue which in turn leads to the release of inflammation-related cytokines. These cytokines, especially tumor necrosis factor alpha (TNF-α), interleukin 6 (IL-6), and monocyte chemoattractant protein 1 (MCP-1), play a chief role in obesity-related disorders such as resistance to insulin [126]. All these pro-inflammatory mediators induce oxidative stress and inflammation in pancreatic β-cells. This results in the reduction of pancreatic cell mass and ultimately leads to apoptosis and impaired insulin secretion [127].

Among various pro-inflammatory cytokines, TNF-α and IL-6 are one of the most important pro-inflammatory mediators that involve in the pathogenesis of DM by making insulin resistant (Fig. 4). TNF-α activates transcriptional pathways that include oxidative stress and result in the production of ROS which in the downstream reaction causes the degradation of cells [128]. Besides the generation of ROS, TNF-α causes insulin resistance through other pathways such as impairing insulin signaling through serine phosphorylation, reduction in the expression of GLUT4, and alteration of protein and lipid metabolisms that cause lipolysis which further leads to an increase in the level of non-esterified fatty acids ultimately leading to the development of insulin resistance [129]. Alike TNF-α, IL-6 also induces insulin resistance through various pathways like JAK/STAT pathway, STAT 3 phosphorylation, SOCS-3 transcription, tyrosin phosphorylation of IRS-1and2, and inhibition of insulin receptor phosphorylation. The antioxidant and anti-obesity effects of various

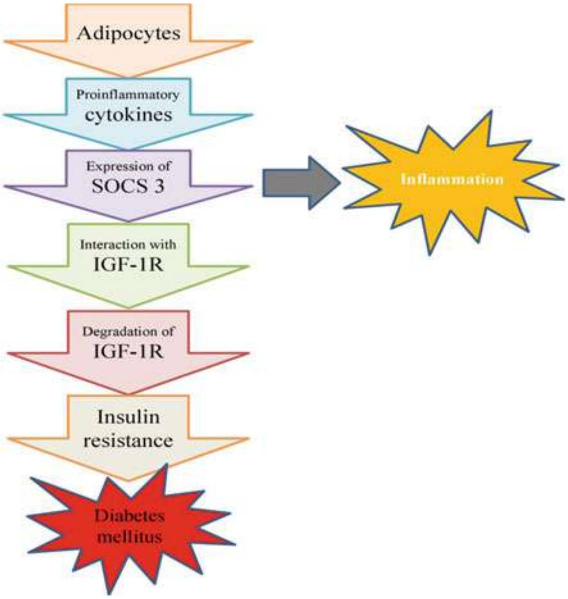

Fig. 4 Role of pro-inflammatory cytokines in induction of diabetes mellitus

bamboo *spp.* have been proven and reported by multiple workers relating to various species.

The anti-obesity effect of leaf extract of *S. quelpaertensis* has been reported by Kang et al. [130]. The bamboo leaf extract was supplemented in the dose of 150 mg/kg to high-fat diet-induced obese mice. After the treatment period of 70 days, the results showed the anti-obesity effect of leaf extract as the body weight and adipose tissue of obese mice significantly reduced compared to obese control and induced phosphorylation of AMPK pathway in mature 3T3-L1 adipocytes. That protective effect against obese-induced hepatic steatosis has been suggested due to a reduction in SGPT, SGOT, LDH levels and lipid droplets in the liver. A similar experiment was conducted by Higa et al. [131] that reported the reduction of body weight, abdominal fat storage, and serum MCP-1 concentration by 60% compared to high-fat-induced obese mice. From the experiment conducted by Li et al. [132], it is evident that bamboo shoot fiber is a potential prebiotic fiber that modulates and increases the gut microbiota diversity and improves host metabolism which in turn results in anti-obesity when compared to other high-fiber diets. The anti-obesity effect of stem extract of *P. bambusoides* was revealed by the in vitro experiment performed by Goh et al. [136] in 3T3-L1 cells of mice. After the cells reached full confluency, the growth medium was induced with a mixture of dexamehanose, 3-isobutyl-1-methylxanthine, and insulin. The cells were further treated with different extracts of ethanolic, methanolic, and hot aqueous extract of bamboo stem. The expression levels of differentiation markers for the adipogenesis process such as C/EBPβ, PPARγ, and FABP4 were measured and showed a significant increase compared to the control groups regardless of their extraction methods. An increase in the adipocyte volume and triglyceride content was also reported. Also, increased expression of PPARα has been reported [134]. This proves the mechanism by which bamboo extract works in adipogenesis, adipocyte function, and in turn in the mitigation of DM. Based on these results, it is evident that besides the most commonly used part of bamboo, i.e., shoots and leaves, the stalks and twigs can also mitigate DM.

7.4 Saccharide Hydrolyzing Enzymes

Management of blood sugar levels is a critical strategy in the control of DM and its related complications. Postprandial hyperglycemia affects and alters many biomolecules of the body that may lead to serious health complications [99]. Inhibitors of saccharide hydrolyzing enzymes have been useful as an oral hypoglycemic drug for the control of diabetes. Phenols that have an inhibitory effect on the activities of key enzymes linked to type-2 diabetes, i.e., α-amylase and α-glucosidase have potential use in dietary intervention in the management or control of postprandial hyperglycemia associated with type-2 diabetes [99]. α-amylase breaks down the dietary saccharides into oligosaccharides and disaccharides that are ultimately converted into monosaccharides by α-glucosidase. α-amylase reduces the rate of glucose absorption and postprandial glucose rise [135]. The glucose liberated by this process is absorbed in the gut as a result, and the glucose level postprandial is increased. Therefore, inhibition of enzymes responsible for breaking down saccharides may reduce the sugar level.

Synthetic drugs like acarbose which are used to reduce postprandial glucose levels are associated with some side effects such as abdominal distension, flatulence, meteorism, and diarrhea. The phenolic groups have a high affinity toward glucose and can effectively inhibit the diffusion of glucose. Bioactive compounds such as phenols, flavonoids, isoflavones, flavones, anthocyanins, catechin, isocatechins, vitamins C, E, etc. act as antioxidants and help in the inhibition of enzymes responsible for the breakdown of complex polysaccharides like α-amylase and α-glucosidase that are responsible for increasing the glucose level in plasma [99]. A novel polysaccharide BSSP2 that is a homogenous highly branched beta-type polysaccharide has been characterized and isolated from the shoot shells of *L. oldhami* by Zheng et al. [68] The polysaccharide extract was administered in three different concentrations of low dose (100 mg/kg b.w.), medium dose (200 mg/kg b.w.), and high dose (400 mg/kg b.w.). The results showed improvement in the loss of body weight and serum insulin loss. The NDF content in the bamboo shoots is reported to be in the range of 2.25 g/100 g (*D. strictus*) to 7.40 g/100 g (*D. manipurianus*); ADF content ranged from 0.48 g/100 g in *B. bambos* to 3.75 g/100 g in *G. albociliata*; Lignin content ranged from 0.11 g/100 g (*D. hookeri*) to 2.70 g/100 g (*G. albociliata*); cellulose content ranged from 0.18 g/100 g in *B. bambos* to 1.74 g/100 g in *D. asper,* and the amount of hemicellulose ranged from 0.40 g/100 g in *G. albociliata* to 6.77 g/100 g in *D. manipureanus* [22]. An overall increase of 36.97% in NDF and 11% in ADF of bamboo shoot fortified biscuits was reported to the control biscuits

[136]. Li et al. [132] reported the purified shoot fiber consisted of 74.5% total dietary fiber with 73.4% insoluble component and 1.1% soluble. A comparison of the effect of bamboo fiber with cellulose and commonly consumed fibers on high-fat diet-fed mice revealed that bamboo fiber is the most effective among all, as the mice treated with bamboo fiber showed improvement in lipid profile and glycemic control.

Dietary fiber can attenuate the α-amylase enzymatic activity in two ways: (i) Dietary fiber helps in either increasing the viscosity of mucous in the gastrointestinal tract or entraps the enzymes and substrates with the network system of fibers, thereby lowering the accessibility between the enzyme and substrate. (ii) Dietary fiber forms a complex of enzyme-inhibitor or enzyme-inhibitor-substrate as a result, changing the conformation of α-amylase [137]. Dietary fiber decreases energy intake, and blood glucose excursions reduce glucose absorption in the digestive tract, and insulin response, and controls glycemia, thereby reducing the risk of DM by reducing the blood sugar level [138, 139]. Dietary fibers also affect glucose control by delaying gastric empty, small bowel transit time, and the digestion and absorption of macronutrients [140]. Bamboo shoots are rich in dietary fiber. Bamboo shoot dietary fiber has a higher capacity for swelling; water holding; and binds easily to fat, cholesterol, and bile acid and as a result of these the dietary fiber of bamboo shoots is associated with various health benefits, including hypolipidemic and antidiabetic activities [139]. Employing different extraction techniques like ultrasonic-assisted enzymatic extraction (UAEE) and shear homogeneous-assisted enzymatic extraction (SHAEE), and analysis of *Chimonobambusa quadrangularis* shoot fiber showed enhancement in the glucose absorption capacity of bamboo shoot extract that is extracted by conventional method [141]. Moreover, the α-amylase inhibition activity of the dietary fibers showed the highest inhibition in SHAEE (19.89%) followed by UAEE (18.28%). Also, the glucose dialysis retardation index was heightened in SHAEE which indicates that glucose absorption in the gastrointestinal tract in an in vitro system was delayed [141]. This in turn helps to delay the absorption of glucose in the gastrointestinal tract, thereby inhibiting the increase of postprandial blood glucose [142].

8 Conclusion

Despite advancements in modern medical treatment techniques, DM remains one of the most major causes of mortality which is increasing rapidly. Despite the use of exogenous insulin and chemically available synthetic drugs, diabetes cannot be curtailed completely. Therefore, it is of utmost importance to reach out for a plant-based treatment system that is economic with the least side effect. Plant-based bioactive compounds are being used as prophylactic agents to prevent and treat a variety of chronic diseases. Although these bioactive compounds have low potency compared to pharmaceutical drugs since they are consumed regularly, and in significant amounts as part of a normal diet, they may have a noticeable physiological effect over time. Bamboo, being a rich reservoir of nutrient and phytochemicals, decreases the blood glucose level and increases the body weight loss and serum insulin loss in a dose-dependent manner. Furthermore, the shoots, shells, and leaves could act as a potent antioxidant, by increasing the various enzymatic and non-enzymatic antioxidants, and improvement in adipogenesis, adipocyte function, lowering serum cholesterol levels, triglyceride levels reinforcing the anti-diabetic and anti-hyperglycemic activity of bamboo. The inclusion of this plant as an additive or as a vegetable can help in maintaining health as it is cheap, easily grown, and available in almost all parts of the world. Moreover, pharmaceutical companies could use bamboo as an alternative for the production of various health supplements and nutrient additives by using nanoparticles made from bamboo extracts that may deliver therapeutic agents to certain targeted locations in a regulated manner. It is essential to promote scientific evidence and increase awareness among consumers regarding their anti-diabetic benefits.

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Bamboo Act as a Phytoremediation Candidate for Heavy Metal Contaminated Soil: A Synthesis

Mamta Rani, Mamta Lathwal, Anand Narain Singh, and Nirmala Chongtham

Abstract In recent decades, due to rapid urbanization and industrialization activities, the stoichiometry of biogeochemical cycles and the addition of unwanted heavy metal concentrations in the soil component have augmented more degree of contamination worldwide. In contrast, developing countries, especially India and China, are significantly facing more severity of soil contamination. Heavy metals are metal (lloids) with an atomic number greater than 20 and specific gravity >5 g/cm^3. They are non-biodegradable and non-thermal degradable, persistent, and cause toxicity to the soil. They enter the food chain through plants grown on heavy metal-contaminated soil and cause many life-threatening diseases. The plants which accumulate high concentrations of heavy metals in their different parts from the heavy metal-contaminated soil have some special characteristics like large biomass production, resistance to biotic and abiotic stresses, wide distribution, well-developed root systems, and capacity to store contaminants in above-ground biomass. Scientific studies have revealed that some specific plants, such as *Thlaspi* sp., *Brassica* sp., *Sedum alfredii*, *Alyssum* sp., *Viola* sp., *Pteris vittata* can be considered ideal candidates for the remediation of contaminated soil. Bamboo is one such potent plant that has faster growth and rapid biomass accumulation efficiency and moreover, high resistance to biotic and abiotic stresses. Therefore, bamboo can be harnessed for worldwide distribution, large CO_2 sequestration rate, high O_2 emission, and extraction of heavy metals (Cd, Cu, Pb, Cr, As, Zn) in their parts. In the present chapter, the current status, sources, effect of heavy metals on plants and animals and phytoremediation ability to vary bamboo species have been discussed that can be employed as phytoremediation candidates for the reclamation of heavy metal polluted soil.

Keywords Bamboo · Heavy metal · Soil pollution · Waste water · Phytoremediation · CO_2 sequestration · Phyto-extraction · Human health

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M. Rani · M. Lathwal · A. N. Singh · N. Chongtham (✉)
Department of Botany, Panjab University, Chandigarh 160014, India
e-mail: cnirmala10@gmail.com

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1 Introduction

Soil is a crucial component of the biosphere which is exposed to different types of pollutants, including heavy metals, that is exacerbated due to natural and anthropogenic activities. Excessive addition of these heavy metals affects all organisms through biomagnification because every living being depends upon soil for their food cycle. This is relevant to those countries where unsustainable intensive agriculture, industrial and urban development is in progress [1]. Degradation of soil resources with heavy metals is an important concern as it immensely contributes to reduced soil quality and a decline in the yield and quality of the crops growing that sustainably affects agricultural development [2]. Heavy metals are categorized into the group of non-biodegradable, persistent, inorganic chemical constituents with an atomic mass of more than 20 and belonging to the d-block having density higher than 5 g/cm^3 which shows cytotoxic, genotoxic mutagenic effects on living beings [3, 4]. Several researchers have found that the agricultural soil in different parts of the world has degraded or exhibited a reduction in their fertility and agricultural productivity due to the addition of contaminants naturally or anthropogenically, i.e., irrigation with contaminated water, use of pesticides, mining, smelting, etc. [5, 6]. Bamboo is a widely distributed, fast-growing, renewable, and environment-enhancing resource that has great potential to improve poverty alleviation and environmental conservation [7]. It has wonderful features such as soil erosion control, carbon sequestration, high accumulation of heavy metals, and natural nitrogen and growth habit which makes bamboo important for solving the problems of degraded lands [8]. Due to the extensive rhizome-root system and accumulation of leaf mulch, bamboo serves as an efficient agent in preventing soil erosion, runoff reduction, facilitates infiltration, moisture conservation [9], and mitigates the adverse drought effects on flora and fauna [10]. It also stabilizes the slopes and fragile riverbanks, retains the soil in deforested areas, and protects earthquake-prone places and mudslides [11]. The extensive foliage produces a dense litter layer on the forest floor, which contributes to the addition of organic matter, nurturing the topsoil, restoring soil fertility, reversing acidification, and increasing microbial activities as well as soil enzyme activity [12, 13].

There are several examples in the world where bamboo has been implemented for ecological restoration, such as in Africa; bamboo species have been successfully used in land rehabilitation, for treatment of polluted Lake Victoria, and wastewater treatment at Murchison Bay prison in Luzira [14]. In India, bamboo-based agroforestry models improve the ecological parameters of a highly degraded basaltic tract of Jabalpur [15]. In order to restore degraded agricultural lands in central India, three bamboo species (*Bambusa bambos, B. nutans,* and *Dendrocalamus strictus*) were successfully implemented in seven agroforestry models to combat land degradation [16, 17].

Being one of the most productive and fastest-growing grass on the planet, with decay-resistant litter, bamboo potentially acts as a valuable sink for carbon storage. One hectare of bamboo stand absorbs about an average of 17 tons of carbon per year. Bamboo plantations can play a major role in "carbon trading" in a developing country like India. "Carbon trading," which is also known as "cap and trade," is a method developed to reduce the carbon emissions which contribute to global warming. Under this arrangement, countries with excess emissions credits can sell their credits to countries that find it difficult to reduce their emissions. Reforestation and afforestation projects are part of the Kyoto Protocol's Clean Development Mechanism (CDM) which facilitates developed countries to reach their targets for reducing greenhouse gas emissions by investing in afforestation and reforestation projects in developing countries in exchange for carbon credits. Bamboo plantations have immense potential for such carbon credits with a significant advantage over other biomass resources due to the species diversity, vigorous growth, early establishment, adaptability to various soil and climatic conditions, short harvesting period, sustainability in yield, and multifarious uses. Hence, it may be considered the best among biomass resources for making the planet healthy. The species diversity allows it to come up in any part of the world with some exceptions and to tolerate climatic exigencies. Bamboo plantations are suitable for clear felled forest lands, degraded lands, boundaries of agricultural lands and non-agricultural lands, and other common property resources like coastal areas, roadsides, canal banks, railway lines, etc. It has immense potential as a bio-energy resource that helps in the retention of carbon already sequestered in the fossil fuels such as coal, oil, and gas and can save the vast natural forest cover. The contribution of bamboo to environmental clean-up and climatic change is depicted in Fig. 1.

All these special features make bamboo a potent candidate for the phytoremediation of contaminated soil.

2 Worldwide Heavy Metal Contamination in Soil

Heavy metal contaminations in the soils have continuously arisen around the globe due to the futile race for development. In China, agricultural soil is polluted by Cu, Cd, Pb, and Zn which contribute 10% of the total contaminated soil [18, 19]. In 2013, it was estimated that Pb pollution caused 0.6% burden of the world's disease [20] and estimated 8 53,000 deaths due to lead toxicity [21].

Similarly, in the USA, Europe, Poland, and Iran, agricultural soil is contaminated by Pb with 12.3, 16, 16.4, and 6.124 mg/kg concentration, respectively. Japan faced the biggest pollution disease (Itai-Itai) caused by Cd contamination [22]. The United States, Europe, Australia, Russia, and India are also severely contaminated by Cd [23, 24]. Bangladesh experienced the worst arsenic poisoning in the region since most of the people are consuming severely contaminated As (>10 μg/L) water [25] and found more than 24,000 adult deaths annually according to Flanagan et al. [26]. WHO described this critical condition of Bangladesh as "the largest poisoning of a population in the world" [27]. The estimated global consumption of Cd is around 20,000–24,000 t/year [28]. Strincone et al. [29] estimated the natural emission of Cd at 15,000–88,000 t/year, much higher than emission from anthropogenic causes.

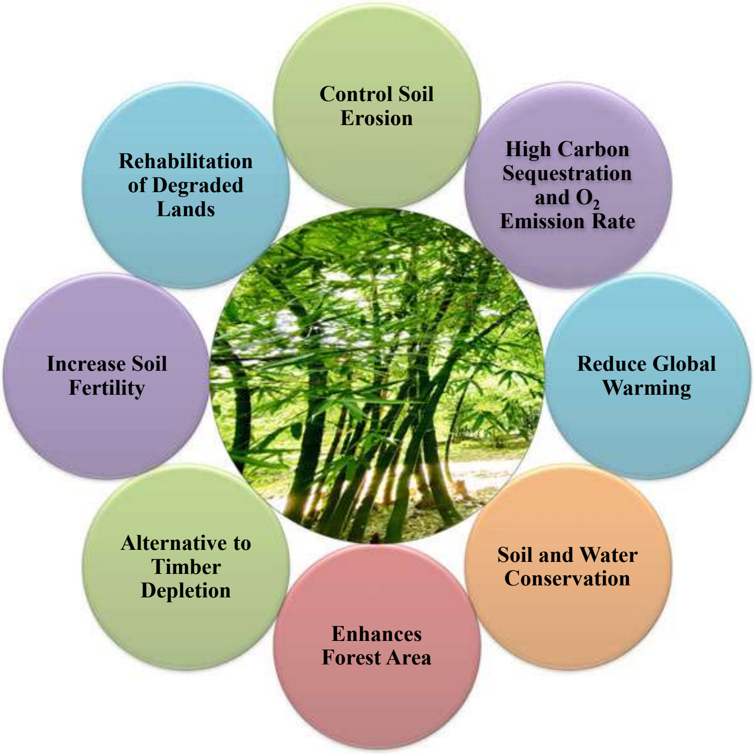

Fig. 1 Ecological benefits of bamboo

Globally, maximum Hg is released from the Asian countries (with 47.5% of the global total anthropogenic mercury emission) with a major contribution from the regions of China and India. On a large scale, North America and European Union emit about 43.4t/year and 44.1t/year Hg, respectively, majorly from coal-fired power plants [30]. Around the globe, 4% of agricultural land resources are degraded due to soil erosion, water logging, excessive use of land, drought, salinity, and excessive use of fertilizers or pesticides. Figure 2 shows the degraded land in various countries such as China [31], India [32], Japan [33], Bangladesh [34], Nigeria, and Africa [35] caused by natural and anthropogenic factors.

3 Heavy Metal Contamination in the Indian Soil

Indian soil is also contaminated due to industrialization, sewage water irrigation, transportation, pesticides, and fertilizer application. According to the Ministry of Environment, Forests and Climate Change, 32% of Indian land is considered

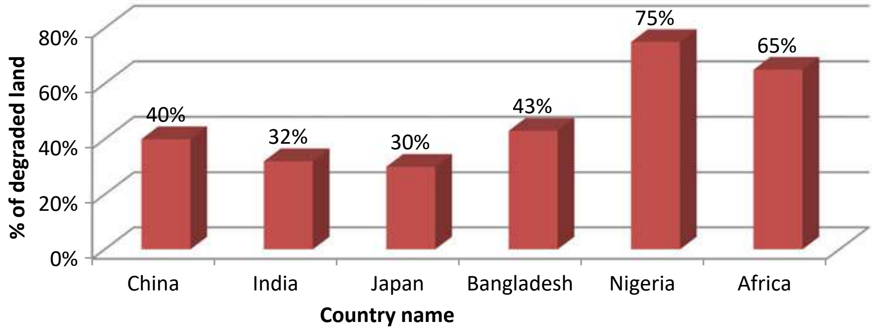

Fig. 2 Degraded land of different countries

degraded, and 25% of it is undergoing desertification [36]. During 2018–2019, 29.7% of India's total geographical area underwent degradation [37]. According to the New Delhi-based National Academy of Agricultural Sciences (NAAS) of 2020 [38], the annual soil loss rate in our country is about 15.35 tons per ha, resulting in a loss of 5.37–8.4 million tons of nutrients from the soil. The NAAS estimates that India's rainfed crops lose 13.4 million tons of production each year due to water erosion which amounts to Rs 205.32 billion. Every year, 175 million hectares of agricultural land become less productive due to limited agricultural land availability. The Centre for Science and Environment released a report on the State of India's environment in which they described the percentage of land under degradation in different states of India [39]. According to this report, 12 states' land was degraded, namely, Jharkhand (68.8%), Rajasthan (62.1%), Delhi (61.7%), Goa (52.6%), Gujarat (52.2%), Nagaland (50%), Maharashtra (46.5%), Himachal Pradesh (43.1%), Tripura (42.7%), Ladakh(46.2%), Karnataka (36.3%), Odisha (34.4%), and Telangana (31.7%) due to natural and anthropogenic activities. In 2020, RBI reported that the maximum use of fertilizers was in Telangana (245.3 kg/ha) followed by Punjab (242.7 kg/ha), Tamilnadu (220.6 kg/ha), Haryana (213.8 kg/ha), Uttar Pradesh (174.3 kg/ha), Gujarat (174.1 kg/ha) and West Bengal (164.9 kg/ha) in 2010–2011 [40]. In 2018–19, fertilizer consumption was increased in Telangana (245.3 kg/ha) and Haryana (224.5 kg/ha) and limited in other states compared to 2010–11. Excessive fertilizer, pesticide use, and wastewater irrigation cause soil pollution by adding heavy metals to the soil [41]. The most common heavy metal contaminants in soil are As, Cd, Cr, Cu, Hg, Pb, and Ni. According to the Agency for toxic substances and disease registry's (ATSDR) priority list of hazardous substances, arsenic had (1st), Pb (2nd), Hg (3rd), and Cd 7th rank known as human carcinogens [42]. The average concentration of heavy metals in Indian soils obtained Fe (23,774.84 μg/g), Mn (872.54 μg/g), Zn (359.94 μg/g), Cu (183.67 μg/g), Cr (161.42 μg/g), As (148.70 μg/g), Ni (112.41 μg/g), Pb (61.87 μg/g), Co (37.63 μg/g), and Cd (14.16 μg/g) [43]. Indian rivers are polluted with different metals such as As (9.87 μg/L), Cd (70.52 μg/L), Cu (314.93 μg/L), Fe (14.55 mg/L), Cr (450.26 μg/L), Pb (374.58 μg/L), Ni (245.01 μg/L), and Zn (2.65 mg/L) [44]. Most of these metals

Table 1 Maximum permissible limits set by WHO and USEPA

Sr. no	Heavy metal	Maximum permissible level in soil (ppm)	Maximum permissible level in water [45]	
			WHO [21]	Gaur et al. [47]
1	Cd	0.06 mg/kg [48], 3–8 mg/kg [49]	0.003 mg/l	0.005 mg/l
2	Pb	10 mg/kg [48]	0.01 mg/l	0.01 mg/l
3	Ni	50 mg/kg [50]	0.01 mg/l	0.1 mg/l (EPA)
4	Cu	20 mg/kg [51]	2 mg/l	1.3 mg/l
5	Zn	50 mg/kg [48]	3 mg/l	5 mg/l [50]
6	Fe	–	0.3–3 mg/l [52]	0.3 mg/l (USA, standards)
7	Co	8 mg/kg [48]	0.001–0.01 mg/l [52]	–
8	Cr	100 mg/kg [48]	0.05 mg/l	0.01 mg/l
9	As	5–20 mg/kg	0.01 mg/l	0.01 mg/l
10	Hg	0.13 mg/kg	0.006 mg/l	0.002 mg/l

are above the maximum permissible range set by WHO/ FAO. Table 1 shows the maximum permissible ranges in soil and water. Many other pieces of research were also carried out to check the heavy metal contamination in soil and water in different states of India, briefly described in Table 2.

4 Heavy Metals

Heavy metals are elements with specific weights higher than 5 g/cm^3. A number of them, e.g., cobalt (Co), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), zinc (Zn), copper (Cu) are essential micronutrients required in trace amounts for normal growth and take part in redox reactions, electron transfers and other important metabolic processes in plants, if their amount exceeds than permissible range they show a deleterious effect on plants [72]. Whereas, others such as lead (Pb), cadmium(Cd), chromium (Cr), mercury (Hg), and arsenic (As), are potentially highly toxic for plants even at minute concentration because they don't have any biological role in the plant metabolism or in living organisms known as non-essential heavy metal.

4.1 Sources

Heavy metals in the environment have various origins as they can arise from natural processes such as rock weathering, volcanic eruptions, forest fires, and soil-forming

Table 2 Heavy metals contamination in Indian soil

Place	Area	Soil	Water	References
Madhya Pradesh	Pitampur industrial area	Cd: 0.05–0.1 mg/kg Co: 26.8–63.9 mg/kg Cr: 68.1–252.4 mg/kg Cu: 82.4–252.4 mg/kg Ni: 32.1–38.1 mg/kg Pb: 5.2–6.1 mg/kg Zn: 76.6–763 mg/kg	Cr: 84.2 μg/l Pb: 3.7 μg/l Cd: 1.2 μg/l	[53]
Andhra Pradesh	Pantancheru industrial area Medak district		Effluent: Ni: 4.7–57.4 μg/l Pb: 0.3–14.2 μg/l Zn: 32.9–293 μg/l Mn: 2.4–11,384 μg/l Cr: 2–69.7 μg/l Fe: 34.6–497.2 μg/l Ground Water Ni: 3.9–264.8 μg/l Zn: 21.4–310.8 μg/l As: 4.2–1139 μg/l Pb: 0.3–7.2 μg/l Sr: 134–2681 μg/l	[53]
Rajasthan	Zinc smelting area in Udaipur	Zn: 65–1860 mg/kg Cd: 0.07–10.4 mg/kg Pb: 27.5–180 mg/kg Ni: 19.8–50.2 mg/kg Co: 7.6–18.5 mg/k/g Cu: 21.2–70.0 mg/kg	Zn: 2.2–9.7 μg/l Cd: 0.004–0.081 μg/l	[53]
Rajasthan	Pali textile industries		Zn: 0.03–12.16 μg/ml Pb: 0.01–1.42 μg/ml Cr: 0.01–0.27 μg/ml Cu: 0.02–0.52 μg/ml As: 0.01–0.49 μg/ml Ni: 0.08–1.42 μg/ml	[53]
Chattisgarh	Korba industrial 90% power plant area	Cd: 0.050–8.10 mg/kg Co: 1.726–25.1 mg/kg Cr: 0.096–172.3 mg/kg Cu: 2.536–40.5 mg/kg Ni: 1.828–14.1 mg/kg Pb: 5.944–15.3 mg/kg Zn: 1.35–29.4 mg/kg		[53]
Tamilnadu	Coimbatore industrial area	Ni: 47–178 mg/kg Cd: 0.5–4.2 mg/kg Cr: 43–241 mg/kg Pb:47–214 mg/kg		[54]

(continued)

Table 2 (continued)

Place	Area	Soil	Water	References
Maharashtra	Industrial area in Thane Region		As:12–500 μg/l Cd: 4–21 μg/l Hg: 1–12 μg/l Ni: 5–8 μg/l	[55]
Tamilnadu	Manali industrial area in Chennai	Cr:149.8–418 mg/kg Cu:22.4–372 mg/kg Ni:11.8–78.8 mg/kg Zn:63.5–213.6 mg/kg Mo: 2.3–15.3 mg/kg		[56]
Uttar Pradesh	Kanpur unnao industrial area of Ganga plain	Zn:975 mg/kg Ni: 482 mg/kg Cr: 2652.3 mg/kg		[57]
Tamilnadu	Vellore tannery industries	Cr: 16,731–79,865 mg/kg	36.7 mg/l	[58, 59]
Orissa	Chlor-alkali plant (Hg pollution)	Hg:41–2520 mg/kg		[60]
Eastern India	Copper mines impact (Khetri Cu mine)	Cu: 763 mg/kg Ni:136 mg/kg Pb:9.9 mg/kg		[61]
Jharkhand	Cu mines in Mosaboni	Cu: 154 mg/kg Ni: 136 mg/kg Pb: 9.9 mg/kg		[62]
Orrisa	South Kaliapani, Chromite Mine Area	Cr: 11,170 mg/kg mine effluent irrigated land	0.02–0.12 mg/l	[63]
Karnataka	Arsenic Toxicity Near Gold Mining Area	As: 99–9136 mg/kg		[64]
Punjab	Agricultural field of Amritsar soil	Fe: 2809–5692 mg/kg Zn: 73–320 mg/kg Mn: 154–194 mg/kg Pb: 7.7–118 mg/kg Ni: 9.67–24.32 mg/kg Cu: 8.4–24 mg/kg Cd: 0.55–1.39 mg/kg		[65]
Punjab	Kharif crops of Punjab near Satluj and Beas river village	Cr: 8.86–35.58 mg/kg Cu: 9.0–48.55 mg/kg Co: 1.03–4.65 mg/kg Cd: 0.516–1.58 mg/kg Pb: 5.5–9.67 mg/kg		[66]
Punjab	Mansa district of Punjab	Ni: 47.7 mg/kg Hg: 23.8 mg/kg (APL) Se:21.1 mg/kg (APL) Cd: 3.1 mg/kg (APL)		[67]

(continued)

Table 2 (continued)

Place	Area	Soil	Water	References
Haryana	Kurukshetra city	Pb: 0.35–1.90 mg/Kg Cd: 0.025–0.175 mg/kg		[68]
Haryana	Polluted river Yamuna	Sediment Cd: 0.82–4.6 mg/kg Cr: 6.8–35.8 mg/kg Fe: 4.15–16.2 g/kg	Ni: 0.10–0.21 mg/l	[69]
Haryana	Bhiwani, Jind, Gurgaon, Rohtak, Sonipat, Rewari, Hisar, Narnaul, Mehendergarh, and northern capital Chandigarh	Zn: 17.4–41.1 mg/kg Ni: 46.47–73.8 mg/kg Cu: 1.23–60.07 mg/kg Cr: 78.07–109.33 mg/kg		[70]
Haryana	Rohtak district roadside	Zn: 66.1 mg/kg Ni: 47.11 mg/kg Cu: 36.55 mg/kg Cd: 1.69 mg/kg Pb: 99.05 mg/kg		[71]

or can be originated from anthropogenic processes such as industrial waste, fertilizer applications, smelting, and sewage disposal [73]. These activities cause the leaching of metals into groundwater or accumulate on the soil surface.

All heavy metals are non-biodegradable and persistent in nature. Some heavy metals are immobile as they can't move from the place where they are accumulated, and others are termed as mobile as they can be taken up by the plant's root system via diffusion, endocytosis, or through metal transporters [74]. They exist in colloidal, ionic, particulate, and dissolved phases in the atmosphere. Solubility of these metals in soil and groundwater is predominantly controlled by pH, amount of metal, cation exchange capacity, organic carbon content, the oxidation state of the mineral components, and the redox potential of the system. Table 3 summarizes the natural and anthropogenic sources of heavy metal.

4.2 Adverse Effects of Heavy Metals on Crop Plants and Animals

The effects of metals in soil are very complex, and these effects are dependent on chemical processes such as adsorption–desorption, complexation-dissociation, oxidation–reduction, ion exchange, and transporters. Adsorption–desorption and complexation-dissociation reactions mainly affect metal activity in the soil, while

Table 3 Sources of heavy metals in soil and water

Heavy metal	Sources		References
	Natural	Anthropogenic	
As	Weathering of rock, microbial colonization, and volcanic eruption	Mining, smelting, combustion of fossil fuels, production of glass and semiconductors, fertilizers, and chemotherapeutic drugs for cancer, pesticides, and wood preservatives	[75, 76]
Cd	Dust storms, sea salt spray, volcanic activities, weathering, erosion, and wildfire	Ni–Cd batteries, coatings, and platings, stabilizers for plastics, fossil fuel combustion, phosphate fertilizer, and waste incineration; ferrous and non-ferrous metal production; and cement production	[77, 78]
Cr	Tectonic and hydrothermal events	Metallurgical industries such as chrome alloy and Cr metal production, leather tanning, metal corrosion inhibition, textile dyes, and wood preservation, fly ash	[79, 80]
Hg	Degassing, weathering of rock, volcanic eruption, and wildfire	Artisanal, gold mining, and coal combustion	[81–83]
Pb	Erosion of natural deposits, natural fires, sea salts pray, and volcanic eruption	Mining, ore processing, and Pb-acid battery recycling (PABC), Aerial emission from combustion of leaded petrol, battery manufacture, herbicides, and insecticides	[84, 85]
Ni	Volcanic eruption	Fertilizers, smelting, mining, Industrial effluents, kitchen appliances, surgical instruments, steel alloys, automobile batteries	[86–88]
Cu		Pesticides, fertilizers	[89]

oxidation–reduction can also change metal valency [72]. Heavy metal stress inactivates or denatures various important enzymes and other proteins and interferes with substitution reactions of essential metal ions from biomolecules. This reaction disturbs the integrity of membranes, resulting in the alteration of basic plant metabolic reactions such as photosynthesis, cell elongation, transpiration, respiration, and homeostasis [90]. Moreover, it stimulates the production of reactive oxygen species such as superoxide radical (O_2^{-}), hydroxyl radical (OH), and hydrogen peroxide (H_2O_2). These highly reactive species lead to lipid peroxidation, especially of the cellular membranes, and cause leakage, damage of biomolecules, and also cleavage of DNA strands collectively [91]. To cope with the heavy metal stress, plants exhibit changes in redox status, the level of signal molecules, the activity of antioxidant system enzymes, membrane permeability, glutathione (GSH) and phytochelatin (PCs) contents, protein content, proteins and genes encoding enzymes of the flavonoid biosynthesis pathway [92, 93]. The impact of heavy metals is strongly related to their doses, plant species, and the plant developmental stage as well as environmental factors of a given climatic zone. When contaminated produce is consumed by animals and human beings, heavy metals start to accumulate in the tissue through biomagnification. They may cause many life-threatening diseases, such as many types of cancers (lungs, skin, brain, etc.), Itai-Itai disease, Minamata disease, acrodynia, and gastrointestinal problems by replacing the essential metal required for normal metabolism [94]. When the Ca^{2+} is replaced by Cd^{2+} ions lead its deficiency which interferes with neurological processes as well as bone formation. Emerging problems of food safety become a worldwide suspicion primarily due to their complicated relationship with human health [95, 96]. The impacts of heavy metals on plant and human health are briefly summarized in Table 4.

To overcome these problems, it is necessary to remediate the contaminated soil. This can be possible through various remediation strategies; one of them is

Table 4 Impact of heavy metal pollution on plants and human health

Heavy metal	Effects on plants	Effects on humans	References
As	Compromised photosynthetic rate, disturbed carbohydrate metabolism, subdued nitrogen assimilation, elevated phytochelatin synthesis, overproduction of reactive oxygen species (ROS) leading to oxidative stress, increase in lipid peroxidation	As in the form of arsenate, it interferes with oxidative phosphorylation and ATP synthesis because arsenate is an analog of phosphate. Skin damage, circulatory system issues	[97–99]
Cd	Retarded growth, chlorotic leaves, brown root tips, and decline in growth of root affect photosynthesis by inhibiting Fe reductase, interference in the uptake of minerals, lipid peroxidation, synthesis and accumulation of proline amino acid, and decrease in enzyme activity	Carcinogenic, mutagenic, and teratogenic; endocrine disruptor; interferes with calcium regulation in biological systems; causes renal failure and chronic anemia; Kidney damage and reduced neural development	[100–102]
Pb	Serious disorders in photosynthetic properties, cell division, and inhibition of enzymes responsible for seed germination	Cardiovascular diseases, loss of short-term memory, learning and coordination disability, renal dysfunction, and reduction in intelligence affect the gastrointestinal mechanism	[103–105]

(continued)

Table 4 (continued)

Heavy metal	Effects on plants	Effects on humans	References
Zn	Chlorosis of younger leaves due to deficiency of P, retarded growth, senescence, and inhibition of photosystems I, II, increase in free calcium ions, enlarged mitochondria, distorted cell wall and disintegrated nucleolus, the thickened cell wall of xylem and phloem vessels, affect the uptake and transport of essential nutrients, seed germination inhibition and promote the accumulation of other heavy metal like copper and manganese	Higher concentration causes dizziness and fatigue	[100, 106–108]
Ni	High concentration of Ni alters metabolic activities of plants inhibiting enzymatic activities, photosynthetic electron transport, chlorophyll biosynthesis and mitochondrial dysfunction	Carcinogen cause lungs, nose and sinuses cancer; allergic dermatitis, genotoxic, reproductive toxic, nephrotoxic, hepatotoxic and cause hair loss, increase RBC content in blood	[89, 109–111]
Hg	Oxidative stress, chlorosis, drying of leaf margins, curly leaves, browning of roots, and falling leaves	Insomnia, depression, fatigue, anxiety, autoimmune diseases, memory loss, damage to brain, kidney and lungs	[112–115]
Cu	Inhibition of cell division, cell elongation, chlorophyll synthesis and photosynthetic activities, disordered the metabolic activities and alteration in cell differentiation	Brain and kidney damage, liver cirrhosis and choronic anemia, stomach and intestinal irritation. Gastrointestinal issues, liver or kidney damage	[116–119]
Cr	Cr toxicity symptoms includes growth reduction and wilting Oxidative radicals cause destruction of membrane lipids and DNA damage, inhibition of germination, growth and development of root and seedling, reduction in biomass and induction of leaf chlorosis and necrosis	Allergic dermatitis, Diarrhea, Nausea and vomiting, kidney and liver damage, can damage circulatory and nervous system	[120–123]

phytoremediation, in which plants are used to restore the properties of the contaminated soil. Green plants are the lungs of nature with the unique ability to purify impure air by photosynthesis and remove or minimize the toxic contaminants from soil and water ecosystem by absorption, accumulation, immobilization, and biotransformation process known as phytoremediation.

5 Phytoremediation

Phytoremediation is made up of two words "Phyto," which means plants, and "remediation," which means to cure and remove evil. It can be used for the removal of heavy metals as well as organic pollutants. It is a novel, cost-effective, efficient, eco-friendly, and solar-driven remediation strategy. The idea is aesthetically pleasant and has good public acceptance. It is suitable for application at very large field sites where other remediation methods have cost-effective or practicable. The establishment of vegetation on the polluted soils also helps to prevent erosion and metal leaching. Fast-growing and high biomass-producing plants such as willow, poplar, bamboo, and *Jatropha* could be used for both phytoremediation and energy production [124]. Plant suitable for phytoremediation should ideally have the following characteristics like easily cultivated and harvested, widely distributed with a high growth rate and produces more above-ground biomass, and branched root system for more accumulation of the target heavy metal from the soil with high translocation index, tolerance index, highly adaptive to the prevailing environmental and climatic conditions, high economic value, resistant to the pathogens and pests, repulsion to herbivores to avoid food chain contamination. Phytoremediation includes the different techniques for the reduction of contaminants like phytoextraction (or phytoaccumulation), phytofiltration, phytostabilization, phytovolatilization, and phytodegradation as depicted in Fig. 3 [125].

5.1 Phytofiltration

It is the removal of contaminants from the surface of the contaminated water by plants [126]. It can be done by rhizofiltration (use of plant roots) or blastofiltration (use of seedlings), or caulofiltration by using excised plant shoots [127].

5.2 Phytostabilization/Phytoimmobilization

It is the immobilization of the contaminants in contaminated soil with the help of certain plants [128]. This technique helps to prevent the off-site migration of contaminants like in groundwater or their entry into the food chain by reducing their mobility

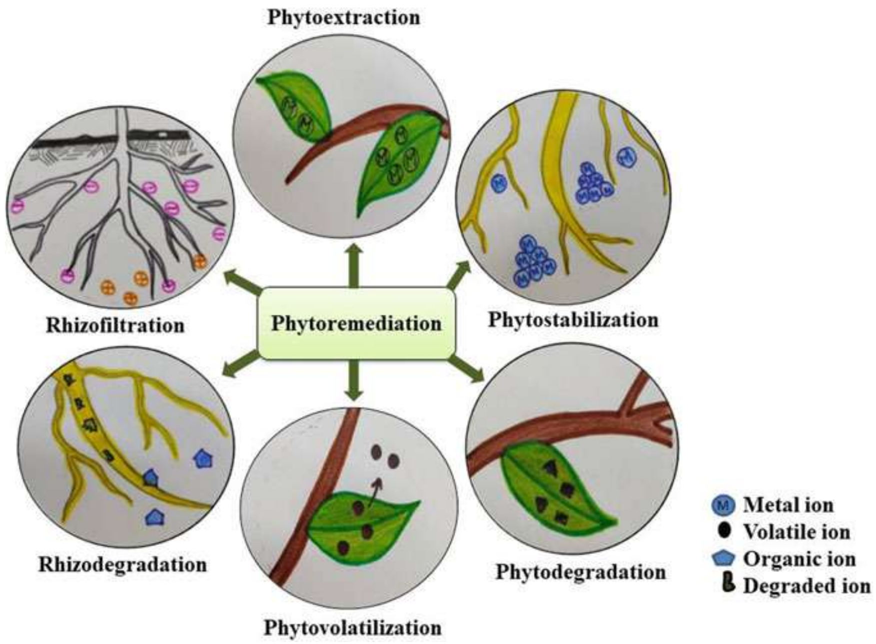

Fig. 3 Different processes of Phytoremediation

and bioavailability in the environment [129]. Plants can stabilize the heavy metals in the soil through absorption by roots, precipitation, and by making complex or metal valence reduction in the rhizosphere [84, 130], e.g., *Virola surinamensis* [131], and *Acanthus ilicifolius* [132] are capable for Cd immobilization. Plants excrete special redox enzymes that convert highly toxic metals to relatively less toxic state, which decreases metal stress and damage to some extent. It limits the accumulation of heavy metals in biota and minimizes their leaching into underground water. However, phytostabilization is not a permanent removal process because the heavy metals remain in the soil, only their movement is limited.

5.3 Phytovolatilization

Phytovolatilization is the most controversial of phytoremediation technologies. Plant uptakes the pollutant from the soil via the xylem and releases them into the atmosphere through transpiration with the help of stomata after changing into volatile form. This technique is not a permanent cure for the removal because contaminants are only transformed from one segment to another from where they can be redeposited [133].

5.4 Phytodegradation

It is the degradation of organic pollutants with the help of enzymes such as dehalogenase and oxygenase released by plants. This process is independent of rhizospheric microorganisms [134]. Due to this, green plants can be regarded as "Green Liver" for the biosphere. But this process is only limited to removing organic pollutants, not heavy metals because they are non-biodegradable.

5.5 Rhizodegradation

Rhizodegradation is the degradation of organic pollutants in the soil with the help of microorganisms in the rhizosphere [135]. Rhizosphere degradation can be enhanced by increasing the metabolic activity of the microorganisms. Plants can enhance microbial activity about 10–100 times higher in the rhizosphere by secreting exudates that contain carbohydrates, amino acids, and flavonoids. These secretions provide carbon and nitrogen sources to the soil microbes and create a nutritive environment for their growth and metabolic processes.

5.6 Phytoextraction/Phytoaccumulation

It is the uptake of contaminants from soil or water by plant roots and their translocation and accumulation in above-ground biomass, i.e., shoots [136]. Translocation of metal from root to shoot is a crucial biochemical process because the harvesting of root biomass is not generally feasible [137, 138]. It is the most useful phytoremediation technique for the removal of heavy metals and metalloids from contaminated soils, sediment, or water [139]. The efficiency of phytoextraction depends on many factors including bioavailability of the heavy metals in soil, soil properties, speciation of the heavy metals, and plant species concerned. The bioavailability of heavy metals in the soil is a critical factor affecting the efficiency of the phytoextraction of heavy metals. Strong binding of heavy metals with the soil particles or precipitation causes a significant fraction of heavy metals to become insoluble and makes them less available for plant uptake. Plants have developed certain mechanisms for solubilizing the heavy metals in the soil. Their roots secrete metal-mobilizing substances in the rhizosphere called phytosiderophores [140]. Due to the secretion of H^+ ions by the roots, it acidifies the rhizosphere and increases metal dissolution. H^+ ions can displace heavy metal cations absorbed by the soil particles [141]. Interaction of microbial siderophores can increase labile metal pools and uptake by the roots [142].

Phytoextraction of heavy metals can be done by two methods: natural and induced. In natural, plants are grown in the natural condition for the uptake of metals, i.e., no soil amendment is made. In induced, different chelating agents are used such as EDTA, citric acid, elemental sulfur, and ammonium sulfate are added into the soil to increase the bioavailability of heavy metals in soil for the uptake by the plants, also known as chelate-assisted phytoextraction [140, 143, 144]. The chelating agents form water-soluble complexes with the heavy metals in the soil and help in their absorption from the soil particle. The low pH of the soil causes an increase in the solubility of metal salts. These chemical treatments show secondary pollution like EDTA is non-biodegradable, and it leaches out into groundwater and makes an additional environmental hazard [145, 146].

The phytoextraction potential of plant species is mainly determined by two factors, i.e., shoot metal concentration and shoot biomass [147]. Two different approaches are tested for the phytoextraction of heavy metals one is by using hyper-accumulators which produce comparatively less biomass but accumulate high concentration of heavy metals in their plant parts, and the other is by using other plants that produce large biomass but accumulate heavy metals in lesser concentration compared to hyper-accumulators [148, 149]. Plants with multiple harvests in a single growth period (*Trifoilum* sp. and other grasses) can have great potential for the phytoextraction of heavy metals [150]. Grasses are preferable for phytoremediation than shrubs or trees because of their growth rate, adaptability to stressful environment, and high biomass production [151]. Vamerali et al. [152] said that the use of field crops for phytoremediation purposes should not consider for the use of animal feed or direct human consumption.

Some plants have a large potential to cope with heavy metal contamination as they accumulate or stabilize the heavy metal or hinder their path to enter the plant. These plants are known as hyper-accumulators, indicators, and metal excluders.

a. *Metal excluders*: They accumulate heavy metals from soil into their roots but restrict their transport and entry into their aerial parts [153, 154]. These plants may have a low potential for metal extraction but may be efficient for the phytostabilization purpose [155, 156].
b. *Metal indicators*: These plants generally indicate the concentrations of heavy metal in the substrate [153]. They accumulate heavy metals in their aerial parts and indicate the presence of that metal in that area.
c. *Metal Hyper-accumulators*: These plants can accumulate heavy metals in their above-ground biomass to levels far exceeding those present in the soil or nearby growing non-accumulating plants [157]. The term "hyperaccumulator" was first coined by Brooks et al. [158] to define plants with Ni concentrations greater than 1000 mg/kg dry weight (500.1%). According to Baker and Brooks [159], "Hyper-accumulators are the plant species, which accumulate heavy metal greater than 100 mg/kg dry wt. for Cd or greater than 1000 mg/kg dry wt. for Ni, Cu, and Pb or greater than 10000 mg/kg dry wt. for Zn and Mn in their shoots when grown on metal-rich soils". Hyper-accumulators achieve a root-to-shoot metal concentration ratio (called translocation factor or TF) greater than 1 [138, 160]. Hyper-accumulators can be used for the phytoremediation of toxic and hazardous heavy metals as well as for the phytomining of precious heavy metals such as Au, Pd, and Pt. Some plants have a natural ability to hyper-accumulation for heavy

metals, known as natural hyper-accumulators. On the other hand the accumulation capacity can be increased by modifying their genetic material with the help of biotechnological methods. Such plants are known as genetically modified plants.

6 Mode of Accumulation/Tolerance

The plant uses numerous mechanisms to deal with the heavy metals present in the soil by providing tolerance. All responses can be broadly classified as avoidance or tolerant types [161]. The first line of defense produced by the plant causes a reduction in the uptake of metals when stimulated with the toxicity of heavy metals, which is accomplished with the help of cellular and root exudates. These exudates limit the metals from entering the cell by increasing efflux or biosorption to cell walls and are classified as an avoidance mechanism. Many plants have exclusive mechanisms that are categorized as tolerance mechanisms for each metal ion. In this mechanism, the metal ions are sequestered in less active compartments protecting the sensitive components of the cells from metal interactions. The compounds involved in this process are amino acids, glutathione, phytochelatins, metallothioneins, and enzymes such as superoxide dismutase, peroxidase, and catalase [90]. However, when a cell is continuously faced with extreme stress, its routine defense responses may get exhausted; in that case, plants activate various specialized mechanisms for the detoxification of metals, during which the metals might be chelated, transported, sequestered, or detoxified in the plant's vacuole. The synthesis of stress-related proteins, hormones, antioxidants, and signaling molecules, including heat-shock proteins, is initiated when the plant is required to activate any of these systems [74]. Plants under stress are also interested in having symbiotic relations with other organisms, such as mycorrhizal fungi, which accumulate metals in the rhizosphere preventing their availability for the plant. This is another strategy to thrive during tough times. The Pb is absorbed by roots via an apoplastic pathway or via Ca^{2+} permeable channels. It is least mobile than the other metals tended to accumulate mostly in the stem and root. Cadmium is absorbed by plant roots through apoplastic and symplastic pathways and then translocated to plant shoots via xylem loading long-distance transport and phloem redistribution [162]. It competes with the cations (Ca, Mg, Zn and Mn) for exchange sites in soil and uptake by the plants. Zn is absorbed as Zn^{2+} through mass flow and diffusion mechanism by roots. Vacuole acts as the main organ where Zn has accumulated in *Arabidopsis halleri* [163]. Ni is taken up by plants by passive diffusion through the cation transport system, chelated Ni compounds, and by active transport using transport proteins such as permeases.

7 Bamboo as a Phytoremediator

Bamboo, the largest grass, belonging to the family Poaceae sub-family Bambusoideae and tribe Bambuseae, has a wide natural distribution, spreading from approximately 46°N latitude to approximately 47°S latitude and from sea level to as much as 4,300 m (approx. 14,000 feet) in elevation. A total of 121 genera and 1662 species of bamboo are found worldwide covering an area of 31,470 ha [164]. Among these, China has the highest bamboo diversity in the world with 39 genera and 500 species, followed by India with 29 genera and 148 species, and Southeast Asia has nearly 20 genera with 200 species.

Bamboo has a rapid rate of growth with high CO_2 fixation and reaches maturity in three years due to a unique system of root rhizomes, while other woods need approximately 20 years to reach maturity [165]. It has a high biomass yield, resistant to pests and diseases, and has a robust rhizome system which are the dominant characteristics that facilitate phytoremediation. These characteristics are coupled with high metal ions extraction capacity in the roots and have high endurance against heavy metal stress [166]. Different parts of bamboo, including the leaves, stem, root, rhizomes, and fibers can aid in environmental clean-up by removing contaminants from wastewater, air, and soil. It can remove contaminants with five mechanisms rhizosphere bioremediation, phytoextraction, phytostabilization, phytotransformation, and rhizofiltration. Rhizoflitration process in bamboo leads to the widespread growth of bamboo roots in wastewater from industry, animal breeding, and contaminated area. The greater surface areas cause oxidative stress and damage to bamboo plants. Bamboo species such as *Phyllostachys pubescens*, *P. praecox, Indocalamus latifolius, Pleioblastus kongosanensis, Sasa fortunei,* and *Pleioblastus fortunei* have been shown to have a high endurance in metal-contaminated soils, enabling a considerable uptake and accumulation of heavy metals. Studies have indicated that bamboo species have more developed fine roots than other forest plants [168]. Medium and large bamboo species have well-developed, massive, and complex root patterns [169]. The total below-ground bamboo (African Alpine Bamboo) biomass in the top 10 cm layer of mineral soil was estimated to be 25.6 t ha^{-1}, of which 13.6 t ha^{-1} was rhizome of roots are known to contribute more to the absorption of heavy metals and nutrients [167]. Bamboo can counter hazardous heavy metals in their rhizome and culm tissue that mainly accumulate in the cell wall, vacuoles, and cytoplasm. After harvesting, instead of dying and decaying, toxins remain inside their tissue where they pose no danger to humans. Limited studies have been done regarding bamboo in phytoremediation.

Some recent studies have shown that it has a high ability to adapt to metalliferous environments and has a high capacity to absorb heavy metals. However, excessive concentrations of heavy metals may be biomass and 12.0 t ha^{-1} root biomass [170]. When the soil is contaminated, the plant root system is the first organ to be polluted, which can cause root physiological dysfunctions and thus influence shoot physiology and growth [171]. Translocation from the soil to the above-ground organs is dependent on the rate of trapping in different compartments of root cells, and the long-distance transport of toxic metal elements between organs occurs via the xylem and phloem [172]. In recent years, studies have been focused on the uptake and transport of heavy metals in soil by bamboo [173–175]. Wang et al. [176] reported that bio-adsorbents based on bamboo for removing metal ions in an aqueous solution show a great ability to bind metal ions. Other bio-adsorbents based on bamboo charcoal, bamboo root biomass, and sawdust also have a great capacity to adsorb the metal ion in their particles [177]. Results of other studies reported that bamboo as a fine biochar had a positive impact on increasing the microbial community related to size, impacting carbon cycling by decreasing their soil enzyme activity and leading to increasing (higher) CO_2 emissions [178].

The phytoremediation of heavy metal-contaminated soil by using different bamboo species has been carried out by various researchers in several countries. The genera which are widely used for phytoremediation purpose are *Phyllostachys, Pleioblastus, Dendrocalamus, Indocalamus, Sasa, Gigantocloa,* and *Bambusa.* They showed great accumulation capacity for heavy metals such as Cd, Pb, Zn, Cu, Si, Cr, and Fe with large biomass production.

7.1 Cr Accumulation and Their Physiological Responses in Bamboo

Phyllostachys pubescens showed a great capacity to grow in 180 mg Cr/L with an irrigation flow rate of 600 mm/yr. Cr bioaccumulation was found mostly concentrated in the below-ground parts after 6 weeks of cultivation which indicates its phytostabilization potential, while the aerial parts of bamboo exhibited high translocation factor and increased bioaccumulation of Cr after 12 weeks of cultivation [179]. It is also reported that *P. pubescens* removed approximately 42 and 60.7% Cr from the soil after 6 and 12 weeks, respectively, starting from approx. 300 mg/kg Cr concentration in soil and ending with around 118 mg Cr/kg in soil [180]. Ranieri et al. [181] observed a 100% survival rate of *P. pubescens* grown in a soil concentration of around 100 mg Cr/kg. Their study also reported that aerial parts of the bamboo exhibited less Cr concentrations (0.86 mg/g d.wt) while the roots (1.31 mg/g d.wt.), exhibited high concentrations, which indicates its phytostabilization/phytodegradation potential. Therefore, it is suggested that *P. pubescens* could tolerate higher metal stress and have the potential to be used as a phytoremediation agent for Cr-contaminated soil up to 200–300 mg/kg. Other bamboo species such as *Bambusa vulgaris*, *B. blumeana*, *B. bambos*, *Dendrocalamus asper*, *D. birmanicus*, *D. membranaceus* when planted on chromium-contaminated tannery sites in Kenya reported 100% survival rate of all the bamboo species in the tannery soil except for *D. birmanicus*, which had 83.3% survival rate. *B. bambos* had translocation factor > 1, indicating the potential for phytoextraction with accumulation ranging from 1337 to 3398 mg/kg Cr [182]. Sinha et al. [183] reported that the accumulation of Cr in the above-ground part ranged from 1.87–34.44 mg/kg d.wt. with maximum concentration in *Dendrocalamus strictus* (34.44 mg/kg d.wt.).

7.2 Pb Accumulation

When bamboo species are exposed to heavy metal stresses, many ultra-structural changes occur that help the bamboo to cope with heavy metal stress, like secretion of substances by roots, thickening of the cell wall, formation of crystals in the xylem, etc.

Cai et al. [184] examined the physiological response of *Sasa aregenteostriata* against Pb treatment and found that the plant regulates enzymatic and non-enzymatic systems simultaneously to overcome Pb damage such as superoxide dismutase (SOD) activity with phytochelatins (PCs), peroxidase (POD), and glutathione reductase (GR) activity with glutathione (GSH) as well as catalase (CAT) and ascorbate peroxidase (APX) with soluble protein level. While conducting studies on the same species, Jiang et al. [185] recorded maximum accumulation in their roots whip system (9969.46 mg/kg) and synthesis of antioxidant substances (glutathione and phytochelatins) to alleviate the Pb toxicity. Their study also reported its stronger tolerance, accumulation capacity, and reasonable detoxification mechanism against lead toxicity. *Indocalamus latifolius* showed high peroxidase (POD) and catalase (CAT) activity at 500 mg/kg concentration of Pb; and high lipid peroxidation at 1000–2000 mg/kg Pb as Pb was reported to be a strong stimulator of MDA(malondialdehyde) [186]. When *Phyllostachys pubescens* was grown on Pb-contaminated water, Pb accumulated at the rate of 4283 and 482 mg/kg in root and shoot, respectively. High Pb (400 mM) concentration leads to abnormality in the shape of chloroplasts, the disappearance of the endoplasmic reticulum, shrinkage of the nucleus, nucleolus, and loss of thylakoid membranes [187].

Five dwarf bamboo species viz. *Sasa argenteostriata*, *Sasaella glabra*, *Indocalamus decorus, Sasa auricoma* and *Sasa fortunei* were treated with two levels of soil Pb stress (0 and 1500 mg/kg) by Liao et al. [188]. It was observed that *S. argenteostriata*, *S. glabra*, and *I. decorus* follow the tolerance strategy by accumulating the Pb along the cell wall and transporting it to the vacuoles, while *S. auricoma* and *S. fortunei* arranged Pb linearly along the cell wall and adopted exclusion strategy to cope up with Pb absorption. In a study conducted by Li and Gao. [189] in *Pleioblastus kongosanensis*, *Indocalamus latifolius*, *Sasa fortunei* that toxicity symptoms were seen in *I. latifolius* after 40 days and in *P. kongosanensi* and *S. fortunei* after 25 days of the Pb treatment. *Pleioblastus fortunei* accumulated more Pb in leaves (8212 mg/kg) followed by root (6195 mg/kg), rhizome (1652 mg/kg), and stem (1424 mg/kg.). The content of mineral elements (Na and K) in *P. fortunei* changed significantly, and the leaves turned yellow due to limiting mineral uptake [190]. In natural polluted environment, it is determined that *Phyllostachys pubescens* can tolerate Pb stress up to 1600 mg/kg, and it has a relatively strong Pb absorption capacity with accumulation ranges from 148–4282.8 mg/kg [191]. Jiang et al. [192] demonstrated that two dwarf bamboos *Arundinaria argenteostriata* and *A. fortune* could be used as a potential phytoremediator for lead-contaminated soil because of their strong tolerance, accumulation capability for Pb, and reasonable detoxification mechanisms against Pb-induced toxicity compared to the other bamboos. EDTA promotes Pb^{2+} absorption and distribution in bamboo tissues under Pb toxicity.

7.3 Cu Accumulation

Different bamboo species *Dendrocalamus asper, Phyllostachys pubescens, P. fastuosa, P. auresulata, Pleioblastus chino,* and *Gigantocloa* were tested for phytoremediation of Cu contaminated soil and found affected in the Cu accumulation. The Philippine giant bamboo *Dendrocalamus asper* showed the capability of removing high amounts of Cu from artificially contaminated water (up to Cu 0.650 mg/g d.wt. at 20 ppm Cu and pH 5), but its effectiveness is greatly affected by the initial copper concentration and pH. Individually, each of these factors promotes copper uptake at increased levels, but together they may compete and hinder remediation. Phytoremediation using *D. asper* was most effective at high copper concentrations and low pH. However, for lower copper concentrations (<3.81), a neutral pH may be more ideal for *D. asper* [193]. A hydroponic study was conducted by Li et al. [194] and Chen et al. [19, 195] for the estimation of ultra-structural changes and phytoremediation potential of *Phyllostachys pubescens* for Cu contamination. Both species were able to accumulate Cu in the concentration 524–809 mg/kg d.wt. in root and less than 95 mg/kg d.wt. in the shoot. Cu was mostly concentrated in the vacuole, followed by the cytoplasm and the cell wall. Vacuoles played an important role in the Cu tolerance of *P. pubescens* and were found to be the main Cu-accumulating organs. Bian et al. [196] ranked the Cu content in the different tissues of *P. pubescens* as roots > rhizomes > leaves > branches > stems. Furthermore, Zn was mainly concentrated in the branches and leaves while the rhizomes had the lowest levels; and Cd was mostly concentrated in the roots, and the lowest levels were found in the branches.

Phyllostachys fastuosa, when exposed to the Si and Cu contaminated solution in hydroponics, showed some ultra-structural changes that help them to cope with high Cu concentrations, i.e., maximum sequestration in the roots, binding of Cu(II) with amino and carboxyl ligands, formation of Cu(I)S organic compounds that help in Cu storage [197]. Jiang et al. [118] observed that Cu accumulation was more in *Pleioblastus chino* (hisauchii) (723–2408 ug Cu/kg) than *Phyllostachys auresculata* (spectabilis) (1572–2871.8 ugCu/kg) under Cu stress condition. The percentage of senescent shoots increased with the increase in Cu 500–2000 mg/kg, and *P. aurescu-lata* have higher chlorophyll content than *P. chino* at 1000–2000 mg/kg Cu. *Gigantocloa* sp. "Malay Dwarf" grown in hydroponics with Si and Cu contaminated solution, accumulated silicon and copper in decreasing order as following leaves > stem > root and root > leaves > stem, respectively, and shows an increase in Mg, Ca, and Fe uptake under Cu toxicity [198]. Sympodial bamboo accumulated more Cu and Si than monopodial in both leaves and stems, whereas, in the case of Zn, monopodial bamboo has a high accumulation potential compared to sympodial bamboo [199].

7.4 Cd Accumulation

Phyllostachys pubescens showed great ability of Cd accumulation under Cd stress. Liu et al. [187] observed that *P. pubescens* grown with 400 μM Cd accumulated mainly in the root (377.2 mg/kg) followed by the stem (129.8 mg/kg) and leaves (25.6 mg/kg). Excessive Cd caused a decrease in the dry weight of the plant, abnormality in the shape of the chloroplast, loss of thylakoid, disappearance of endoplasmic reticulum, and shrinkage of nucleus and nucleolus.

Cd concentration in *P. pubescens* ranged from 28.51 to 132.13 mg/kg in the stems and 40.80–159.25 mg/kg in roots under 5 to 120 mg/kg Cd contaminated soil. It is mostly accumulated in the cytoplasm, followed by the vacuole and cell wall. The bioaccumulation factor (BAF) and translocation factor (TF) values in all treatments exceeded 1.0 and 0.70–1.06, respectively [200].

7.5 Zn Accumulation

Liu et al. [201] found that *Phllostachys pubescens* accumulated Zn from 2329.29–8642.51 mg/kg in the root, which was 58.23 times higher than the control under Zn contamination. A high concentration (400 μM) of Zn adversely affects seed germination by reducing the radical length (50.48–82.04%). The anatomical studies revealed that cell structure, root tips, and organelles were significantly altered at 200 μM Zn stress. Some abnormalities were also evidenced in the cell walls, vacuoles, mitochondria, plasmalemma, tonoplast, and xylem parenchyma of the root cells.

Chen et al. [202] reported that *P. pubescens*, when grown on Zn polluted water, accumulated 2329 mg/kg Zn in the root, 889 mg/kg in the shoot, and 490 mg/kg in leaves. Leaf biomass and shoot length decreased by 45% and 14% under 200 μM and 400 μM Zn concentration, respectively. The ultra-structural study revealed distorted and slightly thicker cell walls, breakage of plasmalemma, swelling of mitochondria, deformed and wrinkled epidermal layer under 200 μM Zn concentrations.

7.6 Remediation of Mining-Contaminated Sites

When 2-year-old *Indocalamus latifolius* was exposed to different concentrations of Pb, Cu and Zn with EDTA decline in photosynthetic rate, intracellular CO_2 concentration, conductance to H_2O_2 and net assimilation as well as transpiration at higher concentration were recorded [203]. Bian et al. [204] reported that *P. praecox* showed a healthy growth rate, normal fully expanded green leaves and shot with no toxic symptoms when grown on Cu, Cd, and Zn contaminated soil. When *Phyllostachys pubescens* was grown on Pb–Zn mining-contaminated soil, it accumulated a high level of Pb (286 mg/kg) [205]. An investigation by Shukla et al. [206] reported that among five woody plants species, i.e., *Terminalia arjuna, Prosopis juliflora, Populus alba, Eucalyptus tereticornis, and Dendrocalamus strictus*, the root and stem of *D. strictus* plants had the highest Mn and Zn accumulation potential. Singh et al. [21] reported that *Dendrocalamus strictus* accumulated Fe (27,790 mg/kg) and Pb (68 mg/kg) when planted on mine spoil soil in a tropical environment in India. Some of the bamboo species which contribute to the phytoremediation of heavy metal contamination are listed in Table 5.

7.7 Bamboo in Waste Water Treatment

According to Piouceau et al. [208], *Bambusa vulgaris* and *Bambusa oldhamii* are the most productive and potent species for wastewater water treatment. Pig slurry treatment with bamboo plantation shows no negative impact on bamboo growth, although it increased their photosynthetic rate, specific leaf area, the number, and the diameter of shoots produced. Bamboo wetland systems are useful in wastewater treatment as well as for preventing abrasion on the edge of the river and reducing seawater intrusions, as reported by Cao et al. [209]. Wang et al. [210] observed that carboxylated bamboo fibers can be applied as a potential bio-adsorbent for metal ions removal due to their rich in carboxyl groups. Moreover, they also used carboxylated bamboo to remove Pb (II) ions from the aqueous solution, and their results showed that the adsorption capacity of Pb reached 127.1 mg/g for carboxylated bamboo fibers with 4.13 mol/g carboxyl group content. *Melocanna baccifera* raw and activated charcoal was found efficiently remove the lead from an aqueous solution at pH 5.0 and 60% KOH pre-treatment by adsorption and desorption processes [211]. Babatunde et al. [212] reported that *Dendrocalamus asper* is potentially effective in the rhizo-filtration and phytostabilization of Cu.

Briter-Water, an European Union funded project in France, established multiple bamboo groves (1500m^2) that serve as a natural water filter for food industry effluents or runoff by removing 99% of organic waste from the water. "Phytorem" was the French company that implemented the first such water treatment facility outside a Delifruits factory in Valence Southwest, France, and reported successful results due to robust and tightly woven rhizomes of bamboo.

In the Western Indian Ocean, the scientist planted three fields of bamboo as a test plot for treating the highly polluted runoff from pig farming in the French island of reunion and proved effective in removing nitrates from the soil. In this study, *Bambusa vulgaris* and *B. oldhamii* responded best to applying pig slurry and found an increase in growth rate and biomass production as the pig slurry provided a rich fertilizer [208].

Table 5 Bamboo in the phytoremediation of heavy metal contaminated soil

Bamboo Species	Heavy metal	Effects on bamboo	References
Phyllostachys pubescens	Cu	Reduction in root size, cell division was inhibited; the root becomes dark brown and increases in senescence of shoot, Irregular and thick cell wall, distortion of mitochondria and nuclei, the disappearance of endoplasmic reticulum, and decrease in dry weight	[46, 194]
	Zn	Decrease in dry weight of shoot, root length, root surface area, root volume, distortion, and thickness of cell wall increased, breakage of plasmalemma, swallowing of mitochondria, and deformation of the epidermal layer	[201, 202, 204]
	Pb	Decrease in biomass, root length, number of root tips, leaf hair, loss of protective layer on stem, swollen and distorted structure of cell wall, chloroplast abnormality, and dissolved thylakoids	[187, 191]
	Cd	Hinder water and nutrient uptake, irregular chloroplast, dissolution of thylakoid membrane that leads to decrease in photosynthetic rate resulting stunted growth, wilting, decrease in dry weight. Distortion of the cell wall, reduction in the size of mitochondria, and damage root tips were recorded	[187, 200]
	Lead–zinc mining area	Accumulated 286 mg/kg Pb and 210 mg/kg without showing any toxic symptoms	[205]
	Cr	100% survival rate and no toxic symptoms observed	[179–181]

(continued)

Table 5 (continued)

Bamboo Species	Heavy metal	Effects on bamboo	References
Dendrocalamus strictus	Mine spoil soil	Maximum absorption of lead and iron by *D. strictus* but compared to other plants	[207]
Pleioblastus fortune	Pb	Reduction in mineral uptake (Na, K) causes yellowing of leaves, chlorosis, and necrosis	[190]
Phyllostachys auresculata (spectabilis), Pleioblastus chino (hisauchii)	Cu	Decrease in net photosynthetic rate, stomatal conductance, intracellular CO_2 content, chlorophyll content, and increase in a senescent shoot	[118]
Dendrocalmus giganteus, D. bambos, D. strictus, Bambusa oldhamii, B. vulgaris, Phyllostachys aurea, P. Japonica	Cu	Sympodial bamboo accumulated more Cu, Si than monopodial in both leaves and stem but in the case of Zn accumulation, monopodial bamboo has high accumulation compared to sympodial bamboo	[199]
Gigantocloa sp.	Cu	Increase in Mg, Ca, and Fe	[198]
Pleioblastus kongosanensis, Indocalamus latifolius, Sasa fortune	Pb	Decrease in shoot length and number of new root emergence	[189]
Dendrocalamus asper, B. vulgaris, D. membranaceus, Bambusa blumeana, D. birmanicus, B. bambos	Cr	All bamboo species show a 100% survival rate except *D. birmanicus*	[182]

(continued)

Table 5 (continued)

Bamboo Species	Heavy metal	Effects on bamboo	References
Phyllostachys praecox	Zn	Accumulated high concentration of Zn compared to other metals with healthy growth and fully expanded green leaves	[204]
Indocalamus latifolius	Cu, Pb, Zn	Decline in net assimilation, transpiration, and photosynthetic rate, intracellular CO_2 concentration, conductance to H_2O_2, increase in malondialdehyde (MDA), peroxidase (POD) and catalase (CAT) activity	[186, 203]
Sasa argenteostriata	Pb	Inhibition of glutathione, phytochelatin regulation of enzymatic and non-enzymatic systems synergistically, such as SOD with phytochelatins, peroxidase, and GR with GSH, as well as catalase and APX with soluble protein	[184, 185]
Sasa argenteostriata, S. fortunii *S. auricoma* *Sasella glabra* *Indocalamus decorus*	Pb	Decrease in plant biomass and MDA content; increase in SOD, POD, CAT, and proline content; damage in chloroplast leads inhibition of photosynthesis, reduction in thylakoid volume and number of osmiophilic granules	[188]

8 Conclusion

Increasing industrialization and growth of industrial activities related to the modern lifestyle led to have demand for various products that contain toxic and hazardous heavy metals, which have adverse effects on plants and humans. Therefore, the utilization of sustainable remediation techniques such as phytoremediation, which uses green plants to remediate contaminated sites, has become imperative. Various plants have been used as phytoremediator, which has great accumulation capacity but small biomass production. But bamboo is one such plant that has the potential to accumulate high concentrations of heavy metals in their different parts and tolerance to contaminants with large biomass production. Phytoremediation of heavy metals using bamboo, especially in industrial areas and urban territories, has proven to be beneficial. Presently the use of bamboo as a resource for phytoremediation is still in its infancy. Although bamboo does not reach the standard of hyper-accumulators in the capacity of heavy metals accumulation, it is a considerably valuable plant for phytoremediation purposes, especially due to its greater biomass production. Apart from this, it has many ecological benefits such as reduction in CO_2, water pollution, soil erosion, increased O_2 emission, soil fertility, and green forest. Current research has focused on common heavy metal ions such as lead, zinc, and copper and the screening of some bamboo species for the phytoremediation of these heavy metals [190, 213, 214]. More field experiments need to be conducted as the main test sites are greenhouse. The mechanism of uptake, transport, and detoxification of heavy metal ions in bamboo is still unclear. Bamboo grown at contaminated sites has shown potential to serve the crucial dual function of purification (through absorption of heavy metals, nitrogen, and phosphorus), filtration of polluted water, and producing biomass suitable for a range of industrial, domestic, and artisanal uses [215]. The uptake ability of heavy metals of indigenous bamboo species needs to be explored to select the best species and conduct in-depth research on planting methods and other management measures.

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Bamboo Shoot Processing: Conventional to Modern Optimisations

Natasha Saini, Nirmala Chongtham, and Madho Singh Bisht

Abstract Bamboo shoot, a traditional delicacy, having an imperative place in the food regime of some regions, is getting cognizance in the modern world for their nutritional and functional properties. Although, fresh shoots are given preference, most of the edible bamboo species need to be processed prior to consumption so as to detoxify them from the anti-nutrients, especially cyanogenic glycosides; and to enhance their short shelf life (2–3 days post-harvest) which is usually influenced by physicochemical factors along with microbial and enzymatic activities. Boiling, water soaking, fermentation, open sun drying, and pickling are conventional practices that can remove the anti-nutrients effectively, maintain an adequate nutritional profile and make shoots more palatable with improved texture, aroma, and flavour to be used in various recipes. However, modern consumers are unprecedentedly interested in the health-promoting efficacy, accessibility, affordability, and durability of food along with basic nutrition, and they are profoundly attentive to the ways food is procured and processed. Thus, a lot of new processing techniques have developed, including different drying methods, viz, double-pass and convection solar drying, microwave drying, oven drying, vacuum drying, osmotic dehydration, and lyophilisation, alongside evaluating their physicochemical properties. Brining and canning are among popular processes which favour the long-term preservation of shoots while retaining vitamins, minerals, and macronutrients. High hydrostatic pressure processing indicated better sensory acceptability while storing bamboo shoots. Besides processing shoots for direct consumption, various processes are also used to fortify shoots in different recipes for value addition. Efforts being made for instigation on processing and preservation of bamboo shoots can minimise food wastage, enhance shelf life, create resilient food systems and unravel its monetary perspective.

Keywords Bamboo shoot · *Dendrocalamus* · *Bambusa* · Poaceae · Processing · Drying · Fermentation · Functional food

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N. Saini · N. Chongtham (✉)
Department of Botany, Panjab University, Chandigarh 160014, India
e-mail: cnirmala10@gmail.com

M. S. Bisht
Environmental Studies Department, NEHU, Shillong 793022, India

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1 Introduction

Food processing was in practice since early times to make food innocuous, transportable, and for maintaining their dietary values during preservation. Initially, simple methods like cooking, smoking, curing, air drying etc. were used, which improved with progressive advancement in thermal treatments and pasteurisation. The level of processing further enhanced in consecutive centuries and is still developing to achieve certain goals in the food industry, mainly 'preservation' to reduce spoilage and microbial infestation to limit foodborne ailments; 'improved palatability' for superior tasting and access to nutrients; 'transportation stability' for expansion of supply chains oriented towards market and growing economy; 'convenience food production' which needs minimal preparation at household requisite by growing urbanisation and number of working people [1–3]. Processed food has made a global market of around 7 trillion dollars, backed by rapid industrialisation and globalisation. Even in developing nations, food processing is an auspicious section of the manufacturing division and the aid of food processing industries to the domestic GDP expands with the country's national income [4–6].

Bamboo shoot is a rich source of nutrients and health-beneficial properties and is now declared a superfood [7]. However, the anti-nutrients have to be removed before consumption. The processing of bamboo shoots is an ancient practice so as to make them palatable by detoxifying from the anti-nutritional components. The most prevalent anti-nutrient in shoots of edible bamboos is a cyanogenic glycoside, which is not itself harmful as it is compartmentalised separately from its hydrolysing enzymes (β-glycosidase and α-hydroxynitrile lyase) in the intact cells. But, when cell integrity is disrupted upon chewing or marinating, the enzymes are brought together with cyanogenic glycosides and degrade them into a toxicant hydrogen cyanide (HCN) and an aldehyde or ketone [8–10]. HCN can intoxicate individuals from a mild to severe level as it blocks the respiratory electron transport chain by deactivating cytochrome C oxidase enzyme and bring about symptoms like headache, dizziness, rapid breathing, blood pressure lowering, gastrointestinal problems, mental confusion, and even cardiac arrest [8, 11–13]. The content of this anti-nutrient in shoots is variable in different species and ranges between 31.68 ppm and 2604.00 ppm in fresh shoots [13–15].

Moreover, bamboo shoots attain unfavourable sensory modifications and physiognomies after a short duration of harvesting; they can maintain their wellness only up to a trivial period of 2–3 days under unaltered environmental conditions [16]. This short shelf life may be accredited to high moisture content ($\geq$90%), which makes shoots highly susceptible to microbial spoilage, which further enhances by peeling the outer protective layers and chopping, which results in a high surface water activity and accretion of surface fluids which are nutritious and promote microbial growth [17–19]. Furthermore, like other vegetables, during storage and transport, bamboo shoots undergo rapid deterioration owing to elevation in respiration, enzymatic discolouration, and lignification due to disproportion amongst ROS and ROS-scavenging systems under stress conditions [20–25]. Processing can break the barriers to meet the increasing demand for this new functional food by enhancing its short shelf life and making them available during off-seasons. This possibly can promote their consumption in diverse regions and broaden the marketing period with vaster market dimensions. Moreover, this may also lead to increase sale prices and ease in vending, which subsequently prevent deserting of a hefty amount of fresh shoots.

2 Minimal Processing of Bamboo Shoots

Bamboo shoots need preliminary processing prior to any preparation or further sorting. As bamboo shoot arises from an underground rhizomatous bud, the apical portion is protected by culm sheaths that cover the growing shoot till it remains tender. The newly emerged shoot comprises some inedible portions, including the culm sheath, tip, and hard base, which need to be removed. Minimal processing in general, starts with thoroughly washing the shoots followed by unpeeling the inedible culm sheath, chopping off the tip and basal portion, then slicing, shredding, or cutting into the required size or shape, thereafter subjecting them to various methods to obtain desirable processed products (Fig. 1).

3 Boiling and Soaking

Boiling and soaking are among the instant methods for processing fresh bamboo shoots implemented by native people based on their traditional knowledge particularly to get rid of the bitter taste of shoots which is actually imparted by the presence of cyanogenic glycosides. Chopped/ sliced bamboo shoots are boiled in water for a few minutes to an hour, depending on the bitterness level, and then water is discarded or replaced if required as it contains the toxic anti-nutrients. Besides detoxification, boiling enhances tissue softening, tenderness, colour, and flavour as well as affects the bioavailability of nutrients by changing the chemical composition of shoots and vegetables [26–28]. Traditionally, soaking is a preferred method for non-thermal processing of bamboo shoots by natives of Northeastern India who practice soaking of shoots in water for a few hours to >2 days prior to their preparation into any cuisine [29]. This process using simple water is also chosen due to economic and labour point of view which provide palatable shoots without any cost. Soaking may also stimulate microorganism-led activities, which affect the sensory as well as chemical properties of shoots and decrease the goitrogenic potency of cyanogen-containing plants [30, 31]. The impact of these traditional methods and their validation by some researchers is discussed in this section (Table 1).

Cooking chopped bamboo shoots by boiling for 18–20 min in water was able to remove the unpleasant taste of moderately acrid species while changing the water after around 10 min once or twice was effective for species having strong acridity [32].

Fig. 1 **a** Harvested bamboo shoots; **b**–**g** Different stages of preliminary/minimal processing of bamboo shoot

It was also reported by Ferreira et al. [33] that boiling bamboo shoots in water at 98 °C for 20 min released approximately 70% of the HCN, and upon increasing the time and temperature of boiling, around 96% of the acridity was removed. Elimination of taxiphyllin was also practised while cooking or long-term pre-soaking of shoots in 2% brine by changing the water various times during processes by Bhargava et al. [34]. Steaming and baking of fresh shoots could reduce the cyanogenic glycoside

Table 1 Effect of different processing methods on nutrients, bioactive compounds, and anti-nutrients in bamboo shoots

Compound	Bamboo species	Fresh	Soaked	Boiled	Fermented	Brined (5%)	References
Moisture (g/100 g)	*Dendrocalamus giganteus*	90.70	–	–	88.83	–	[63]
		89.02	92.68	89.64	–	–	[16]
	D. latiflorus	90.14	92.48	90.76	–	–	
	D. sikkimensis	91.24	93.79	91.81	–	–	
	D. latiflorus	91.39	92.82	92.34	91.19	90.61	[28]
Ash (g/100 g)	*B. nutans*	0.90	–	0.72	–	–	[44]
	B. vulgaris	0.80	–	0.66	–	–	
	D. strictus	0.90	–	0.82	–	–	
	D. asper	0.80	–	0.75	–	–	
	D. giganteus	0.89	–	–	0.78	–	[63]
		1.03	0.72	0.76	–	–	[16]
	D. latiflorus	0.94	0.74	0.68	–	–	
	D. sikkimensis	0.76	0.55	0.56	–	–	
	B. balcooa	0.86	–	–	0.83	–	[65]
	D. latiflorus	0.79	0.68	0.72	0.82	0.66	[28]
Protein (g/100 g)	*B. nutans*	21.10	–	17.30	–	–	[44]
	B. vulgaris	25.70	–	13.50	–	–	
	D. strictus	19.20	–	17.10	–	–	
	D. asper	25.80	–	11.60	–	–	
	D. giganteus	3.64	1.72	1.27	–	–	[16]
	D. latiflorus	3.13	1.77	1.01	–	–	

(continued)

Table 1 (continued)

Compound	Bamboo species	Fresh	Soaked	Boiled	Fermented	Brined (5%)	References
	D. sikkimensis	3.03	1.65	0.94	–	–	
	B. balcooa	3.78	–	–	2.56	–	[65]
	D. hamiltonii	2.84	–	2.47	0.89	–	[43]
	D. latiflorus	3.15	1.52	1.29	0.57	1.21	[28]
Amino acid (g/100 g)	*D. giganteus*	2.26	1.78	1.53	–	–	[16]
	D. latiflorus	1.85	1.39	1.27	–	–	
	D. sikkimensis	1.87	1.32	1.22	–	–	
	D. hamiltonii	3.241	–	2.99	0.67	–	[43]
Carbohydrates (g/100 g)	*B. nutans*	3.30	–	5.10	–	–	[28]
	B. vulgaris	3.40	–	5.00	–	–	
	D. strictus	2.60	–	5.00	–	–	
	D. asper	2.90	–	3.10	–	–	
	D. giganteus	5.10	–	–	1.50	–	[63]
	D. giganteus	5.65	4.46	4.11	–	–	[16]
	D. latiflorus	2.50	1.72	1.88	–	–	
	D. sikkimensis	2.99	1.95	2.14	–	–	
	B. balcooa	4.50	–	–	1.45	–	[65]
	D. hamiltonii	4.33	–	4.14	3.51	–	[43]
	D. latiflorus	3.42	1.74	2.72	1.17	1.95	[28]
Starch (g/100 g)	*D. giganteus*	2.38	1.41	2.67	–	–	[16]
	D. latiflorus	0.98	0.60	1.11	–	–	

(continued)

Table 1 (continued)

Compound		Bamboo species	Fresh	Soaked	Boiled	Fermented	Brined (5%)	References
		D. sikkimensis	1.31	0.78	1.49	–	–	
		D. hamiltonii	0.49	–	0.40	0.31	–	[43]
		D. latiflorus	1.18	0.91	1.67	1.89	1.51	[28]
Fat (g/100 g)		*D. giganteus*	0.39	–	–	0.25	–	[63]
			0.49	0.32	0.39	–	–	[16]
		D. latiflorus	0.38	0.23	0.29	–	–	
		D. sikkimensis	0.51	0.35	0.40	–	–	
		B. balcooa	0.67	–	–	0.44	–	[65]
		D. latiflorus	0.38	0.36	0.31	0.34	0.22	[28]
Crude Fibre (g/100 g)		*B. nutans*	0.76	–	0.75	–	–	[44]
		B. vulgaris	0.97	–	0.97	–	–	
		D. strictus	0.98	–	0.96	–	–	
		D. asper	0.71	–	0.70	–	–	
Dietary Fibre (g/100 g)	NDF	*D. giganteus*	2.65	–	–	4.18	–	[63]
			5.60	4.32	4.48	–	–	[16]
		D. latiflorus	5.88	4.66	4.62	–	–	
		D. sikkimensis	4.66	3.53	3.36	–	–	
		D. hamiltonii	5.84	–	4.98	–	–	[43]
		D. latiflorus	5.39	4.72	4.65	6.53	5.55	[28]
	ADF	*D. giganteus*	2.15	–	–	3.28	–	[63]
			0.83	0.82	1.02	–	–	[16]

(continued)

Table 1 (continued)

Compound		Bamboo species	Fresh	Soaked	Boiled	Fermented	Brined (5%)	References
		D. latiflorus	0.86	0.84	1.07	–	–	
		D. sikkimensis	0.93	0.92	1.15	–	–	
		D. hamiltonii	8.52	–	7.61	–	–	[43]
		D. latiflorus	0.75	0.81	0.87	1.14	0.86	[28]
	Lignin	*D. giganteus*	0.56	–	–	1.40	–	[63]
		D. hamiltonii	1.29	–	1.00	–	–	[43]
	Cellulose	*D. giganteus*	1.59			1.89	–	[63]
		D. hamiltonii	4.55	–	3.98	–	–	[43]
	Hemi–cellulose	*D. giganteus*	0.50			0.90	–	[63]
		D. hamiltonii	2.68	–	2.63	–	–	[43]
Vitamin C (mg/100 g)		*D. giganteus*	3.28	–	–	1.09	–	[63]
			2.21	0.81	1.26	–	–	[16]
		D. latiflorus	2.38	0.93	1.36	–	–	
		D. sikkimensis	2.43	0.85	1.42	–	–	
		B. balcooa	2.45	–	–	1.09	–	[65]
		D. latiflorus	2.95	1.59	1.14	2.23	0.43	[28]
		D. hamiltonii	1.87	0.94	1.34	–	–	[41]
Vitamin E (mg/100 g)		*D. giganteus*	0.69	–	–	0.21	–	[63]
			0.56	0.48	0.40	–	–	[16]
		D. latiflorus	0.52	0.45	0.39	–	–	
		D. sikkimensis	0.59	0.53	0.42	–	–	

(continued)

Table 1 (continued)

Compound	Bamboo species	Fresh	Soaked	Boiled	Fermented	Brined (5%)	References
	D. hamiltonii	0.59	0.25	0.28	–	–	[41]
Phenols (mg /100 g)	*Bambusa balcooa*	191.37	53.07	56.83	298.53	–	[39]
	B. tulda	443.97	58.17	120.77	641.73	–	
	B. nutans	489.83	–	180.21	–	291.34	[40]
	D. giganteus	336.56	–	164.62	–	157.41	
		347.27	187.97	182.80	891.73	–	[39]
	D. hamiltonii	586.36	–	354.11	611.6	192.77	[40, 43]
		505.93	56.74	88.47	745.56	–	[39]
		610.00	280.00	190.00	–		[41]
	B. balcooa	97.50	–	–	255.00	–	[65]
	D. latiflorus	612.24	–	482.43	–	383.27	[40]
		414.43	–	–	948.73	–	[28]
	D. giganteus	616.50	526.78	249.34	–	–	[16]
	D. latiflorus	627.39	556.55	273.70	–	–	
	D. sikkimensis	450.29	424.45	187.14	–	–	
Phytosterols (mg/100 g d.w.)	*B. nutans*	164.20	97.24	–	–	171.00	[40]
	D. giganteus	196.14	203.65	201.18	–	–	[16]
	D. latiflorus	89.90	93.88	92.56	–	–	
	D. sikkimensis	122.08	127.23	125.44	–	–	
	D. giganteus	136.23	89.56			139.33	[40]
	D. hamiltonii	198.27	108.00	149.5	434.11	322.34	[40, 43]

(continued)

Table 1 (continued)

Compound		Bamboo species	Fresh	Soaked	Boiled	Fermented	Brined (5%)	References
			470.00	330.00	420.00	–	–	[41]
		D. latiflorus	146.33	76.00	–	–	175.23	[40]
			160.76	–	–	–	287.48	[28]
Cyanogenic glycosides (ppm d.w.)		*D. giganteus*	988.17	358.58	137.80	–	–	[16]
		D. latiflorus	1106.16	440.88	166.58	–	–	
		D. sikkimensis	1517.47	457.82	170.28	–	–	
		D. hamiltonii	308.88	–	87.12	104.54	–	[43]
		D. latiflorus	1027.22	349.25	184.90	61.63	41.09	[28]
Minerals (mg /100 g)	Ca	*B. balcooa*	180	240	230	160	210	[45]
		B. bambos	190	210	230	180	260	
	Mg	*B. balcooa*	210	180	120	120	130	
		B. bambos	230	190	140	130	140	
	P	*B. balcooa*	560	530	440	360	310	
		B. bambos	750	590	370	350	250	
	Na	*B. balcooa*	20	30	20	20	18,450*	
		B. bambos	20	30	20	30	19,230*	
	K	*B. balcooa*	4230	3700	2760	3520	1520	
		B. bambos	5980	3810	2770	3370	1270	
	S	*B. balcooa*	230	250	210	200	210	
		B. bambos	260	290	240	250	230	
	Cl	*B. balcooa*	1220	900	720	810	24,240*	

(continued)

Table 1 (continued)

Compound		Bamboo species	Fresh	Soaked	Boiled	Fermented	Brined (5%)	References
		B. bambos	1530	1060	1390	1070	24,780*	
	Si	*B. balcooa*	150	110	100	120	70	
		B. bambos	130	90	80	90	70	
	Fe	*B. balcooa*	8.2	7.2	6.8	8.2	6.3	
		B. bambos	8.0	7.0	5.9	8.0	5.8	
	Cu	*B. balcooa*	2.6	2.8	2.0	2.6	2.3	
		B. bambos	2.5	2.7	1.7	2.3	2.0	
	Mn	*B. balcooa*	2.5	1.9	1.4	0.9	–	
		B. bambos	3.6	2.8	2.0	1.9	–	
	Zn	*B. balcooa*	6.8	6.6	6.0	5.6	4.3	
		B. bambos	10.0	10.0	7.7	9.4	8.1	
	Ni	*B. balcooa*	0.9	0.5	0.8	0.8	0.8	
		B. bambos	0.7	0.4	0.6	0.6	0.6	

*Extremely high content of minerals chlorine and sodium was due to salt treatment
d.w.—dry weight, NDF—neutral detergent fibre, ADF—acid detergent fibre

content by 40–70%, but appeared to be less efficient than processing through boiling [35]. Reducing the effect of different conventional processing techniques like water soaking, boiling, steaming, etc. on the HCN content of bamboo shoots was reported by Awasthi and Tewari [36]. Boiling for 30 min removed around 50–100% HCN. Other processes of HCN exclusion, like soaking bamboo shoots in water, intermittent cooking, and bath cooking at ambient pressure or degradation through ferric chloride application, were also found to be effective.

Rana et al. [37] optimised the procedure to process bamboo shoots (*Dendrocalamus strictus)* for depleting cyanide content by boiling in NaCl solution with response to surface methodology while trying four separate variables, viz, bamboo shoot thickness, NaCl concentration, amount of saline solution, and boiling treatment duration. The best possible conditions for maximum removal of cyanide were 23 min of boiling of 1.25 cm thick bamboo shoot pieces in 216 ml of 2.4% NaCl solution, which resulted in around 98.3% reduction in cyanide content altogether. The most influential factor for cyanogen's reduction was NaCl concentration followed by bamboo shoot thickness and boiling duration, while the quantity of NaCl solution have no significant impact. The use of three NaCl concentrations (1%, 5%, and 10%) with different time periods (10, 15, 20, and 25 min) of boiling was also used by Pandey and Ojha [38] to eliminate anti-nutritional components, particularly cyanogenic glycosides while evaluating the nutritional profile of bamboo shoots in four species. The best treatment for maximum exclusion of cyanogenic glycosides along with considerable retention of nutrients during boiling of shoots was found to be 5% NaCl (15 min) for *Bambusa bambos*, 1% NaCl (10 min) for *B. tulda*, 1% NaCl (15 min) for *Dendrocalamus strictus* and 5% NaCl (10 min) for *D. asper.*

The effect of various processing methods on phenol content in young shoots of *Bambusa balcooa, B. tulda, Dendrocalamus giganteus,* and *D. hamiltonii* was analysed [39–41]. They reported a reduction in total phenols by 35–89% during 24 h of soaking in water and 47–82% after 20–30 min of boiling with the highest depletion in *D. hamiltonii* shoots (Table 1). A decrease of 11% after boiling and 30–48% after water soaking in phytosterol content of bamboo shoots was also reported. Moreover, water-soaked shoots of *D. hamiltonii* were stored and analysed for changes in their phenol and phytosterol levels weekly for up to ten weeks [40]. During preservation, the phenol and phytosterol content shown inconsistent results with extending time, but ultimately there was not much difference in the total content at the end of storage. The inconsistency in compounds might be attributed to the use of different parts of shoots at variable ages for storage which advocates the importance of uniformity in samples for analytical experiments. Zhang et al. [42] also observed a reduction in total phenols in boiled and stir-fried forms of bamboo shoots when compared to fresh samples. The effect of boiling was also studied on sensory, physicochemical, and nutrimental aspects of *D. hamiltonii* edible shoots by Bajwa et al. [43]. Shoots boiled for 15 min showed a reduction of 72% in cyanogenic content, while proteins, carbohydrates, and starch content were retained commendably at 87%, 95%, and 83%, respectively; the taste and texture of shoots were also affected. Kumbhare and Bhargava [44] showed a decrease in protein content upon boiling of shoots, but carbohydrates were increased, which was attributed to the hydrolysis of complex carbohydrates into simpler sugars, whereas no significant change in dietary fibres was there (Table 1).

A study was conducted by Rawat et al. [16] to standardise adequate precooking processing methods that lead to maximum depletion of anti-nutritional factors with substantial retention of nutrients (Table 1). Shoots of three bamboos, viz, *Dendrocalamus giganteus, D. latiflorus,* and *D. sikkimensis* were processed by soaking in water (6, 12, and 24 h) and boiling (10, 20, and 30 min) and measured their effect on organoleptic, nutritional, phytochemical, and anti-nutritional factors of shoots. Most of the nutrients like amino acids, carbohydrates, protein, ash, fat, vitamin C, and vitamin E were decreased in processed shoots. On the other hand, an elevation in moisture (0.09%–4.91%) and starch content (2.52%–27.61%) was shown in boiled shoots as compared to the fresh ones. A reduction in NDF and total phenolic content was observed after all the processing durations, while ADF reduced after soaking (1.20%–2.33%) but enhanced after boiling (13.25%–26.88%). Total phytosterols were also higher (2.54%–5.67%) in processed shoots of all three species. The anti-nutrient cyanogenic glycoside was largely depleted after boiling (75.76%–96.10%) followed by soaking (51.71%–86.59%) treatments. Upon aggregating all the characteristics, the duration of 20 min of boiling and 12 h of soaking was considered as most efficient and time-saving preliminary cooking treatments of shoots for innocuous consumption. Reduction in carbohydrate, protein, ash, fat, and vitamin C content after boiling and water soaking of *D. latiflorus* shoots was reported by Thounaojam et al. [28]. The dietary fibre components, viz, NDF and ADF were insignificantly altered during these processes, while starch content was increased by 42% after boiling of shoots. Soaking (12 h) and boiling (20 min) also affected the mineral composition in shoots of *Bambusa sps.* [45], where soaking treatment proved to be relatively apt because of retaining greater content of Mg (83–86%), P (80–95%), K (64–87%), and elevating Na, Ca, and S while un-affecting Cu and Zn content.

4 Fermentation

The age-old processing method of fermentation utilises microorganisms to preserve food for the long term. It involves the decomposition of complex carbohydrates with the activity of microorganisms and enzymes [46]. The most common trio of microorganisms are bacteria, moulds, and yeasts that are engaged in the fermentation of an extensive range of food items [47, 48]. This process enhances the nutrient value, wholesomeness, and absorbability of foods and is a healthy substitute for many toxic chemical preservatives [49]. Fermentation can be spontaneous or prompted and different types of fermentation can be used for different food materials [6].

Bamboo shoot fermentation is a traditional and popular processing method in the Northeastern region of India, Nepal, and Bhutan which allows them to preserve shoots for years [50]. They process shoots for households as well as for marketing purposes. Prominent species preferred for the process of fermentation include *Dendrocalamus sikkimensis, D. hamiltonii, D. strictus, Bambusa balcooa, B. tulda,* and *Melocana* *baccifera* depending on the availability in the region. Generally, three different types of fermented shoot products are processed in Manipur state (India), namely *soibum, soidon* and *soijin* by using two separate methods, viz, *Andro type* and *Kwatha type. Andro type* fermentation is done in earthen pots in which sliced edible shoots are pressed, covered tightly, and kept for 6–12 months under process. With increasing duration, the volume of content in the pot is reduced, so, fresh shoots are added at the top in between to keep the pot full during the whole process. On the other hand, in *Kwatha type,* a big bamboo basket is lined completely using leaves conventionally (plastic sheet is also used nowadays) while keeping the bottom perforated for exuding out the fermentation liquid. Sliced shoots are packed tightly to full capacity and wrapped from above, then pressed deeply by putting weights on the top, it is then left for 6–12 months for completion of the process. *Soijin* is the premature product of these fermentation practices, while *soibum* is the product of the complete process. Formulation of *soidon* is done using the tender apical portion of bamboo shoots, particularly *Cephalostachyum capitatum* and *Teinostachyum wightii* by longitudinally slicing them and fermenting them in earthen pots. In this process, fermentation is induced by adding juice from the already fermented shoots and is carried out for 5–6 days while stirring them regularly [51, 52]. Another fermentation form *mesu* is prepared in Sikkim (India), where the edible portion of juvenile bamboo shoots is chopped into small pieces, cleaned thoroughly with water, drained off, and hard-pressed into a bamboo-made cylindrical vessel, then covered with a lid to make it airtight. The vessel is positioned in an upside-down direction to clear out any exudate and kept for a week or two for fermentation under a natural anaerobic system [53].

Fermentation imparts a particular flavour (typically sour) and distinct aroma to bamboo shoots and the cuisines constituting them, which are attributed to certain aroma-active compounds. The most important aroma-active components found in bamboo shoots are acetic acid, (E,Z)-2,6-nonadienal, methional, p-cresol, 2-heptanol, linalool, and phenyl acetaldehyde [54]. Most abundant of these is *p*-Cresol which lent a barn-like odour to bamboo and is bio-transformed from tyrosine, a major free amino acid in bamboo shoots [55, 56].

The causal microorganisms of fermentation were revealed to be predominantly *Lactobacilli*, *Pediococci*, *Leuconostocs,* and *Enterococcus.* Upon characterisation through phenotypic properties combined with molecular techniques, certain strains of lactic acid bacteria were identified in conventionally fermented shoots (Table 2), viz*, Lactobacillus brevis, Lb. curvatus, Lb. plantarum, Pediococcus pentosaceus, Leuconostoc mesenteroides subsp. mesenteroides, Leuc. fallax, Leuc. lactis, Leuc. citreum,* and *Enterococcus durans* (53,57]. Eleven more bacterial strains were identified in fermented shoots by Sarangthem and Singh [58]; 4 at the species level, which were *Micrococcus luteus, Bacillus coagulans, B. licheniformis,* and *B. subtilis;* seven at genus level which includes a *Micrococcus* species and six *Bacillus* species. Sonar and Halami [60] characterised 11 strains of lactic acid bacteria from different forms of fermented bamboo shoots from various Indian states (Table 2), including *Lactobacillus sp.* (n = 2), *L. plantarum* (n = 3), and one each of *Lb. fermentum, Lactococcus* sp, *Lb. brevis, Lb curvatus, Leuconostoc sp, and Lb. xylosus.* The cultures were also investigated for their technological and functional properties. Different isolated representatives showed variation in their activities. The highest phytic acid disintegration ability was shown by *Lb. brevis*, highest protease activity and lipolytic activity were exhibited by *Lb. xylosus*. *Lb. plantarum* was the most common species found in the fermentation products, which also showed maximum cell hydrophobicity. These studies also indicated that most of the lactic acid bacteria showed putative probiotic and antagonistic quality against certain pathogenic bacteria. Along with that, they may also enhance the particular flavour, aroma, and texture of the fermented bamboo shoot products.

Besides above-discussed attributes, fermentation affects the nutritional composition, bioactive compounds, and the anti-nutrients in bamboo shoots (Table 1). Giri and Janmejoy [61] inspected the influence of fermentation and the period of process in bamboo shoots for organoleptic and nutritional properties and observed that the fermentation (20 days) of *Bambusa tulda* shoots (soibum) improved the polypeptides digestion, which led to an enhanced level of free amino acids, synthesis of

Table 2 Microorganisms characterised by various fermented forms of bamboo shoots

Sr. no	Bamboo species (fermented form)	Microorganisms	References
	Dendrocalamus hamiltonii Mesu (Kalimpong Market, Sikkim) Mesu (Gangtok Market)	*Lactobacillus plantarum* *Lactobacillus brevis* *Pediococcus pentosaceus*	[57]
	Mesu Soidon, Soibum Soijim	*Enterococcus durans* *Lactobacillus brevis* *Lactobacillus curvatus* *Lactobacillus plantarum* *Leuconostoc citreum Leuconostoc fallax* *Leuconostoc lactis* *Leuconostoc mesenteroides subsp. mesenteroides,* *Pediococcus pentosaceus,*	[53]
	Bambusa balcooa *Dendrocalamus hamiltonii*	*Bacillus sutilis* *Bacillus licheniformis* *Bacillus coagulans* *Micrococcus luteus*	[58]
	Dendrocalamus latiflorus	*Enterococcus faecium* *Lactobacillus plantarum* *Lactococcus lactis subsp. lactis*	[60]
	Soibum (Assam) Soidon (Manipur) Hecche (Arunachal Pradesh) Eup (Arunachal Pradesh) Hirring (Arunachal Pradesh)	*Lactobacillus brevis* *Lactobacillus fermentum* *Lactobacillus plantarum* *Lactococcus sp* *Lactobacillus curvatus* *Lactobacillus sp.* *Lactobacillus plantarum* *Leuconostoc sp.* *Lactobacillus xylosus* *Lactobacillus plantarum*	[59]

diacetyl acetoin, esters, and volatile phenols, which divulge a particular flavour to shoots. The free phenolic compounds were markedly released, while aspartic and ascorbic acids were almost diminished in soibum. With an increase in the duration of fermentation, the shoots were more preferred by people due to improved palatability, which also enhanced the volatile phenols and esters in the product but affected the other compounds. The nutritional quality of fermented shoots of *Dendrocalamus hamiltonii* was found to be superior over fresh shoots as they contain more protein (8.5 g/100 g) and fat (0.6 mg/l00g) compared to the latter (protein 3.9 g/100 g and fat 0.5 mg/l00g). People of Khasi tribe in Meghalaya use this fermented product as a condiment for preparing various local dishes [62]. Upon processing of *D. giganteus* shoots, enhancement in fibre content during fermentation and canning was observed. However, carbohydrates, ash, vitamins, and fat content were reduced in both treatments, and that is why it is best to consume fresh shoots [63].

The biochemical composition of soibum has been analysed and it was found to be distinctly rich in dietary fibre while low in lipids and deprived of trans-fatty acids [64]. Mineral elements such as Cl, Cu, K, Mn, and Na were detectable in considerable quantities. Fermentation further increased the acidity of shoots by bio-converting reducing sugars into acid until their complete exhaustion. Sarangthem and Singh [58] showed a considerable depletion in anti-nutrients, viz, phytates, saponins, alkaloids, and hydrogen cyanide (HCN) content after fermentation of sliced bamboo shoots. From fermentation exudates, 11 different strains of bacteria were isolated and the role of *Bacillus coagulans, B. licheniformis, B. subtilis,* and *Micrococcus luteus* was assessed in deprivation of HCN. Fermentation enhances the palatability of bamboo shoots and is considered among the most cost-effective and efficient processes to reduce anti-nutrient components.

Badwaik et al. [65] fermented the bamboo shoots in two batches where shoots were allowed to ferment anaerobically for 12 days at 32 °C for batch-1 or with the assistance of *Garcinia pedunculata* (1%) for batch-2. While studying their microbiological and physicochemical variations during the process at regular intervals of 48 h up to 12 days, they recorded a noticeable elevation in total phenolic content up to 255 mg/100 g and 239 mg/100 g for batch-1 and batch-2, respectively, as compared to fresh shoots (97.5 mg/100 g).

An enhancement in phenol content in shoots of four edible species was observed after fermentation by Nirmala et al. [39]. Fermentation also affected the shoots of *D. hamiltonii* by increasing the total phenols (4.3–17%), phytosterols (119%), iron (83%), and zinc content (200%), maintaining the manganese and copper elements efficiently, whereas caused reduction in vitamin C and E (37–38%), total ash (52%), water-soluble ash (55%), insoluble acid ash (31%), and pH value of shoots [43, 66]. The effectual maintenance of mineral content in fermented shoots of *B. bambos* and *B. balcooa* was also reported by Saini et al. [45]. Thounaojam et al. [28] reported an elevation of 21%, 52%, and 60% in NDF, ADF, and starch content while depletion in other nutrients, viz, carbohydrates, proteins, fats, and vitamin C content after fermentation in the shoots *of D. latiflorus.*

5 Pickling

Bamboo shoot pickles are a traditional delicacy in many parts of India and are prepared at the domestic as well as commercial levels by simple salting with or without adding condiments. Zheng et al. [67] analysed the effect of pickling on the nutrients and structure of bamboo shoots. Fresh shoots were washed, blanched in boiling water, split in half, and placed in low (8%) and high (20%) concentrations of brine. The samples were poured into earthen jars, sealed, and allowed for pickling fermentation at 10–25 °C for 3 months. The pickling process lent a softer texture to bamboo shoots, which owes to the reduction in protopectin content by converting them to water-soluble pectins and enhancing their level. A distinct turgor loss was observed in parenchymatous cells leading to the disintegration and collapsing of the cell wall structure. A total of 17 amino acids were detected in bamboo shoots, of which aspartic acid showed maximum reduction after pickling, trailed by alanine and glutamic acid, while an overall decrease in amino acid content was also recorded.

6 Brining, Canning, and Storage

Preservation of surplus fresh food using salt/brine and canning them is an ancient method to avoid food wastage and to avail those foods during off-seasons. Bamboo shoots are marketed and exported in canned form by many countries like Thailand, China, Japan, etc. The nutritional profile of marketed canned salted shoots of *Phyllostachys* species showed the occurrence of carbohydrates, proteins, fats, ash, dietary fibre, moisture, and vitamins like riboflavin, thiamine, and niacin [68]. Minerals were also present, where sodium content seemed to be highest as it was added purposely, followed by potassium, phosphorous, calcium, and copper. Upon examining the same species in canned form without salt, the only difference observed was a variation in sodium. Nirmala et al. [39] analysed the effect of canning on phenol content in young shoots of *Bambusa balcooa, B. tulda, Dendrocalamus giganteus,* and *D. hamiltonii*. They reported a reduction in total phenols by 76–93% upon canning where the highest depletion in content was observed in *D. hamiltonii* shoots. A decrease in total phytosterols by 10% brine treatment but an upsurge by treating with 5% brine was reported by Bajwa et al. [40]. Phenol was also depleted during brining (5 and 10%), where the maximum loss was 83% in 10% brine-treated *D. hamiltonii* shoots. In another study, Bajwa et al. [43] investigated the impact of salting (5%) on organoleptic properties and nutritional aspects of *D. hamiltonii* shoots and reported a reduction in carbohydrate, amino acid, protein, phenol, and cyanogenic content in 5% brine stored shoots. The cellulose, ADF, and phytosterol contents were elevated during brining. Moreover, brining also altered the colour of shoots from ivory white to light yellow and tasted from slightly acrid to a little salty, which improved the edible acceptability of shoots. The sensory quality of brined shoots was also reported to be improved by Thounaojam et al. [28], who also showed increased levels of ADF and NDF, while other nutrients were lowered upon storage in brine for one month (Table 1). Saini et al. [45] investigated variations in elemental mineral composition after storage for 6 months at 4 °C in brined solution (5%). Storage reduced the quantity of approximately all the macromineral elements (K, P, S, Si, Mg,), while a minimal effect was noted in the case of micromineral elements (Fe, Zn, Cu, Ni, Mn).

7 Drying

Drying or dehydration is one of the oldest methods of food processing and preservation by sufficiently lowering moisture content to a level where the activity of microorganisms is inhibited. The majority of microorganisms are unable to grow at water activity less than 0.88 [69–71]. Drying techniques render the food commodity in solid form and lighten its weight and volume, which makes food packaging, storage, and transportation easy, along with infusing different aromas and flavours into food [72].

Different approaches for processing bamboo shoots through drying were also among the traditionally implicated methods, which continued to be used with many improvised techniques (Table 3).

7.1 Sun Drying

Sun drying is a broadly practised traditional method of drying bulk-produced food by utilising the ultimate source energy i.e. sun until the advancement in mechanical dryers. When solar radiations fall on the surface of fresh crop, some portion is absorbed while some get reflected. The absorbed radiation vaporises the water content of the crop and a portion of it is lost to the atmosphere through radiation and to the surface through conduction. For sun drying, chopped/ sliced bamboo shoots are spread evenly on plates or clean clothes and kept in direct sunlight at temperatures 30–37 °C and dried till the moisture content is reduced below 10% [73, 74]. Sun drying took a long time of more than 100 h to reduce the moisture content of shoots of *Bambusa vulgaris* to 8.25% due to varying erratic drying and unmanageable weather conditions, which can also cause spoilage of bamboo shoots. The colour of the shoots changed significantly and became moderately hard as they require a puncture force of 7.5 to break sun-dried shoots. Although sun drying is considered an economical and energyless process, at larger scale quality of bamboo shoots, can be compromised, which is also challenging for establishing a viable enterprise [75].

Table 3 Bamboo shoot Drying techniques used by different workers

Sr no	Drying technique	Remarks	References
1	Comparison of superheated steam with low-temperature and high-temperature hot air drying	low- temperature drying (at 70 °C) provided the best colour in bamboo shoots (light colour) along with the elimination of the bitter taste	[85]
2	Hot air drying at 70 °C temp. with 0.2 m/s air velocity	Shrinkage of bamboo shoot parallel to their fibres is different from that occurring perpendicular to their fibres	[87]
3	A two-stage hybrid method of drying: hot airflow drying followed by vacuum freeze drying (AFD) and reversed process, i.e, vacuum freeze drying followed by hot airflow drying (FAD)	FD bamboo shoots were superior in terms of sensory, nutrition, and cell structure, with lesser energy consumption	[89]
4	Microwave-assisted hot air drying at different power levels	The colour and quality of dried bamboo shoot slices at higher power were deteriorated	[79]
5	Convection solar drying (CD), double-pass solar drying (DPSD) and open sun drying (OSD)	DPSD is economically and technically favourable for drying bamboo shoots while significantly reducing drying time	[93]
6	Osmotically dehydrated bamboo shoots dried by using three methods, viz, tray drying (TD), fluidised bed drying (FDB), and vacuum drying (VD)	Osmo-vacuum-dried shoots (OD–VD) treatment at 55 °C was best in terms of microstructure, rehydration, colour, and firmness	[22, 92]
7	Effect of hot air drying (HAD) and freeze drying (FD) on the physical quality	Porosity, firmness, colour, and rehydration ratio are well maintained in FD shoots with overall better quality	[83]
8	Effect of sun drying (SD), tray drying (TD), oven drying (OD), microwave drying (MWD), and freeze drying (FD) on physical characteristics	freeze drying produced a good quality product in terms of rehydration ratio, texture, and colour	[75]

7.2 Microwave Drying

Microwave drying is centred on the conversion of alternating electromagnetic field energy into thermal energy and is characterized by volumetric heating [76]. Drying through a microwave is an alternative technique because of the availability of even energy to the core of the foodstuff, space usage, aseptic conditions, saving of energy, and rapid starting and shutdown properties. It also lessens the duration of drying and prevents enzymatic degradation of food [77].

Bamboo shoots can be dried using a domestic microwave by placing sliced pieces in the centre tray and weighing the sample every 30 s after starting the process till there is no variation in the weight and moisture retention should be less than 10% in the shoots [78]. The influence of microwave power on drying time, drying rate, moisture content, moisture ratio, effective moisture diffusivity (D_{eff}), microstructure, and rehydration features was examined on bamboo shoots (*Bambusa vulgaris*) by Bal et al. [78–80] through microwave drying (power levels varied between 140 and 350 W). Drying of 250 g shoot slices took place in 40–135 min, which showed an apparent reduction in drying time compared to other methods. Or even microwave drying reduced the moisture content below 9% in just 420 s, accredited to high energy input, rapid penetration of microwave radiations, and forced eviction of gases [75, 81]. When microwave output power was enhanced, the D_{eff} (effective moisture diffusivity) values also elevated from 4.153×10^{-10} to 22.835×10^{-10} m^2/s and it was found to be correlated with moisture value. Moreover, as the level of power elevated from 140 to 350 W, the shoot samples become firmer owing to case hardening and a reduction of around 23% was reported in protein content. Correspondingly, water activity declined from 0.71 to 0.38, while the proportion of rehydration improved up to 280 W but decreased beyond 350 W of power. Scanning electron microscopic (SEM) study revealed alterations in the microstructure of shoots at a higher power level which showed blatant collapsing, shrinkage, and case hardening of the tissue. Microwave drying enhances certain browning compounds, as evident from browning index values and the colour of shoots deteriorated at high power [75, 79].

7.3 Oven Drying

The chopped bamboo shoots are dried at a constant temperature of 60 ± 0.5 °C in an oven by spreading them uniformly on the oven trays and the sample is weighed every hour and processed till its weight becomes constant [82] or they can be kept in the oven overnight at the same temperature. It took over 16 h to lower the moisture content of shoots of *B. vulgaris* to 8.41% in an oven. Oven-dried shoots attain yellowish colour and become hard, requiring a puncturing force of 8.4 N, which is less than microwave-dried shoots [75].

7.4 Tray Drying

Bamboo shoots were dried on an aluminium tray (1.05 m X 0.45 m) in cross-flow hot air with an airflow rate of 1.2–1.8 m/s at 70 ± 2 °C by evenly spreading the slices over the tray for 6 h or till the level of moisture came down to around 10%. The tray drying seems to be quite efficient in terms of duration, as in just 6 h moisture content of shoots reduced to 8.17%, but shoots became quite firm, requiring a puncture force of 8.34 to break tray-dried shoots. Upon rehydration, the firmness of shoots is less than fresh ones. Upon assessment of colour as per instrumental as well as visual observations, the lightness of tray-dried shoots was closer to fresh shoots, and they have higher values of yellow coordinates rather than red ones [75].

7.5 Hot Air Drying

For hot air drying (HAD), the sliced bamboo shoots are spread in a single layer uniformly on the drying tray and placed in a convective hot air dryer. The drying was performed for 2–4 h at constant temperatures of 50, 70, and 90 °C with a drying air velocity of 1.5 ± 0.1 ms^{-1}. The impact of drying on texture, microstructure, and change in colour of sliced shoots of *Dendrocalamus latiflorus* was examined to evaluate the overall quality of bamboo shoot slices. The firmness of rehydrated bamboo shoots was lesser after HAD (59–64%) compared to fresh shoots, which might correspond to a change in pectin content. HAD caused a lowering in protopectin content and enhanced water-soluble pectins of bamboo shoots [83]. As protopectins decompose at high temperatures during air drying and their solubilisation is promoted [84]. Upon analysing the microstructure, parenchyma cells of dried bamboo shoots by HAD changed visibly, which showed cell wall contraction, cell crumpled, an undistinguishable porous structure, and shaded boundaries amid cells. Those changes were more prominent with enhancement in drying temperature, with complete disappearance of porosity at 90 °C. Colour of these shoots also turned toward a yellow hue, which was considered non-enzymatic browning due to the Maillard reaction [83].

Hot air drying (low temperature and high temperature) was compared with superheated steam drying (120–160 °C) by Wongsakpairod [85] for drying kinetics and product quality of bamboo shoots. The preliminary boiling or blanching (employed to reduce the bitter taste of shoots) is refrained before superheated steam drying. The colour of shoots was darker when dried using superheated steam compared to hot air-dried and the lightest colour (least changed) was observed at 70 °C. Conventional convective hot air drying is also advantageous for lesser energy requirement, hassle-free handling of production conditions, and larger yields than other desiccation techniques. However, lots of limitations are there as this method causes very hard texture, intense browning, low rehydration capacity, and loss in nutritive content of shoots [86]. A linear correlation between moisture content and dimensionless volume change upon hot air drying of bamboo shoots was reported by Madamba [87].

7.6 Freeze Drying/Lyophilizing

Freeze drying happens when water is directly evaporated from ice by skipping the liquid phase, the process is called sublimation. The first step involves freezing of shoot sample in a deep freezer for at least 24 h and then putting them in a freeze drier at a pressure of 0.76 mbar and temperature of −49 °C under vacuum conditions [75].

Freeze-dried bamboo shoots maintained colour, hardness and even microstructure quite similar to that of fresh shoots. Upon observing the micrographics, parenchyma cells of freeze-dried bamboo shoots showed a regular honeycomb-like structure similar to fresh shoots with distinct boundaries present among cells with less tissue shrinkage. The smooth and thin cell walls enabled spongy, non-crisp, and porous texture, which also facilitated better rehydration capability to freeze-dried shoots. The firmness of shoots is accredited to the maintenance of pectic components, as a high amount of protopectin (8 mg/g) was retained in shoots which indicates less decomposition and prevents its conversion to a soluble form. The ratio of rehydration was higher in FD shoot samples at 25ºC as well as 100ºC in comparison to the rest of the drying treated samples. The colour of bamboo shoots is also maintained well after freeze drying as it showed the least value of ΔE (total colour difference) 9.25 from the fresh ones [67, 75]. As this process is performed at low temperature, it upholds nutrients and vitamins, inhibits microbiological action, and offers fine-quality product [88]. FD method provides a superior product which, in fact, is an energy expending and expensive technique, so, it could be applied to preserve quality bamboo shoot products at a commercial level in food industrialisation, but unsuitable for the rural and tribal sectors due to economic issues [86].

A two-stage fusion technique for dehydrating bamboo shoots to test the cost-effectiveness of the method was used [89]. So, to economise the FD process, bamboo shoots were dried first by A) hot air flow and subsequently by vacuum freeze drying and B) the reverse of the first process, then compared the two processing sequences for the usage of energy and physicochemical characters of shoots. The results showed that the sequence of drying in process ‘B’ provided a similar quality of dried shoots as obtained after freeze drying but at a significant economical cost.

7.7 *Osmotic Dehydration*

Osmotic dehydration is a drying method with minimised exposure of foodstuff to heat; is advantageous in averting colour variation caused by enzymatic oxidation and the loss of volatile constituents, while lowering the water activity, preventing the damage and acidity of material caused by the high temperature [90]. There are many beneficial aspects of water exclusion by the osmotic dehydration method, which may include the probability of improving the functional properties of food products, and enhancing the product’s overall quality after processing while saving energy. Osmotic dehydration also minimises the colour deterioration of plant-based food by enzymatic oxidative browning. Commonly used osmotic agents are sucrose, salt, or a combination of both. Salt is mainly used for vegetables and nonvegetarian products as the imparted salting effect is acceptable in these forms, while sucrose is used in the case of fruits for its candying impact. The standard terms for the osmotic dehydration of bamboo shoots (*Bambusa pallida*) ranged as 8.89–11.08% NaCl in 50°Brix sucrose solution, osmotic solution temperature at 34.09–44.54 °C and processing duration of 72.64–104.48 min to achieve properties that yield maximum water loss, sensory score and rehydration ratio and minimal solid gain during desiccation of the bamboo shoots [91]. Badwaik et al. [92] compared kinetics and associated characteristics for pretreated osmotic dehydrated bamboo shoots (treated with 50°B sucrose syrup and 10% salt at 40 °C and 90 min) after drying at 45, 55, and 65 °C, using three different methods, viz, tray drying, fluidised bed drying, and vacuum drying. The drying rate constantly increased with elevated temperature. Osmo–vacuum-dried shoot (OD–VD) showed a greater ratio of rehydration (highest at 55 °C) as well as higher firmness and shrinkage compared to other drying methods. The OD–VD process resulted in a comparatively lower value of lightness component on the surface (*L* value), while higher values of chromatic components of redness to greenness and blueness to yellowness (*a* and *b* values) compared to other drying methods. All the dried bamboo shoots experienced alteration in microstructure; however, the OD–VD treatment at 55 °C was found to be comparatively better for drying the osmotically dehydrated shoots.

7.8 Solar Drying

Two different solar drying methods, viz, typical cabinet-type natural convection solar drier (CD) and a forced convection double-pass solar drier (DPSD) were used for drying bamboo shoots [93]. Parameters like drying temperature, air velocity, relative humidity, insolation, and water vaporisation were recorded every hour during drying. The average relative humidity and drying temperatures in the drying chambers were 23.7%, 55.2 °C and 37.6%, 47.5 °C in DPSD and CD, respectively. An average of 670 Wm^{-2} radiation was implied during all running experiments. DSPD was observed to be the fastest drying process with a falling-rate duration of 7 h. The inclusive drying efficacy was 15.83% and 23.11% for CD and DPSD. Even though the assembling cost of DPSD was considerably higher than the CD, the drying costs per kg of bamboo shoots were significantly lesser (42.8%) by using DPSD as compared to CD, which makes DPSD economically and technically favourable for drying bamboo shoots indicating a significant reduction in duration of drying when compared to traditional drying. Preliminary work on cost-efficient solar drying was carried out by Sudhakar & Sharma [94], which suggested that an uninterrupted drying of shoots at a constant temperature of 40–75 °C can be achieved with solar dryer constituting phase change materials and latent heat storage.

Besides analysing the physical and kinetic effects of various drying techniques, the nutritional profile of dried bamboo shoots was also worked upon in different forms (Table 4). Muchtadi and Adawiyah [95] dried shoot of *Dendrocalamus asper* in a cabinet dryer for 7–8 h at 60 °C and compare the proximate composition with fresh bamboo shoots. A distinct loss of starch content (67.5%) and ascorbic acid (88.9%) was recorded, which might be due to the gelatinisation of starch during drying, whereas the un-stability of ascorbic acid at high temperature.

Vacuum freeze-drying method in three forms, viz, fresh, boiled (20 min), and soaked (24 h) shoots of *D. hamiltonii* was used by Santosh et al. [96] and found

Table 4 Nutrients, bioactive compounds, minerals, and cyanogenic content in bamboo shoots during different drying methods

Compound		Bamboo species	Fresh	Tray-dried	Sun-dried	Oven-dried	Microwave-dried	Freeze-dried
Moisture (g/100 g)		*Bambusa vulgaris*	9.44	8.17	8.25	8.41	8.54	8.35
		Dendrocalamus hamiltonii	–	–	–	3.50	–	–
Ash (g/100 g)		*B. vulgaris*	10.55	10.34	10.16	9.79	9.90	10.50
		D. hamiltonii	–	–	–	8.92	–	–
Protein (g/100 g)		*B. vulgaris*	31.58	25.30	28.54	26.32	21.04	30.47
		D. hamiltonii	–	–	–	9.61	–	36.03
Amino acid (g/100 g)		*D. hamiltonii*	–	–	–	–	–	24.22
Carbohydrates (g/100 g)		*D. hamiltonii*	–	–	–	9.80	–	21.47
Starch (g/100 g)		*D. hamiltonii*	–	–	–	12.25	–	6.11
Fat (g/100 g)		*B. vulgaris*	5.40	1.59	1.69	1.80	2.83	2.41
		D. hamiltonii	–	–	–	14.63	–	13.27
Crude Fibre (g/100 g)		*B. vulgaris*	6.8	6.56	6.67	6.54	6.34	6.71
Dietary Fibre (g/100 g)	NDF	*D. hamiltonii*	–	–	–	–	–	64.12
	ADF		–	–	–	–	–	14.81
	Lignin		–	–	–	–	–	5.50
	Cellulose		–	–	–	–	–	9.31
	Hemi–cellulose		–	–	–	–	–	53.78
Vitamin C (mg/100 g)		*B. vulgaris*	3.63	2.55	3.06	2.63	3.09	3.40
		D. hamiltonii	–	–	–	–	–	17.48
Vitamin E (mg/100 g)		*D. hamiltonii*	–	–	–	–	–	5.44
Phenols (mg /100 g)		*B. vulgaris*	307.55	229.60	195.05	227.55	224.95	227.66

(continued)

Table 4 (continued)

Compound		Bamboo species	Fresh	Tray-dried	Sun-dried	Oven-dried	Microwave-dried	Freeze-dried
		B. nutans				1930.66		
		D. giganteus				1927.29		
		D. hamiltonii	–	–	–	1934.54	–	5450.00
		D. latiflorus				1950.67		
Flavonoids (mg CE/100 g)		*B. vulgaris*	527.01	284.87	346.86	327.01	371.24	438.29
Phytosterols (mg/100 g)		*D. hamiltonii*	–	–	–	–	–	320.00
Cyanogenic glycosides (ppm)		*B. vulgaris*	93.23	5.82	4.98	4.82	4.67	6.58
		D. hamiltonii	–	–	–	–	–	3692.48
Minerals (mg /100 g)	Ca	*B. vulgaris*	198.15	132.94	148.26	150.53	130.78	160.00
		D. hamiltonii	–	–	–	170		116.33
	Mg	*B. vulgaris*	283.97	193.73	168.27	203.42	183.38	206.66
		D. hamiltonii	–	–	–	230		169.00
	P	*B. vulgaris*	387.81	327.62	387.45	300.22	315.72	327.74
		D. hamiltonii	–	–	–	590.00		507.67
	Na	*B. vulgaris*	119.31	41.33	38.26	71.87	100.24	94.39
		D. hamiltonii	–	–	–	20		11.00
	K	*B. vulgaris*	3676.80	3613.46	3166.24	3672.02	3617.65	3663.42
		D. hamiltonii	–	–	–	5050.00		4910.00
	S	*D. hamiltonii*	–	–	–	290.00	–	239.67
	Cl	*D. hamiltonii*	–	–	–	890.00	–	860.00
	Si	*D. hamiltonii*				190.00	–	189.00

(continued)

Table 4 (continued)

Compound		Bamboo species	Fresh	Tray-dried	Sun-dried	Oven-dried	Microwave-dried	Freeze-dried
	Fe	*B. vulgaris*	30.94	4.20	10.17	7.05	6.24	7.37
		D. hamiltonii	–	–	–	7.10	–	8.47
	Cu	*B. vulgaris*	2.01	1.54	1.35	1.79	1.83	1.86
		D. hamiltonii	–	–	–	2.10	–	2.68
	Mn	*B. vulgaris*	1.91	1.26	1.49	0.97	1.52	1.76
		D. hamiltonii	–	–	–		–	2.20
	Zn	*B. vulgaris*	7.84	7.01	6.30	7.14	6.26	7.13
		D. hamiltonii	–	–	–	8.9	–	8.20
	Ni	*D. hamiltonii*	–	–	–	0.7	–	1.53
	Se (μg/100 g)	*B. vulgaris*	3.39	2.95	2.48	2.70	2.58	3.18

NDF—neutral detergent fibre, ADF—acid detergent fibre
Sources [40, 74, 96, 97]

Table 5 Bamboo shoot's fortified products

Sr no	Bamboo species/ form	Fortified product	Effect on product	References
1	*Dendrocalamus strictus*	Fritters (Pakora)	Increased crude fat and total ash	[109]
2	*Bambusa bambos* *B. tulda* *D. strictus* *D. asper*	Pickles, nuggets, crackers	Enhanced flavour and nutritional value	[110]
3	*D. hamiltonii*	Candy, Chutney, Chukh, Nuggets, Crackers	Good taste and better nutritional value, Crackers being the most acceptable product	[112]
4	*D. asper*	Bamboo shoot flour	Rich source of fibre and starch	[113]
5	Bamboo shoot dietary fibre	Fortified frozen dough	Increased viscoelasticity, extensibility, and plasticity; improved processing properties of frozen dough	[114]
6	Bamboo shoot dietary fibre	Fortified milk pudding	Improved rheological and textural properties of milk pudding	[115]
7	*D. hamiltonii*	Bamboo shoot cookies	Increase in nutrients, minerals, and bioactive compounds; cookies fortified with boiled freeze-dried shoots showed higher acceptability	[96, 97]
8	*D. hamiltonii*	Crispy salted snacks (Namkeen)	Sensory attributes, bioactive components and antioxidant activity improved with the best results in boiled bamboo shoots fortified Namkeen	[41]

that the fresh freeze-dried shoots contained the highest amount of amino acids (24.22 g/100 g), proteins (36.03 g/100 g), carbohydrates (21.47 g/100 g), fats (13.27 g/100 g), vitamin C (17.48 mg/100 g), vitamin E (5.44 mg/100 g), phenols (5.45 g/100 g), phytosterols (320 mg/100 g), and dietary fibres, while the boiled freeze-dried shoots showed lowest cyanogenic glycoside content (219.54 mg/kg) among the three forms. Mineral elements were also immensely amounted (mg/100 g d.w.) in the freeze-dried shoots in three forms which include K (4360–4910), Cl (616.67–860.00), P (488.00–520.33), Ca (116.33–277.67), S (239.67–288.00), Mg (169.00–181.33), Si (127.67–189.00), Na (11.00), Zn (8.20–9.60), Fe (6.67–8.47), Mn (1.03–6.47), Cu (2.25–2.68), Br (1.94–2.89), and Ni (1.23–1.80). In another study, Santosh et al. [97] also evaluated the nutritional profile in oven-dried shoots of

D. hamiltonii and found that the total content was lower than the freeze-dried shoots for all the nutrients (Table 4).

A study was conducted by Singhal et al. [74] on differently dried bamboo shoots using sun drying (SD), tray drying (TD), oven drying (OD), microwave drying (MWD), and freeze drying (FD) and analysed for variability in cyanogenic toxicity, nutritional composition and antioxidant capacity (Table 4). A decreasing trend was observed in all the macronutrients such as fat (47.59–70.56% reduction), protein (3.51–33.38% reduction), fibre (1.32–6.76% reduction), and vitamin C (6.34–29.76% reduction) during different drying procedures. High temperature/radiation treatments showed maximum reduction in the cyanogenic glycoside content compared to low-temperature processes like freeze drying. Nevertheless, freeze drying was best for the retention of nutrients as compared to high-heat drying. Therefore, it is suggested to prefer freeze-drying technology for long-term storage of bamboo, which could be promoted as a supplement in cookeries or as a medicinal powder.

8 High-Pressure Processing

High-pressure processing (HPP) also known as High hydrostatic pressure (HHP) or as Ultra-high pressure (UHP) is a fast-evolving non-thermal processing technique, which extends the shelf life of food as well as minimises the deterioration of heat-sensitive food constituents by destroying pathogenic microbes in foods at pressures ranging from 100 to 1000 MPa at room or lower temperature [98–101]. Unlike in thermal processes, HPP can maintain the temperature of food at a uniform temperature throughout the procedure because the transmittance of pressure is instantaneous and homogenous to the whole of the food for any amount or structure [102, 103]. As covalent bonds are not disrupted at high pressure, the impact of this pressure-based process on the characteristics of food is positive, which ensure quality food product in terms of colour, texture, shape and even flavour and nutritional characteristics of fresh food are retained well [104–106]. Packed food is processed using HPP for the purpose of sterilisation, altered enzymatic activity, and modification of matter by hastening or slowing physical and chemical reactions [107, 108].

HPP is widely in practice for the last two decades for various foods and is also attempted for the quality evaluation of bamboo shoots through 15 days of the storage period at room temperature by Li et al. [24]. Bamboo shoots were vacuum packed in plastic packaging materials of size 15 cm × 25 cm and thickness 0.06 mm and subjected to HPP ranging from 200 to 400 MPa for 5–15 min at 25 °C temperature. It was observed that the bamboo shoots processed for 10 min at 300 MPa showed the best quality upon storage. The weight loss and titratable acidity in these samples were minimally enhanced during storage, from 0% and 0.1317 g kg^{-1} to 0.67% and 0.2793 g kg^{-1}, respectively. The sensory acceptability, colour, and respiratory intensity of the bamboo shoots were considerably maintained with values of 7.55, 77.65, and 25.39 mg CO_2 kg^{-1} h^{-1} respectively. In terms of firmness, the pressure of

400 MPa for 15 min was found best as the shoots were comparatively softer, requiring force 51.15 N with low microbiological content of 84.6 CFU g^{-1}. The activity of peroxidase (POD) and polyphenol oxidase (PPO) in processed bamboo shoots were also inhibited significantly, which indicates HPP can be preferred for preserving the quality of bamboo shoots while storing at room temperature for up to 15 days.

9 Fortification

Besides the conventional processing for direct consumption, various products of bamboo shoots are also used to fortify different recipes for value addition. Nutritional and sensory qualities of food, viz, pakora and vegetables fortified with shoots of *Dendrocalamus strictus* were examined by Pokhariya and Awasthi [109]. On the basis of organoleptic qualities, the overall acceptability of pakora was higher compared to vegetables as it scored better on a nine-point Hedonic Scale for appearance, colour, texture/mouth feel, taste, flavour, etc. Also, the nutritional composition of pakora showed better results for crude protein, fat, and energy values (5.09 g/100 g, 26.11 g/100 g, 334 kcal/l00g f.w, respectively) as compared to bamboo shoot vegetable (3.13 g/100 g, 10.51 g/100 g, 160 kcal/l00g f.w, respectively). This might be the result due to deep frying of pakora. Conversely, crude fibre and total ash content were found to be higher in bamboo shoot-fortified vegetables than in pakora.

Value addition products like pickles, nuggets, chutney, chukh, candy, and crackers have been produced by using the shoots of *D. hamiltonii* and *D. strictus* and evaluated for organoleptic properties, chemical changes and shelf life [110, 111]. The prepared products showed nutritional richness as well as satisfactory organoleptic values and maintained quality in terms of texture and taste during storage. Thus, the value addition of bamboo shoots in various palatable products could enhance the usage of bamboo resources which made them efficient for elevating market perspective as innovative bamboo shoot products, along with providing income resources to the local population.

The traditional processing methods for bamboo shoots as a food resource in Nagaland state of North East India were documented by Kithan et al. [112]. They perceived that majorly six species of bamboo were processed for preparing culinary products like pickles, rhuchak (crushed shoots fermented naturally and used for the whole year), voyen (boiled shoots fried with other components, also roasted and sold in market), ruchu (fresh shoots crushed and extracted juice is fermented which impart a vinegar-like flavour), ruchon/rhuyen (shoos fermented for 5–6 days then the semi-fermented product is sun-dried for 2–3 days, packed in polybags and stored for 1–2 years) in Nagaland.

The application of young bamboo culm flour of *Dendrocalamus asper* in food products and their physicochemical and technical properties has been investigated [113]. Three fractions (F) of Young culms i.e, top (T), middle (M), and bottom (B) were desiccated, powdered, sieved, and divided into two separate particle sizes: F1 (diameter $>$ 0.425 mm) and F2 (diameter $\leq$ 0.425 mm), a total of six samples were prepared: TF1, TF2, MF1, MF2, BF1, and BF2. The proximate constituents of flours were significantly different with protein, ash, and lipid contents below 2%, whereas high fibre (67–79 g/100 g) and starch (6–16 g/100 g) were present. The flours from the bottom fractions displayed a considerably high water absorption index and water solubility index as compared to the rest of the samples. Both F1 and F2 flours from all three parts showed a yellowish-white colour on colour parameters where F1 was clearer than F2. The study opened new perspectives for the young bamboo culm flour incorporation in food as a rich source of fibre and starch especially.

Zhang et al. [114] studied various parameters of bamboo shoot dietary fibre (BSDF) incorporated in frozen dough and found that the BSDF could considerably ($P < 0.05$) expand the extensibility and viscoelasticity after thawing of frozen dough in a dose-dependent manner. The freezable water content and thermal stability of frozen dough were shown to be up-surged through differential scanning calorimetry analysis after the fortification of BSDF. An adequate quantity (< 0.1%) of BSDF in dough might deplete the bound water content significantly ($P < 0.05$) as analysed by low-field nuclear magnetic resonance (LNMR), but a raise in free water and loosely bound water was observed. Moreover, it showed arranged gluten and starch granule network in frozen dough. The authors suggested the BSDF as an innovative quality improver to fortify frozen dough. Furthermore, fortifying milk pudding with 2 g BSDF/100 g maximised the gumminess, viscosity, and hardness while reducing the cohesiveness of the resultant fluid as studied by Zheng et al. [115]. The addition of BSDF also altered the microstructure of the composite by increasing the accumulation of constituent particles and leading to more compaction due to increased cohesiveness between milk pudding and BSDF. Besides these, bamboo shoots powder, or fermented products were reported to improve the quality of cookies and pork pickles, respectively [116–118].

The use of freeze-dried and oven-dried powder of *D. hamiltonii* shoots for fortification of biscuits was reported to increase the level of nutrients, minerals, and bioactive compounds in the fortified biscuits as compared to control biscuits [96, 97]. The fresh freeze-dried fortified biscuits were found to be superior for overall nutrition with amino acids (0.30 g/100 g), proteins (1.27 g/100 g), carbohydrates (20.45 g/100 g), phenols (0.22 g/100 g), phytosterol (0.18 g/100 g), NDF (62.44 g/100 g), and ADF (5.16 g/100 g), whereas boiled shoot (20 min) fortified biscuits has the minimum level of anti-nutrients (5.98 mg/kg); mineral content such as K, P, S, Ca, Na, Fe, Zn, and Mn were also improved in fortified biscuits compared to control. Due to better organoleptic properties, the biscuits fortified with boiled freeze-dried shoots showed higher acceptability compared to others.

Santosh et al. [41] fortified crispy salted snacks (Namkeen) with different forms of bamboo shoots (*D. hamiltonii*), viz, fresh, boiled (20 min), and soaked (24 h) and evaluated the functional properties control as well as fortified products. It was found that the addition of bamboo shoots considerably improved antioxidant activity (2100.95 μg/ml, IC50 of DPPH) as compared to the control namkeen (2824.24 μg/ml, IC50 of DPPH). A significant enhancement in phenol (0.20 g/100 g), phytosterol (0.22 g/100 g), and dietary fibre content in fortified boiled bamboo shoots where sensory attributes were most favoured in 20 min boiled bamboo shoot-fortified namkeen. It is considered that bamboo shoots have a vast potential to be used as an additive that could play an imperative role in improving the quality in terms of health promotion and palatability of fortified products.

10 Conclusion

Bamboo shoots can be eaten fresh (edible species lacking acridity), but most of the species need processing prior to consumption so as to detoxify them from the anti-nutrients, especially cyanogenic glycosides; and to enhance their short shelf life (2–3 days post-harvest) which is usually influenced by physicochemical factors along with microbial and enzymatic activities. After harvesting, they are minimally processed by removing inedible protective sheaths and hard base as well as tip, then sliced or chopped as per requirement. Boiling, water soaking, fermentation, and open sun drying are conventional practices that can remove the acridity and anti-nutrients effectively, of which boiling is most effective instantly (20–30 min) making shoots palatable, while soaking is a more economical and energy-saving process. Various traditional ways of fermentation are available which are very effective for long-term storage of shoots up to a few months to years while imparting the probiotics character to shoots naturally. These techniques also maintain an adequate nutritional profile and make shoots more palatable with improved texture, aroma, and flavour to be used in various recipes. Along with traditional open sun drying, a lot of new drying techniques have been developed, including different drying methods, viz, double-pass and convection solar drying, microwave drying, oven drying, vacuum drying, osmotic dehydration, and lyophilisation. Upon evaluating their physicochemical properties, freeze-dried bamboo shoots were considered best in terms of texture, colour, rehydration ratio, porosity, and retention of nutrients and functional compounds due to low-temperature treatment. Brining and canning are among popular processes which favour the long-term preservation of shoots while retaining vitamins, minerals, and macronutrients. Pressure-mediated technique at room temperature has also imparted better sensory qualities while storing bamboo shoots. It is observed that low-temperature treatments provide better quality bamboo shoots in terms of physical as well as biochemical profile, as heat might damage the microstructure and chemical configuration, which compromises the overall quality of shoots. Besides processing shoots for direct consumption, various methods are also used to fortify shoots in different recipes for value addition which elevates the nutritional base of those products. By integrating the knowledge of conventional and modern processing and preservation techniques for bamboo shoots, wastage can be minimised while creating resilient food systems and its prospective monetary perspective can also be explored. Efforts can be further made to develop economic and efficient techniques which save energy while providing the best quality products which can be produced at the domestic level enterprises to support rural populations of the developing world.

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Fermented Bamboo Shoots: A Potential Source of Nutritional and Health Supplements

Babita Joshi, Aribam Indira, Santosh Oinam, Ashwani Koul, and Nirmala Chongtham

Abstract Juvenile bamboo shoots have long been a part of the traditional food and medicinal systems of many countries, particularly in south-east Asia, where it shows the wide distribution and natural abundance. Recent reports and studies have transformed bamboo shoots from a traditional delicacy to health food, as they are proven to be a rich source of protein, carbohydrates, minerals, fibre and bioactive compounds and are low in fat and sugars. The nutritional richness and scientific validation of traditional health benefits make them an important commodity as nutraceuticals and boost nutritional security. With about 149 species, India has rich bamboo resources, with *Bambusa* and *Dendrocalamus* as major edible genera. However, their full potential in the food and pharmaceutical industry is still untapped due to a lack of appropriate processing and preservation methods, as they have limited seasonal availability, short shelf-life, and the presence of anti-nutrients. Different processing and preservation methods have been traditionally practised in many countries and fermentation are one of the widely accepted methods of processing in many cultures, especially in northeastern states of India. Lactic acid bacteria (LAB) such as *Lactobacillus plantarum, L. brevis, L. fermentum, L. mesenteroides, Enterococcus durans* and *Streptococcus lactis* are predominant microflora involved in the fermentation of ethnic Himalayan bamboo shoots. They produce various aroma components, acids, bacteriocins and exopolysaccharides, which not only make bamboo shoots palatable in terms of flavour, aroma, texture and appearance but also extend their shelf life, enhance their safety and make them highly nutritious with many health benefits, such as a source of functional probiotic as well as a vitamin-B supplier to the human body. The present chapter aims to deliberate on the nutritional and medicinal properties of fermented bamboo shoots, and their potential in pharmaceutical and food processing industries for medicines, additives and health foods.

B. Joshi · A. Indira · S. Oinam · N. Chongtham (✉)
Department of Botany, Panjab University, Chandigarh 160014, India
e-mail: cnirmala10@gmail.com

A. Koul
Department of Biophysics, Panjab University, Chandigarh 160025, India

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1 Introduction

Bamboo is a strong, versatile and renewable woody-stemmed perennial species of grass that belongs to the family Poaceae. Although the use of bamboo shoots in daily cuisine continues to be an age-old traditional practice in many Asian cultures, the food potential of bamboo shoots remained little known all these years. Being low in fat, high in dietary fibre and rich in mineral content, bamboo shoots are an ideal healthy and nutritious vegetable. Fresh bamboo shoots are available for only short periods during monsoon season with limited shelf life and the presence of anti-nutrients are the limitations due to which processing is very essential before consumption and also for long-term storage [25]. Different ways of processing include soaking, boiling, drying and fermentation (Fig. 1). Fermentation is one of the ancient methods of food preservation and became widely accepted in many cultures due to its nutritional value and variety of sensory attributes [18]. During fermentation, the nutritive value of food is enhanced through the biosynthesis of vitamins, essential amino acids and degradation of anti-nutrients [17]. For centuries, human beings have made fermented food responding to the need to prolong the shelf life of perishable raw material. These raw materials which include vegetables, milk, fish, meat and cereals are prone to spoilage as a consequence of enzyme release and bacterial development. The fermentation process includes the biotransformation of substrates by bacteria, yeast and/or moulds that, among other compounds, yield unique and diverse flavours in fermented foods [101]. The foodstuff is subjected to the action of microorganisms or enzymes so that desirable biochemical changes cause significant modification to the food. Fermented foods are generally associated with a unique group of microflora, which enhances flavour, increases digestibility, improving nutritional and pharmacological values. Fermentation has the following effects (i) enrichment of the food through the development of a wide diversity of flavours, aromas and textures in food (ii) enrichment of food substrates biologically with vitamins, proteins, essential amino acids and essential fatty acids (iii) detoxification during the fermentation process (iv) preservation and (v) decrease in cooking time and fuel requirements. Fermented foods are important components of the diet as staples, adjuncts to staples, condiments and beverages and at present, a variety of foods are produced all over the world at household as well as industrial levels in both small-scale and large commercial enterprises. The health benefits of fermented foods are due to either increased activity of beneficial cultures or increased bioactivity of certain compounds during fermentation and the overall effect to provide physiological benefits over and above their potential to provide basic nutrition.

Fermented bamboo shoots are very popular in Asian countries. Various popular traditional fermented shoots include *Naw-mai-dong* in Thailand, *Suansun* in China and *Jiang-sung* in Taiwan (Table 1). Fermentation of bamboo shoots is associated

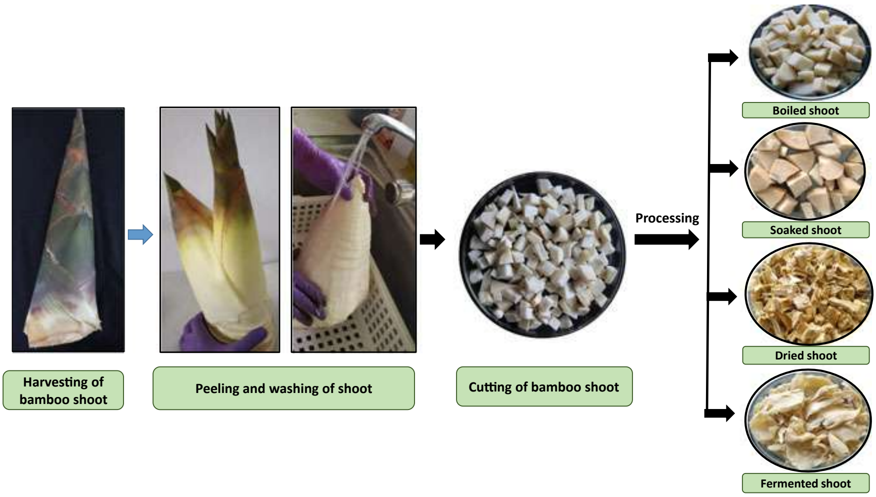

Fig. 1 Different ways of processing bamboo shoots, including boiling, drying, soaking and fermentation

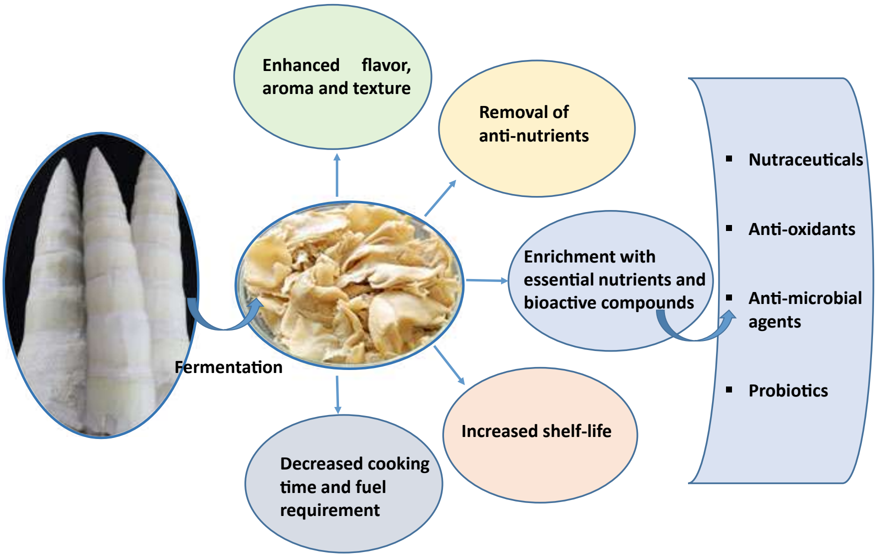

Fig. 2 Beneficial effects of bamboo shoot fermentation

with the action of microbes such as lactic acid bacteria, which makes the product acidic, easily digestible and more palatable in terms of flavour, aroma, texture and appearance [84]. In India, the fermentation of bamboo shoots has extensively been carried out in the northeastern states of Manipur, Meghalaya, Mizoram, Sikkim, etc., since ancient times (Table 1). These fermented bamboo shoots are consumed as curry, pickle or soup in different regional communities [22]. Associated health benefits of fermented bamboo shoots have recently attracted a lot of scientific interest in understanding the functionality of microbial diversity, the development of low-cost, functional foods and pharmaceutical products. The present chapter highlights the different traditional methods for fermenting bamboo shoot, their microbial populations and the effect of fermentation on nutritional, anti-nutritional, and bioactive components that contribute to desirable functional and pharmacological attributes.

2 Traditional Fermented Bamboo Shoots

A diverse bamboo resource is present worldwide, out of which juvenile shoots of about more than 200 species are used for consumption in various forms, but only less than 100 are cultivated for this purpose [29]. Major bamboo genera yielding edible shoots include *Bambusa, Chimnobambusa, Dendrocalamus, Fargesia, Gigantochloa, Phyllostachys, Schizostachyum* and *Yushania.* In India, juvenile shoots of more than 50 bamboo species are used for food purposes, with *Bambusa* and *Dendrocalamus* as major edible genera. Fresh shoots are consumed as a salad or stir-fries like other vegetables, mainly with different local ingredients. Fermented form is the other major way to consume bamboo shoots and is an important part of the local cuisine of various cultures of Asian countries. In Nepal, fermented bamboo shoots called '*tama*' are used with potatoes and beans to make '*Alu tama*' [81]. '*Jiang-sung*' (fermented bamboo shoots) is a widely consumed traditional food in Taiwan [20]. A similar fermented bamboo shoot consumed in Thailand is named *Naw-mai-dong* or *Nor-mai-dorng* [50]. The principle of bamboo shoot fermentation in all the states is similar with slight differences in the processing depending upon the state and ethnic group. The shoots are fermented whole, sliced, crushed-fermented moist and crushed-fermented dry.

Fermented slice: This is the most commonly used form of fermented bamboo shoots in all the states of India. Freshly harvested bamboo shoots are washed, hard sheaths removed and thinly sliced. They are packed and kept under pressure for a few months and allowed to ferment. The fermented shoots can be preserved for several months after the completion of the fermentation process. It is usually consumed after cooking with potatoes, colocasia corms, pumpkins, fish and meat. The peak season for processing fresh bamboo shoots using indigenous techniques is June–August.

Crushed-fermented moist: Cleaned tender shoots are crushed using mortar and pestle and packed in polythene bags or filled in plastic or glass bottles. The fermentation process is complete in 2–3 months and ready for consumption.

Crushed fermented dry: Fresh bamboo shoots are cleaned, washed, and crushed into small pieces and allowed to ferment for 3–7 days in airtight containers and then sun-dried. After proper drying, they are packed in polythene bags for further use.

Table 1 Traditional fermented bamboo shoot products

Country	Fermented shoot product	Bamboo species	Nature of product	Fermentation period	Uses	References
Nepal	*Mesu*	*B. tulda, D. hamiltonii, D. sikkimensis*	Solid, acidic, sour taste	7–15 days	Used as pickle	[90, 93, 94]
Taiwan	*Jiang-sun*	*D. latiflorus*	Solid, Sour, acidic	3 weeks	Used as a seasoning for fish, pork, chicken, and various other foods	[20]
Thailand	*Naw-mai-dong/ Nor-mai-dorng*	*Bambusa edulis*, *B. oldhamii*, *B. pallida*, *Dendrocalamus asper*, *D. latiflorus*, *Thyrsostachys siamensis*	Solid, Sour, acidic	3 days	Used as pickled bamboo shoot product	[50, 65]
India (Arunachal Pradesh)	*Anpo*	–	Solid, dark brown, sour, and slightly pungent	1 month	As vegetable	[92]
	Anpo-shianjita	–	Solid, dark brown, sour, and slightly pungent	1 month	As garnishing ingredient of vegetables	[92]
	Eeku	*B. balcooa, B. pallida D. hamiltonii, D. hookeri, D. giganteus, D. longispathus, M. baccifera*	Moist and creamish colour	Little longer than *Kupe*	Consumed raw or used to prepare curry with vegetables, meat and fish	[92]

(continued)

Table 1 (continued)

Country	Fermented shoot product	Bamboo species	Nature of product	Fermentation period	Uses	References
	Ekung/ Ekhung	*B. balcooa, B. tulda, D. giganteus, D. hamiltonii, Phyllostachys assamica*	Solid, sour, and acidic	1–3 months	Used in the preparation of local dishes, curry or soups	[94]
	Eup/ Eyup	*B. balcooa, B. tulda, D. giganteus, D. hamiltonii, P. Assamica*	Solid, sour, and acidic	1–3 months	Preparation of ethnic dishes	[90, 94]
	Heccha	*B. tulda, D. giganteus, P. Assamica*	Acidic, soft, sour	1–3 months	Preparation of ethnic dishes	[86]
	Hiklu/ Hikku	*B. balcooa, B. tulda, D. giganteus, D. hamiltonii, P. Assamica*	Sour, acidic	1–2 months	Preparation of traditional dishes	[94]
	Hirring	*B. tulda, D. giganteus, P. Assamica*	Solid, Sour, acidic taste	1–3 months	Preparation of curry	[90, 94]
	Iku	*B. balcooa, B. tulda, D. giganteus, D. hamiltonii, P. Assamica*	Solid, Sour, acidic	1–2 months	Preparation of traditional curry and soup	[61]
	Kupe	*B. balcooa, B. pallida D. hamiltonii, D. hookeri, D. giganteus, D. longispathus, M. baccifera*	Acidic, soft, sour	15–30 days	Consumed raw or delicious curry is made with vegetables, meat or fish	[92]
India (Assam)	*Khorisa*	*B. balcooa, D. giganteus, D. Hamiltonii*	Sun-dried solid mass	6–7 days	Preparation of traditional dishes and pickles	[8, 60]

(continued)

Table 1 (continued)

Country	Fermented shoot product	Bamboo species	Nature of product	Fermentation period	Uses	References
	Miya-mecheng	*B. balcooa, B.tulda, B.vulgaris*	Sour, acidic	5–6 days	Consumed with meat, fish, or vegetables	[60]
	Miyamikhri	*B. tulda, D. hamiltonii, M. bambusoides*	Wet, sour, acidic	4–5 days	Used in the preparation of traditional curry	[94]
	Tuairoi	*B. tulda, D. hamiltonii, M. bambusoides*	Dried, solid, and sour	6–7 days	Used in making traditional curry	[94]
	Tuaithur	*B. tulda, D. hamiltonii, M. bambusoides*	Wet, solid, and sour taste	6–7 days	Prepared as curry with dry fish or meat	[92, 94]
India (Manipur)	*Soibum*	*B. balcooa, B. tulda, D. hamiltonii, Melocanna bambusoides*	Wet, solid, sour taste	3–12 months	Used in the preparation of a special local dish called *Iromba* or cooked with fish and meat	[85]
	Soidon	*B. tulda, D. giganteus, M. bambusoides, Teinostachyum wightii*	Wet, solid, sour taste	3–7 days	Used in making *Iromba* or consumed as a vegetable with fish or meat	[49, 90, 94]
	Soijin	*B. balcooa, B. tulda, D. hamiltonii, M. bambusoides*	Liquid, acidic, sour taste	3–12 months	Used as a condiment and flavouring agent	[49, 61, 90, 94]
India (Meghalaya)	*Lung-seij*	*D. hamiltonii*	Moist solid mass	1–2 months	Used in the preparation of traditional curry	[90, 94]

(continued)

Table 1 (continued)

Country	Fermented shoot product	Bamboo species	Nature of product	Fermentation period	Uses	References
India (Mizoram)	*Tuai-um*	–	A slightly acidic and pungent smell	3–4 days	Preparation of ethnic side dish	[92]
India (Nagaland)	*Bastangapani*	*B. vulgaris*, *P. edulis*	Liquid , acidic, sour taste	2 weeks	Use as condiment and flavouring agent	[61, 94]
India (Sikkim)	*Mesu*	*B. tulda, D. hamiltonii, D. sikkimensis*	Solid, acidic, sour taste	7–15 days	Used as pickle	[90, 93, 94]
India (Tripura)	*Melye-amiley*	*M. baccifera, M. bambusoides*	Sour, acidic	4–5 days	Used in the preparation of traditional dishes	[99]
	Moiya-koshak and Midukeye	*M. baccifera, M. bambusoides*	Sour, acidic	2–3 days	Used in the preparation of traditional curry	[99]
	Moiya-pangsung	*M. baccifera, M. bambusoides*	Sour, acidic	2 days	Used in the preparation of traditional curry	[99]

– Not Defined

Table 2 Microflora in traditional fermented bamboo shoots

Fermented shoot product	Country	Microorganism present	References
Ekung	India	*L. plantarum, L.brevis, L. casei, L. fermentum, Tetragenococcus halophiles*	[49, 95]
Eup	India	*L. brevis, L. plantarum, L. xylosus, L. casei, L. fermentum, L. mesenteroides, L. fallax*	[90, 95]
Heccha	India	*L. plantarum, Leuconostoc sp.*	[90]
Hirring	India	*L. brevis, L. plantarum, L.curvatus, L. lactis*	[94]
Jiang-sun	Taiwan	*Enterococcus faecium, L. plantarum, Lactococcus lactis,*	[20, 95]
Khorisa	India	*E. durans, L. brevis, L. curvatus,, L. mesenteroides, L. fallax, L. lactis, L. citreum, P. pentosaceus*	[8, 79]
Lung-seij	India	*L. brevis, L. curvatus, L. mesenteroides, L. fallax, L. lactis, L. citreus*	[100]
Mesu	Nepal, India	*E. faecium, L. plantarum, L. lactis*	[20, 95]
Naw-maidong	Thailand	*Lactobacillus brevis, L buchneri., L. fermentum, L. plantarum, Leuconostoc sp., Pediococcus sp.*	[50]
Soibum	India	*L. brevis, L. plantarum, L. mesenteroides, L. fallax*	[90, 94]
Soidon	India	*L. brevis, L. lactis, L.curvatus, L. fallax*	[85]
Soidonmahi	India	*B. subtilis, B. cereus, B. pumilus, E. faecium, L. brevis, L. plantarum,*	[8]
Soijin	India	*L. brevis, L. lactis, L. fallax, L. mesenteroides*	[49, 90, 94]
Suansun	China	*Lactiplantibacillus fermentum, L. plantarum, L. amyloliquefaciens, L. brucei, L. brevis*	[39, 45]
Tabah bam shoot pickle	Indonesia	*L. brevis, L. plantarum*	[86]
Tuairoi	India	*B. firmus, B. circulans, B. subtilis, B. sphaericus, L. brevis, L. lactis, L. plantarum, Pediococcus pentosaceous*	[94]
Tuaithur	India	*Bacillus circulans, B. firmus, B. sphaericus, B. subtilis, L. brevis, L. curvatus, L. plantarum*	[94]

– Not Defined

Fermented whole shoots: Popular in Arunachal and Manipur, India, this form of fermented shoot requires more time for complete fermentation than the other forms. After harvesting and cleaning, the shoots are fermented in anaerobic conditions after proper packing and using heavy weights.

In addition to the above-fermented bamboo shoot products, there are many popular fermented bamboo shoot-based products such as *Mesu, Soibum, Soidon, Soijim, Ekung, Heccha, Eup, Hirring* and *Lung-seij*. Some tribes of Meghalaya, including *Khasi, Garo* and *Jaintia* preserved shoots by fermentation for more than one year. They immersed the chopped bamboo shoot in a container filled with water, which after fermentation develops a sour crunchy product [61]. Fermented products of Manipur include *Soibum, Soidon* and *Soijin* prepared by *Meetei* people of Manipur. These delicacies of Manipur are eaten as pickles and curry mixed with fermented fish. *Moiya-koshak* and *Medukeye* are the ethnic fermented products of Nagaland prepared by *Debbarma* and *Uchoi* tribes, and *Chakma* tribe, respectively [22]. Tribal people of Arunachal Pradesh ferment the locally available bamboo shoots to produce various products such as *Ekung, Heccha, Eup,* and *Hirring*. Processes involved in the preparation of some traditional bamboo shoot products have been discussed in this chapter.

(i) ***Naw-mai-dong***

Naw-mai-dong is an ethnic fermented bamboo shoot product of Thailand whose annual mass production takes place in the early rainy season; when bamboo shoots are generally abundant [50]. Bamboo shoots are sliced and pickled in bottles or jars that contain water rinsed from rice crops with or without salt. Then fermentation is carried out at ambient temperatures for at least three days which results in the formation of this ethnic pickled bamboo shoot product with pH values ranging from 4 to 5.5.

(ii) ***Jiang-sun***

Jiang-sun (fermented bamboo shoots) is a widely used traditional food in Taiwan. After defoliation of harvested bamboo shoots (*Dendrocalamus latiflorus*), they were chopped to mix with salt (NaCl), sugar and *Dochi* (fermented soybeans). The final concentration of the mixture is approximately 20–30 g kg^{-1} and layered in a bucket to allow fermentation. Fermentation continues for at least 3 weeks, but some producers maintain a fermentation time of 1 month or even longer [20].

(iii) ***Suansun***

It is a traditional Chinese fermented food made from fresh bamboo shoots under spontaneous fermentation conditions. It is widely popular in the southern region of China for its crunchy texture and unique nutritious flavours [45]. Fresh bamboo defoliated shoots after washing and cutting, are immersed into a tank containing mountain spring water or cold boiled water. The tank is sealed without adding salt and spices. Fermentation is carried out at ambient temperature for 15–30 days.

(iv) ***Mesu***

The word *Mesu* was derived from the Limboo language: *me* means young bamboo shoot while *su* means sour [91]. It is an ethnic fermented bamboo shoot product prepared from young tender edible shoots of *Bambusa tulda*, *D. hamiltonii*, and *D. sikkimensis* by people of Sikkim and Darjeeling, India, Nepal and Bhutan. The *Lepcha* calls it *Satit*. It is similar to *Lung-siej* of Meghalaya, *Soibum* and *Soidon* of Manipur and *Naw-mai-dong* of Thailand [91]. To prepare *Mesu*, finely chopped pieces of bamboo shoots along with leaves are tightly packed into a green hollow bamboo stem. Allow fermentation under anaerobic conditions for 7–15 days by turning the whole unit upside down to facilitate drainage during fermentation processes.

(v) ***Soidon***

Soidon is a fermented bamboo shoot prepared by *Meitei* inhabitants of Manipur, India from the tips of the matured bamboo shoot (*B. tulda*, *D. giganteus*, and *Melocanna bambusoides*, *Teinostachya wightii*). The apical meristem of bamboo shoots is taken after the removal of outer casings and lower portions of the shoot. Then, the whole tips are submerged in an earthen pot of water with *Soijin* or the sour liquid of the previous batch in 1:1 dilution. *Heibung* (*Garcinia pedunculata*) leaves may be added to the fermenting vessel to increase the flavour of *Soidon*. The fermentation period is of 3–7 days and can be stored for a year at room temperature in a closed container [13].

(vi) ***Soibum***

Soibum is a very popular traditional fermented bamboo shoot in Manipur, India especially prepared by *Meiteis* (inhabitants of Manipur), using the tender shoots of *B. tulda*, *B. balcona*, *B. pallida, D. giganteus*, *D. hamiltonii*, *M. bambusoides* [85]. It is whitish or pale yellow in colour, with a faint or pungent aroma and sour taste. The young shoots are harvested, the outer casing removed, the soft inner part extracted and washed and then cut into thin slices. It is a special delicacy of the *Meities* of Manipur eaten as pickles and curries with fermented fish called *Iromba* in the local language. Nongdam [61] has classified *Soibum* into four different forms based on different production approaches by communities of different Manipur localities given in Fig. 3.

(vii) ***Soijin***

It is a traditional sour liquid produced by the *Meitei* community of Bishnupur village of Manipur, India, as a starter for the indigenous fermentation of *Soidon* and can be used as a condiment in the preparation of local curries. For the preparation of a fresh batch of *Soijin*, rice-washed water is diluted at a 1:10 ratio and mixed with the acidic juice extract of *G. pedunculata* fruits. The preparation is then transferred to an earthen pot or a bamboo basket layered with a polythene sheet or a plastic container, to which the freshly prepared apical meristems of bamboo shoots are added for the submerged fermentation with intermittent stirring (3–5 times per day) with a bamboo

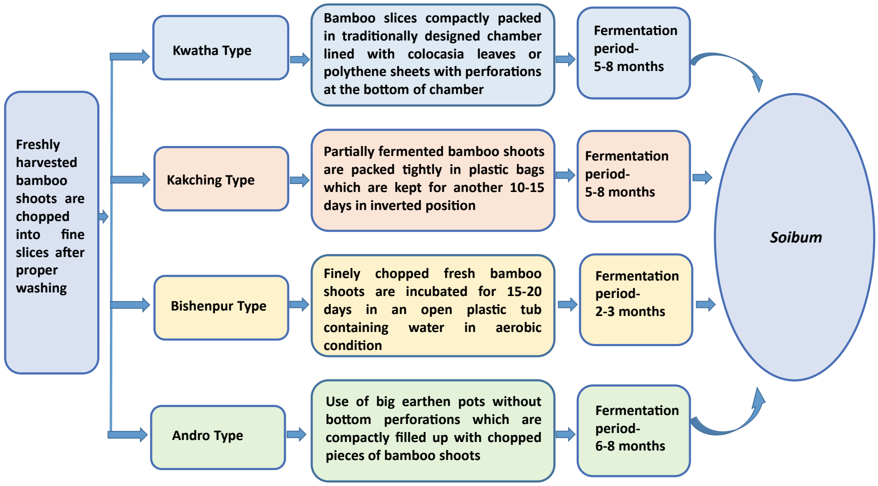

Fig. 3 Fermented shoot (*Soibum*) production approaches by different regional communities of Manipur, India

stick for aeration. Once *Soidon* fermentation is completed, the milky fermentation liquid developed during this fresh batch of fermentation is called *Soijin.* It can be kept as the master starter for a year and used after diluting with water [49].

(viii) ***Lung-siej***

In Meghalaya (India), fermented bamboo shoots made from young shoots of *D. hamiltonii* are known as *Lung-siej* or *Syrwa.* For its preparation, young bamboo shoots are harvested, culm sheaths removed, and the soft tender portion thoroughly washed with water. They are then cut into thin slices and pressed into either hollow bamboo internodes/cylinders closed at one end by the node or in glass bottles. When using bamboo cylinders, shoot slices are stuffed inside the cylinder, and the open end is closed with the help of leaves and sealed by tying up the rim with thread or a thin rope. The bamboo cylinders are then immersed in the nearby stream upside down for about 1–2 months for fermentation. The shoots should be consumed in 1–2 months. For using glass bottles as a container, the sliced shoots are pressed inside the glass bottle, and water is added until the shoots are submerged and the bottle is closed tightly. Shelf-life of fermented shoots is 12 months or more. Preparation of fermented shoots in bottles is preferred because it is much easier, convenient and has a longer shelf-life. *Lung-siej* is consumed by making curry with fish or meat.

(ix) ***Ekung***

Ekung is a fermented bamboo shoot food product, ethnic to *Nishi* tribe of Arunachal Pradesh, India. It is called by different names by different dialects, like *Iku* by *Adi* and *Hikku* by *Apatani* [94]. Young bamboo shoots are collected and cut into small pieces after the removal of the outer sheath. In the forest, near a water body, a pit is dug, and a bamboo basket containing chopped bamboo shoot pieces, covered with leaves is placed inside the pit. The basket is sealed after placing a heavy stone on the leaf surface to drain liquid exudates released during the fermentation. The fermentation is continuous for 1–3 months and the obtained product can be stored for a year in an air-tight container.

(x) ***Eup***

Eup is a dry fermented bamboo shoot prepared by *Nishi* tribe of Arunachal Pradesh, India. It is also popular with synonyms like *Nogom, Ipe* and *Hi* given by *Khampti Adi* and *Apatani* tribes of Arunachal Pradesh [94]. It is prepared by cutting bamboo shoots into small pieces and fermented-like *Ekung*. The whole container is incubated for 2–3 h after which the seal can be opened to bring out the fermented shoots, which are again chopped into small pieces and allowed to sun dry for another 7–10 days till the colour changes from white to chocolate brown. It is eaten as a curry along with meat, fruits, or vegetables. *Eup* can be kept for two years at room temperature.

(xi) ***Hirring***

Hirring is a fermented bamboo shoot product made by the *Apatani* tribe of Arunachal Pradesh, India [94]. For the preparation of *Hirring*, the topmost tender edible portions of young shoots are collected, outer leaf sheaths are removed and shoots are either cut longitudinally into small pieces or whole shoots are flattened by crushing and put into bamboo baskets lined with *Ekkam* (*Phrynium pubinerve*) leaves. The shoots are covered with leaves, sealed and the baskets are placed into a pit and weighed down with heavy stones and fermented for one to three months. The shelf life of *Hirring* is about two or three months. No salt is added during fermentation to any of these three products.

(xii) ***Kupe***

It is a traditional bamboo-based fermented food prepared by *Galo* tribes of Arunachal Pradesh, India [92]. Freshly harvested shoots are defoliated and cut to separate soft and tender shoot tips from the lower mature part. After washing the separated shoot tips, they are sliced into pieces and subjected to fermentation. The fermentation process is different in rural and urban areas. In rural villages, *Kupe* is prepared by putting whole or sliced bamboo shoot tips into a traditional bamboo basket (*Eegin*) lined with *Ekkam* leaves. The bamboo baskets are kept inside a pit near the stream after covering the top with leaves and a heavy weight to drain off excess water oozing out during fermentation. In urban and suburban areas, fermentation is carried out within a bamboo cylinder instead of a bamboo basket. Fermentation is done for 15–30 days and the product is kept for 1–2 years in an air-tight condition.

(xiii) ***Eeku***

Eeku is a moist and creamish colour fermented product also prepared by *Galo* tribes of Arunachal Pradesh from the mature lower portion after removing the top most tender shoot for *Kupe* preparation. Defoliated lower portions are cleaned with water and sliced and chopped into small pieces. The fermentation procedure is similar to *Kupe*, but a little longer than *Kupe* owing to more mature fibre in the raw material. It is consumed raw or used to prepare curry with vegetables, meat and fish.

(xiv) ***Eepe and Eep***

Eepe and *Eep* are sun-dried forms of *Kupe* and *Eeku*, respectively, used by people of *Galo* community of Arunachal Pradesh, India [92]. Both are brown in colour and pungent with enhanced shelf life owing to their dry nature. *Eepe* is comparatively darker than eep. *Kupe* and Eku are dried in the sun for 7–10 days to make *Kupe* and *Eeku,* respectively.

(xv) ***Anpo***

Anpo is a bamboo-based fermented food product prepared by the *Idu-Mishmi* tribe of Arunachal Pradesh, India [92]. Freshly harvested bamboo shoots, after removal of the sheath, are finely sliced in about 0.5–1 cm size. For fermentation sliced shoots are wrapped in wild colocasia leaf and kept airtight by pressing with heavy stones. It is allowed to ferment for about 1 month. *Apo* is consumed as a vegetable after cooking normally within 15 days.

(xvi) ***Anpo-shi-anjita***

Anpo-shi-anjita is another bamboo-based fermented food product prepared by the *Idu-Mishmi* tribe of Arunachal Pradesh. The method of preparation involves mixing of *Anpo* with crushed ginger and then the mixture is sun-dried till it is hard dry. The *Anpo-shi-anjita* being a dried product has elongated shelf life than *Anpo* and can be used for garnishing vegetable.

(xvii) ***Khorisa/Khoricha***

Khorisa/Khoricha is an ethnic fermented tender bamboo shoot product prepared by the Assamese community of India [60]. To prepare *Khorisa,* collected bamboo shoots are washed properly, peeled and pound into a *Dheki* (leg-operated pounder). This ground material along with some water, is then tightly packed in an earthen pot called *Koloh* and covered tightly with banana leaves to allow fermentation in anaerobic conditions for 6–7 days. In another method instead of earthen pots, hollow bamboo stems (*Chunga)* are used for preparing *Khorisa.* If using a hollow bamboo culm, the ground bamboo shoot is transferred into the bamboo culm. The mouth of *Chunga* is closed with a piece of wood or bamboo and kept in a pond or spring for 6–7 days to allow fermentation. For *dry Khorisa,* the fermented bamboo shoots are squeezed to take out the exudates and then sun-dried. *Khorisa* can be pickled; or added to vegetables, fish and meat.

(xviii) ***Miya-mecheng***

Miya-mecheng is a fermented product prepared by the *Garo* population of Assam, India [60]. It is prepared from young shoots of *B. balcooa, B. tulda*, and *B. vulgaris.* The freshly harvested bamboo shoots are peeled, washed, and sliced to form small pieces, which are then transferred into jars or containers with a small amount of water. The fermentation gets completed 5–6 days and the product can be stored for a long period of time due to extended shelf life. *Miya-mecheng* can be cooked with meat, fish, or vegetables to impart a particular aroma and flavour.

(xix) ***Moiya-koshak***

Moiya-koshak is an indigenous fermented bamboo shoot exclusively produced by *Debbarma* and *Uchoi* tribes of Tripura, India [99]. The synonym for it is *Midukeye* produced by *Chakma tribe*. The procedure for preparation involves wrapping young defoliated bamboo shoots in banana leaves, which provide good conditions for fermentation and protect the product from contaminants. It is then tied with a bamboo strip and placed over a raised platform, which is locally known as *Baka* (bamboo rake), to ferment in this condition for 2–3 days.

(xx) ***Melye-amiley***

It is an indigenous fermented food product exclusively prepared by *Chakma* tribes of Tripura, India [99]. The bamboo shoots of *M. baccifera* and *M. bambusoides* are used in the preparation of *Melye-amiley* through an almost similar procedure used to prepare *Moiya-koshak*. An additional step involves soaking chopped bamboo shoots for 2 days in a traditional earthen container having water.

(xxi) ***Moiya-pangsung***

It is also a fermented product of *M. baccifera* and *M. bambusoides* bamboo shoots exclusively prepared by *Uchoi* tribe of southern Tripura, India [99]. They ferment large pieces of bamboo shoots in a water-filled container for 2 nights and then the fermented product is sliced into smaller pieces before cooking.

(xxii) ***Tuai-um***

It is a traditional fermented food mainly prepared and eaten in the northern parts of Mizoram, India [92]. Finely chopped bamboo shoots pounded with *Sum* and *Suk* (wooden mortar and pestle) are wrapped in *Hnahthial* (*P. capitatum)* leaf and then kept over the fireplace for about 3 days. This pounded and fermented bamboo shoot is either sun-dried or dried over the fire for a longer period of storage. Dried *Tuai-um* soaked in hot water can be used to prepare a tasty side dish.

3 Microflora of Fermented Bamboo Shoots

Traditional acidic non-salted bamboo shoot fermentation mainly involved mixed lactic acid microflora like *Lactobacillus plantarum, L. brevis, L. casei, L. fermentum, L. curvatus, Leuconostoc mesenteroides, L. fallax* and *Tetragenococcus halophilus* [61]. LAB (Lactic Acid Bacteria) are gram-positive, non-spore-forming, acid-tolerant, cocci or rod shape non-motile bacteria, which produce lactic acid as a major fermentation product. Fermented bamboo shoots are a unique ecological niche for plenty of microorganisms where they can naturally coexist [49]. Vogel et al. [100] have reported ethnic Himalayan fermented bamboo shoot products including *Mesu, Soidon, Soibum* and *Soiiin* as a storehouse of *Enterococcus durans, L. brevis, L. plantarum, L. curvatus, Leuc. mesenteroides, Leuc. fallax, Leuc. lactis, Leuc. citreum* and

Pediococcus pentosaceus. Tamang and Tamang [90] studied 44 samples of *Ekung, Eup* and *Hirring* and reported LABs predominant in the fermented shoots including *L. plantarum, L. brevis, L. casei, L. fermentum, Lactococcus lactis* and *T. halophilus.* They also isolated 66 LAB strains from *Ekung* and *Eup* with the ability to grow in pH 3.9, 6.5% NaCl at 10% and 15 °C, and identified them as *L. plantarum.* The fermentation process to produce *Jiang-sun*, a traditional fermented food of Taiwan also involves *L. plantarum* as a main lactic acid bacterium [21]. In another study, Tamang and Sarkar [93] observed the presence of *L. plantarum, L brevis* and *P. pentosaceus* while investigating the Indian traditional fermented bamboo shoot product called *Mesu.* They reported the dominance of *P. pentosaceus* in the early stage of fermentation while at a later stage of fermentation on the 4th day, *L. brevis* reached its highest peak and in the last phase of fermentation, counts of *P. pentosaceus* and *L. brevis* were dramatically reduced with a predominantly high population of acid-tolerant *L. plantarum.*

The microbes involved in the fermentation determine the characteristic of the fermented bamboo shoot. LABs are interesting candidates to use as starter culture in bamboo shoot fermentation as they possess protective and functional properties such as enhancement of flavour and nutrients, biopreservation, shelf life and detoxification of anti-nutrients present in bamboo shoots [94]. Many authors have investigated their role in the fermentation of pickles because they provide a rapid acid accumulation in the raw material with the production of several organic acids, bacteriocins and exopolysaccharides (EPS) [30, 55, 93]. The production of organic acid (such as lactic acid and acetic acid) and other metabolites contributes to raising some characteristics like aroma, taste, texture, appearance, etc. *L. brevis, L. xylosus* and *L. plantarum* isolated from fermented bamboo shoots showed phytic acid degradation ability, protease, lipolytic activity, as well cell hydrophobicity [86]. All mentioned techno-functional attributes of microbes render fermented bamboo shoots and their products valuable commodities in terms of nutraceuticals and functional food.

4 Effects of Fermentation on Nutritional, Anti-Nutritional and Bioactive Components of Bamboo Shoots

Fresh juvenile shoots are delicious, crispy, and healthy due to the presence of a significant amount of nutrients and bioactive compounds [11, 15, 22, 32, 53, 98]. However, processing leads to physical and chemical changes accompanied by alterations in the nutritional and functional quality of bamboo shoots [9]. Several available reports indicate that fermentation leads to a minimal decrease in mineral elements and enhancement of bioactive compounds such as phenols, phytosterol and dietary fibre content in shoots [8, 25, 71, 75].

4.1 Effect of Fermentation on the Nutrient Content of Bamboo Shoots

Bamboo shoots are highly nutritious health-promoting vegetables that are consumed fresh as well in processed forms. Fresh shoots possess abundant macronutrients such as protein, essential amino acids, carbohydrates and fibres, along with a significant amount of micronutrients, including vitamins and minerals [22]. Fermentation is one of the popular processing techniques that improves the palatability of the shoot due to improved taste and texture. Due to the activity of associated microbes, it also causes a significant alteration in the macro and micronutrient content of bamboo shoots. Nutrient analysis of traditional fermented bamboo shoot products by various investigators has revealed them as a good reservoir of protein, carbohydrates, fibres, folic acid, ascorbic acid and minerals with low-fat content (Tables 3 and 4).

(i) Protein

Proteins are polymers of amino acids which play several metabolic and physiological functions, including the development and maintenance of cells, tissue and organs. Protein might have been degraded to amino acids due to the activities of fermenting microbes and their use in metabolic activities. This degradative process however brings out certain characteristics of flavour that are essential for the quality of the final product. Chongtham et al. [27] revealed that fermented shoots of *D. giganteus* have less protein content (2.57%) than fresh shoots (3.11%). Similarly, Badwaik et al. [8] reported a decline in the protein content of *B. balcooa* shoots after fermentation (2.56%) in comparison to fresh shoots (3.78%). Some studies also reported fermented shoots as a good source of digestible proteins due to increased soluble protein content in fermented shoots compared to fresh shoots. The increase in protein content could be attributed to the microbial synthesis of proteins from metabolic intermediates during their growth cycles [51]. Singhal et al. [84] reported a significant increase in the protein content from 2.98 to 3.49% in the 30-day fermented shoot sample of *B. vulgaris*. In another study by Agrahar-Murugkar and Subbulakshmi [2], fermented bamboo *Lung-siej* was found to have a better nutritive value in terms of its protein content (8.5%). An increase in the fermentation period of bamboo shoots was reported to increase the soluble protein content in the fermented products [77]. Devi and Singh [34] also showed an increase in the soluble protein content in fermented shoots from 3.1% to 7.8% and 8.1% on the third and fifth days of fermentation, respectively.

(ii) Amino acid

Free amino acids are considered essential macronutrient required for human metabolism and their profile in fermented bamboo shoots have not been extensively studied. Chongtham and Bisht [22] investigated the effect of fermentation in ten bamboo species and reported an increase in amino acid content in *B. balcooa, D. hamiltonii*, and *D. latiflorus* after fermentation. The amino acid content of freshly harvested and fermented shoots of *D. giganteus* revealed that there was a decreased amount of amino acid in fermented (2.005 g/100 g fresh weight (f.w.)) as compared

Table 3 Macronutrient analysis of fermented bamboo shoot products

Fermented shoot product	Protein (% DM)	Carbohydrate (% DM)	Fat (% DM)	Moisture (% DM)	Ash (% DM)	Fibre (% DM)	Food Value (kcal/100 g)	pH	References
Ekung	30.1	52.1	3.8	94.7	–	–	363.0	3.9	[94]
	24.6	17.3	2.80	51.6	15.7	12.8	–	4	[87]
	9.1	–	1.50	82.6	1.3	5.6	–	–	[12]
Eup	33.6	45.1	3.1	36.8	–	–	342.7	4.1	[94]
	19.5	9.5	2.24	31.1	14.4	6.7	–	3.9	[87]
	15.2	–	0.46	7.9	1.2	10.8	–	–	[12]
Hecche	27.5	18.6	3.35	44.6	6.2	20.8	–	4.2	[87]
Hirring	33.0	49.3	2.7	88.8			353.5	4.0	[94]
	25.6	25.8	2.14	32.9	12.9	19.7		4.3	[87]
Khorisa (Bhuluka)	–	–	–	–	–	9.9	–	3.01	[79]
Khorisa (Jati)	–	–	–	–	–	8.9	–	3.05	[79]
Khorisa (Kako)	–	–	–	–	–	11.1	–	3.01	[79]
Mesu	27.0	55.6	2.6	89.9			352.4	3.9	[94]
Soibum	36.3	47.2	3.2	92.0	–	–	362.8	3.9	[94]
	23.6	14.6	2.58	38.3	6.5	5.9	–	4.3	[87]
Soidon	37.2	46.6	3.1	92.2	–	–	363.1	4.2	[94]
	20.7	10.2	3.65	50.8	10.9	4.4	–	5.3	[87]

– Not Defined

Table 4 Micronutrient analysis of fermented bamboo shoot products in mg/100 g dry weight (d.w.)

Fermented shoot product	Vit. C	Vit. B_9	Vit. B_{12}	Ca	P	K	Na	Mg	Zn	Fe	Cu	Mn	References
Ekung	106	56.6	14.5	35.4	–	168	10.9	285	39.0	76.0	11.0	19.0	[87, 94]
Eup	17.4	16.8	6.70	76.9	–	181	3.4	288	31.2	90.0	38.0	119	[87, 94]
Hecche	6.70	17.9	7.60	–	–	–	2.2	358	0.60	55.0	9.0	48.0	[87]
Hirring	473	104	25.7	19.3	–	272	3.4	346	77.0	245	17.0	34.0	[87, 94]
Khorisa (Bhuluka)	3.80	–	–	2007	10.7	–	–	–	–	1.72	–	–	[79]
Khorisa (Jati)	2.50	–	–	1490	10.4	–	–	–	–	2.3	–	–	[79]
Khorisa (Kako)	4.90	–	–	1689	15.9	–	–	–	–	2.36	–	–	[79]
Mesu	–	–	–	7.9	–	282	2.8	–	–	–	–	–	[94]
Soibum	22.5	324	31.0	16.0	–	212	2.9	253	25.0	1.0	14.0	39.0	[87, 94]
Soidon	319	322	28.8	18.5	–	245	3.7	314	49.0	68.0	6.6	15.0	[87, 94]

– Not Defined

to freshly collected juvenile shoots (3.863 g/100 g f.w.) [27]. Fermentation of other food products reported an initial increase in amino acid content followed by a swift decline with continued fermentation [56]. The initial increase in amino acid concentration was attributed to microbial degradation of proteins, while a decrease in content during the latter stage of fermentation was due to the utilization of amino acids at a higher rate by microbes to support their own growth and multiplication.

(iii) Carbohydrate

Carbohydrates are the most abundant class of biomolecules, which play several essential physiological functions in the human body apart from being the chief source of readily available as well as a stored form of energy. In the study conducted by Singhal et al. [84] there was a significant reduction in the total carbohydrate content in the fermented shoots as total sugars decreased from 2.27 to 1.92% during the course of fermentation. A similar observation was reported by Badwaik et al. [8] as the content of sugar was found to keep on decreasing after fermentation. Chongtham et al. [27] analysed the shoots of *D. giganteus* bamboo and showed a reduction in the carbohydrate content after fermentation (1.504%) when compared to that of fresh shoots. *Soidon,* a traditional fermented shoot of *Phyllostachys humilis* showed a decrease in carbohydrate content (1.39–1.45%) when compared to raw shoots [34]. Sugars are the main source of energy and were used up by the growing microorganisms for metabolic activities. Thus, fermentation showed to reduce the amount of sugar to a great extent converting them to acid resulting in the rise of acidity [82].

(iv) Fat

Various studies proved that fermented shoot is an ideal nutraceutical food with low-fat content. Singhal et al. [84] reported a 90.2% reduction in the fat content of the fermented shoots of *B. vulgaris* when compared to fresh shoots. Fat content in fermented shoots of *D. giganteus* was reported to 18% decrease when compared to freshly harvested shoots [27]. Chongtham and Bisht [22] revealed fat content of fermented shoots in comparison to fresh shoots increased in *B. bambos, B. nutans, D. giganteus D. hamiltonii*, and *D. latiflorus* while it decreased in *B. balcooa B. tulda, D. membranaceus, D. sikkimensis* and *P. mannii.*

(v) Vitamin

Dietary intake of vitamins is essential for good health and proper development of the body [52]. Vitamin C has antioxidant activity and plays an important role in the biosynthesis of collagen and its deficiency leads to scurvy, widespread connective tissue weakness and capillary fragility [33]. A decreasing pattern in the vitamin C content upon fermentation (1.09%) was observed as compared to the juvenile shoots (3.28%) in *D. giganteus* [27]. The study conducted by Singhal et al. [84] observed a reduction in the vitamin C content by 35.7% in fermented *B. balcooa* shoots. Giri and Janmejay [38] have also reported a total loss of vitamin C during the fermentation of shoots of *B. tulda.* The reason for this could be the water-soluble nature of the vitamin due to which most of the vitamin C might have remained in the liquid portion of the substrate. Also, there is a production of ascorbate oxidase by microbes during fermentation, which catalyses the rapid degradation of ascorbic acid [1]. Chongtham et al. [27] reported a similar reducing trend in the case of vitamin E in fermented shoots for *D. giganteus* (0.21%). Vitamin E is a lipid-soluble vitamin with antioxidant properties and its reduction after fermentation could be due to the degradation of tocopherol isomers mainly α and γ tocopherols [48].

(vi) Mineral

Minerals are a major group of micronutrients regarded as essential for life's processes. They are classified as essential macro and micro minerals. A deficiency of these elements in a diet can lead to very diverse and indefinite metabolic abnormalities [58]. According to Saini et al. [71] fermentation is the best method among boiling, canning, and soaking to retain mineral content in shoots. Fermented *D. giganteus* shoots showed slight variation in trace elements such as cadmium, cobalt, manganese, nickel, and selenium with a considerable reduction in zinc content when compared to fresh shoots [27]. Bajwa et al. [10] reported an increase in sodium and magnesium content with a remarkable decrease in the potassium, phosphorous, chlorine, and copper content after fermentation. Calcium and phosphorous are important minerals required for the growth and maintenance of bones, and their content was decreased by 43.2% and 30.6%, respectively, in the fermented shoots of *B. vulgaris* when compared with fresh shoots [84]. The study also reported a decrease in potassium and magnesium content during fermentation, while a decrease in iron content was not significant. The content of certain minerals such as magnesium, sulphur, sodium, calcium and iron increased in fermented bamboo shoots might be due to the loss of dry matter as microbes degrade carbohydrates and protein [26]. Chongtham and Bisht [22] revealed that among micro-elements, iron was found maximum in fermented shoots. As bioavailability of iron is hampered due to complexes formed with dietary fibres, phytates and polyphenols but fermentation helps in the hydrolysis of these insoluble complexes and releases the free form of the mineral [37].

4.2 Effect of Fermentation on Anti-Nutrient Content of Bamboo Shoots

Fermentation by a host of microbes results not only in the enhancement of flavour, taste and aroma but also detoxification of anti-nutrients present in bamboo shoots. Anti-nutrients are defence-related secondary metabolites produced by plants that act against herbivores and pest attacks. Their presence in our diet gives an unpleasant taste and tends to interfere with the absorption and normal metabolism of nutrients. Moreover, a few anti-nutrient compounds when consumed in higher doses may also cause some serious health complications. Thus, it is essential to screen out and remove these compounds from food to make them more palatable with ensured biosafety. Anti-nutrients present in fresh bamboo shoots include cyanogenic glucosides, saponins, glucosinolates, oxalates and phytates [25]. Various processing techniques for the removal of anti-nutrients have been practised in Asian cultures for centuries and scientific studies about their impact have revealed fermentation as the best method for reducing the anti-nutrient content and improving the quality of bamboo shoots as well as increasing the shelf life of the shoots.

(i) **Cyanogenic glucoside**

A cyanogenic compound called taxiphyllin gives a bitter taste to young shoots, which can be reduced significantly by fermentation due to microbial activity. A decrease in cyanogenic glucoside results due to the breakdown of large sugar molecules during fermentation and rapid utilization of sugars by the microbes, which results in the formation of acids that catalyse the degradation of taxiphyllin into hydrogen cyanide [38]. The cyanogenic glucosides content in shoots of *B. vulgaris* reduced from 434.9 to 164.8 ppm in 30 days of fermentation [84]. Darmayanti et al. [30] reported a significant decrease in HCN content in the 13 days fermented pickle of bamboo shoot (*Gigantochloa nigrociliata*) from 37.80 ppm to 20.52 ppm. Rawat et al. [67] studied the effect of fermentation on cyanogenic glycoside content in ten bamboo species and the reduction of 74.34–87.28% cyanogen compared to the fresh shoots. Sonar et al. [87] reported the cyanogenic glycoside content in the traditionally prepared bamboo shoot products like *Hirring, Soibum, Soidon, Hecche, Ekung* and *Eup* which were within the limit (<10 ppm). Another study by Sarangthem and Singh [74] has also reported that fermentation decreases the cyanogen content in bamboo shoots.

(ii) **Phytate**

Phytates are saturated cyclic acids that form complexes with dietary minerals, especially iron calcium, copper and zinc and affect their bioavailability leading to cause their deficiency. The fermentation process for six months considerably reduced the phytate content of the bamboo shoots. Sarangthem and Singh [74] reported about a 38% reduction in the phytate content as compared to the fresh shoots after fermentation. Phytate content in fresh bamboo shoots of *D. hamiltonii* and *B. balcooa* was 35.95 mg/100 g and 30.67 mg/100 g f.w., which after fermentation reduced to 22.46 mg/100 g and 24.12 mg/100 g f.w., respectively. *L. plantarum* showed the highest percentage of phytic acid degradation in fermented bamboo shoots [90]. Also, Sonar and Halami [86] revealed that *L. brevis, L. xylosus* and *L. plantarum* isolated from fermented bamboo shoots showed phytic acid degradation ability.

(iii) **Glucosinolate**

Glucosinolates are thioesters consisting of sugar entities linked to an organic aglycone via an ester bond that imparts a specific bitter taste to several vegetables including bamboo and inhibit iodine uptake by the thyroid. Although glucosinolates have been reported to have adverse health effects, it is also reported to prevent breast and ovarian cancer [97]. Sharma [80] recorded a significant reduction in glucosinolate content of bamboo shoots of four bamboo species viz. *B. tulda*, *D. giganteus*, *D. latiflorus* and *D. membranaceous* after six months of fermentation as it ranged between 8.69 and 6.99 mg/100 g f.w. When compared with the fresh shoots (29.99–26.45 mg/100 g f.w.). fermentation of brassica has shown a similar reduced effect on glucosinolate content that was attributed to the breakdown of glucosinolate into glucose and sulphur moieties by microbial enzymes produced during fermentation [5].

(iv) **Oxalate**

Oxalates are salts formed from oxalic acid and forms bond with minerals such as calcium, magnesium, sodium, and potassium to interfere with the bioavailability of dietary nutrients thus reducing the nutritional value of consumed food. They are also reported to form insoluble calcium-oxalate crystals that play a role in the formation of kidney stones. Fresh bamboo shoots of different species have been investigated by various researchers and revealed that oxalate content in them ranged from 112.20 to 462 mg/100 g [25]. Fermentation of bamboo shoots was reported to reduce the oxalate content by 37–56% [103]. A similar reduction in oxalate content after fermentation has been observed in other leafy vegetables and the reduction was attributed to the hydrolytic action of enzymes produced during fermentation [41].

(v) **Saponin**

Saponins are glucosides with several functional groups attached to them and interfere with the membrane integrity of the cells and energy metabolism. They are toxic in high concentrations, impart a bitter taste to food and can affect nutrient absorption by inhibiting enzymes as well as by binding with nutrients such as zinc. Fermentation of *D. hamiltonii* and *B. balcooa* shoots for 6 months reduced total saponin content by 18–20% [74]. This reduction in saponin content may be attributed to the action of β-Glucosidase, which catalyses the structural degradation of saponins [54].

(vi)**Tannin**

Tannins are water-soluble polyphenolic compounds that interfere with protein digestibility mainly by forming large complexes through a network of cross-linkages. Fermentation causes a significant reduction of 87 to 98% in the tannin content of fresh bamboo shoots attributed to the hydrolytic action of the microbial enzymes produced during fermentation [80]. Fermentation of *D. latiflorus* caused a maximum reduction of tannin content by 93.76%. In contrast, Sarangthem and Singh [74] reported that fermentation caused an increase in the content of tannins as compared to fresh shoots.

4.3 Effect of Fermentation on Bioactive Compounds of Bamboo Shoots

Bioactive compounds are defined as components of food such as polyphenols, carotenoids, phytosterols, dietary fibres, alkaloids and others that have an impact on physiological or cellular activities in humans or animals upon consumption. Modern scientific research has established a strong correlation between our diet and health, as bioactive compound-rich foods have shown an active role in the prevention and cure of chronic diseases as well as the improvement of general health [22]. A large number of studies have demonstrated fresh bamboo shoots as a good source of bioactive compounds, more importantly, rich in phenols, phytosterols and dietary fibres. However, the amount of these bioactive compounds in shoots has been reported to improve with fermentation, which makes them good candidates for the development of new functional food with potential protective and preservative properties (Table 5).

(i) **Phenolic compound**

Phenolic compounds are the main class of secondary metabolites in plants and more than 8,000 compounds are reported, possessing at least an aromatic ring with one or more hydroxyl substituents [3, 68]. Most abundant plant phenolics include simple phenols, phenolic acids, flavonoids, tannins, stilbenes, and lignans [106]. They have been considered the most important natural antioxidants, primarily attributed to their H-donating hydroxyl (–OH) and redox properties that enable them to act as singlet oxygen quenchers, reducing agents and hydrogen donors [36]. Fresh bamboo shoots are a rich source of phenolic compounds and an increase in the phenolic content fermentation is attributed to the hydrolysis of the glycosidic bonds in the phenolic compounds due to microbial activity resulting in the liberation or formation of various bioactive compounds [22]. Singhal et al. [84] analysed the effect of fermentation on phenol and flavonoid content *of B. vulgaris* shoots and revealed that content increased with fermentation from 29.0 to 42 mg gallic acid equivalent (GAE)/100 g for phenol and from 49.69 to 59.43 mg *catechin equivalent* (CE)/100 g for flavonoids. Badwaik et al. [8] reported similar results in the total phenol content of *B. balcooa,* where a marked increase was observed from 97.5 mg/100 g in fresh shoots to 255 mg/100 g in fermented shoots. The phenolic content in traditional bamboo shoot products like *Hirring, Soibum, Soidon, Hecche, Ekung* and *Eup* ranged from 718.03 to 920.01 μg/g GAE/mL with the highest amount in *Eup* (920 μg/g) and lowest in *Soidon* (718.03 μg/g) [87]. The most important phenolic compounds found in the study were protocatechuic acid, p-hydroxybenzoic acid, and syringic acid.

(ii) **Dietary fibre**

Dietary fibre is the edible part of plants or analogous carbohydrates, which cannot be digested or absorbed in the small intestine, and as such, they proceed to the large intestine. They include polysaccharides, oligosaccharides, lignin, and associated plant substances, which are associated with many health benefits such as reducing the risk of cardiovascular diseases, hypertension, diabetes, obesity, cancer, and certain gastrointestinal disorders [44]. Dietary fibres are broadly classified into two forms soluble and insoluble dietary fibres, based on their capacity to dissolve in water [47]. Soluble fibres include gums, pectins, beta-glucans and oligosaccharides whereas insoluble dietary fibres constitute lignin, cellulose, hemicellulose, chitin, resistant starch and resistant dextrin. Fresh bamboo shoots are rich in dietary fibres including NDF, ADF, hemicellulose, cellulose and lignin [22]. Fermented bamboo shoots were found to be a good source of dietary fibre and its product like *Hecche* had 20% dietary fibre content [87]. Singh et al. [43] analysed various fermented samples of *Soibum* and recommended fermented shoots as a good source of dietary fibre due

Table 5 Total phenol, phytosterol and dietary fibre content in fresh and fermented bamboo shoots of various species

Bamboo species	Shoots	Total Phenolic content (mg GAE/100 g)	Phytosterol (mg/100 g d.w.)	NDF (g/100 g f.w.)	ADF (g/100 g f.w.)	Lignin (g/100 g f.w.)	Cellulose (g/100 g f.w.)	Hemicellulose (g/100 g f.w.)	References
B. balcooa	Fresh	362.36	127.24	6.07	0.51	0.30	0.21	5.56	[22, 66]
	Fermented	459.65	284.73	14.03	3.51	0.32	3.19	10.52	
	Fresh	97.50	–	–	–	–	–	–	[8]
	Fermented	255.00	–	–	–	–	–	–	
	Fresh	191.37	–	–	–	–	–	–	[24]
	Fermented	298.53	–	–	–	–	–	–	
B. bambos	Fresh	721.62	198.69	0.48	0.30	0.18	3.47	3.95	[22, 70]
	Fermented	746.50	275.29	2.80	0.95	1.85	3.77	6.57	
B. nutans	Fresh	558.96	181.59	5.34	1.17	0.78	0.39	4.17	[22, 70]
	Fermented	746.50	267.13	4.36	1.11	0.50	0.61	3.25	
B. tulda	Fresh	479.23	109.57	5.59	0.73	0.61	0.12	4.86	[22, 80]
	Fermented	898.39	352.66	10.22	4.62	1.50	3.12	5.60	
	Fresh	443.97	–	–	–	–	–	–	[24]
	Fermented	641.73	–	–	–	–	–	–	
B. vulgaris	Fresh	29.00	–	–	–	–	–	–	[84]
	Fermented	42.06	–	–	–	–	–	–	
D. giganteus	Fresh	347.27	–	–	–	–	–	–	[24]
	Fermented	891.33	–	–	–	–	–	–	
	Fresh	609.32	158.10	5.60	0.83	0.49	0.34	4.77	[22, 80]
	Fermented	1022.38	543.26	12.87	3.58	2.32	1.26	9.29	

(continued)

Table 5 (continued)

Bamboo species	Shoots	Total Phenolic content (mg GAE/100 g)	Phytosterol (mg/100 g d.w.)	NDF (g/100 g f.w.)	ADF (g/100 g f.w.)	Lignin (g/100 g f.w.)	Cellulose (g/100 g f.w.)	Hemicellulose (g/100 g f.w.)	References
D. hamiltonii	Fresh	678.56	131.73	4.78	0.94	0.38	0.56	3.84	[22, 66]
	Fermented	767.65	169.18	10.23	5.25	1.44	3.81	4.98	
	Fresh	505.93	–	–	–	–	–	–	[24]
	Fermented	745.56	–	–	–	–	–	–	
D. latiflorus	Fresh	659.11	89.90	6.95	0.62	0.47	0.15	6.33	[22, 80]
	Fermented	1027.24	234.06	11.66	5.04	1.02	4.02	6.62	
D. membranaceus	Fresh	596.67	178.00	5.33	1.93	0.37	1.56	3.40	[22, 80]
	Fermented	878.79	498.80	12.40	3.23	1.29	1.94	9.17	
D. sikkimensis	Fresh	450.29	122.08	4.66	0.93	0.51	0.42	3.73	[22, 70]
	Fermented	472.42	247.98	8.23	2.95	1.46	1.49	5.28	
P. manii	Fresh	382.23	264.49	5.72	1.41	0.17	1.24	4.31	[22, 66]
	Fermented	486.14	318.65	9.87	3.42	0.60	2.82	6.45	

– Not Defined

to results showing high fibre content (2.61 and 3.09%) in two samples. Chongtham et al. [27] studied the effect of fermentation on the different components of dietary fibre viz. NDF, ADF, lignin, cellulose and hemicellulose in *D. giganteus* shoots were revealed with increased content of NDF (4.18 g/100 g), ADF (3.28 g/100 g), lignin (1.39 g/100 g), hemicellulose (0.90 g/100 g) and cellulose (1.88 g/100 g) when compared with the fresh shoot. Bamboo dietary fibre developed by the fermentation method resulted in more than 50% hemicellulose content and has a water absorption index higher than most other dietary fibres, which makes them beneficial for human health [46]. Rohadi et al. [69] determined the effect of spontaneous fermentation and starter fermentation (using *L. plantarum*) on dietary fibre-related physical and chemical properties of yellow bamboo shoots (*B. vulgaris*). The results revealed that both spontaneous fermentation and fermentation by starters could improve several properties of the bamboo shoots flour. The flour produced by starter fermentation had a much higher food fibre increase than that of spontaneous fermentation with 73.79 ± 0.15%, 71.45 ± 0.17% and 2.34 ± 0.02% increase in total dietary fibre (TDF), insoluble dietary fibre (IDF) and soluble dietary fibre (SDF), respectively.

(iii) **Phytosterol**

Phytosterols or plant sterols are bioactive components with 28- or 29-carbon alcohols, which constitute the major part of the non-saponifiable fraction of lipids and resemble cholesterol in vertebrates in terms of both function and structure. A wide range of research reported the role of phytosterols in reducing serum low-density lipoprotein (LDL) cholesterol level, total blood cholesterol level, cardioprotective activity, antimicrobial and anti-cancerous activity as well as other beneficial health effects [57, 65, 72]. Bamboo shoots are known to contain significant deposits of phytosterols, which are further enhanced in fermented shoots due to microbial activity [22]. Predominant sterols in fermented bamboo shoots have been identified as β-sitosterol, campesterol, and stigmasterol [76]. Phytosterols content of *D. giganteus* shoots increased from 0.39% to 2.80% after fermentation [88]. Sarangthem and Singh [75] reported enhancement in the total phytosterol content of *B. balcooa*, *D. strictus* and *D. hamiltonii* due to the fermentation of fresh shoots. Sitosterols, the most widely distributed phytosterol, are found abundant in fermented shoots because of their easy microbiological conversion into androstadienedione that is an intermediate product in the synthesis of estrone [75]**.** Zheng et al. [107] analysed the total phytosterol content in bamboo shoot residue after solid-state fermentation at 33 °C for 5 days using an isolated *Aspergillus niger* CTBU and found elevated phytosterol content in the end product as compared to fresh shoot from 523 mg/100 g to 1,168 mg/100 g.

5 Health Benefits of Fermented Bamboo Shoots

Bamboo shoots have immense potential to be used as an important health food as they play a significant role in traditional Asian medicine. The usefulness of bamboo shoots as a health food has been recognized in the recent past due to the interests of various research groups promoting their nutritional values and health aspects. Fermented bamboo shoots being rich in bioactive compounds have tremendous health benefits like anti-cancer, antioxidant, anti-ageing, cardio-protective, weight loss, and probiotics [13, 83]. The fermentation process further improves the pharmacological value bamboo shoots of due to increased bioactive compounds and associated microflora that synthesize health-promoting components such as biologically active peptides, polysaccharides, and phenolic compounds. LAB isolated from fermented bamboo shoots has various technological and pharmacological properties such as acidifying capacity, antimicrobial activities, degradation of phytic acid and oligosaccharides, bile-salt tolerance and enzymatic activities [95]. Behera and Balaji [13] reported the role of *Suansun*, a traditional fermented bamboo shoot product of China, in lowering blood cholesterol and strengthening of the immune system. Several documented health benefits include their role as probiotics, antioxidant and antimicrobial agents.

5.1 Antioxidant Activity

The antioxidant properties refer to the ability to scavenge free radicals produced at the cellular level as a result of pollution, stress, wrong dietary habits, etc. The major components of bamboo shoots involved in an antioxidant defence system include vitamins C and E, phenolic compounds, and minerals such as selenium, copper, manganese, iron and zinc [23]. Fermentation results in increased bioactive compounds such as phenol and flavonoid content further improves antioxidant capacity indicating the potential of the fermented bamboo shoot to protect human health. Park and Jhon [62] found a significant relationship between antioxidant activity and phenolic content. In another study, thirty days of fermented shoot extract of *B. vulgaris* showed higher free radical scavenging activity as compared to fresh shoot shoots [84]. The fermented shoots reported free radical scavenging potential of 2.13, 5.76 and 6.24 μmol *trolox equivalents* (TE)/g as compared to 1.72, 5.71 and 5.82 μmol TE/g in fresh shoots when assessed by ferric reducing antioxidant power assay (FRAP), 2,2-diphenyl-1-picrylhydrazyl (DPPH) and Trolox equivalent antioxidant capacity (TEAC) assays respectively. The antioxidant activity of acetone and methanol extracts of fermented *D. hamiltonii* shoots investigated using hydrogen peroxide scavenging activity showed the presence of antioxidant substances in the methanol extract of fermented shoot indicated by 17.31% of scavenging activity at 10 mg/ml, whereas at the same concentration, acetone extract does not scavenge any free radicals [6]. Waikhom et al. [102] also noticed a good antioxidant potential in fermented shoots of *D. hamiltonii* species. Singh et al. [82] reported the antioxidant potential of *Soibum*, a traditional fermented bamboo shoot of Manipur. The methanolic extracts of different fermented bamboo shoot samples, including *Hirring, Soibum, Soidon, Hecche, Ekung* and *Eup* exhibited significant free radical scavenging activity ranging between 70.84 and 95.37% [87]. *Soibum* showed the strongest radical activity of more than 90%, while *Soidon* showed the lowest activity of 70.84%. Badwaik et al. [8] analysed the antioxidant activity of bamboo shoots in two batches of fermentation, batch-1 with natural anaerobic fermentation of bamboo shoots and the second batch having shoots mixed with pieces of *G. pedunculata.* They also reported increased antioxidant activity during fermentation with 49.20 and 55.35% in terms of DPPH free radical scavenging activity for the two batches of fermentation, respectively. Increased antioxidant activity during fermentation is attributed to biochemical changes that could promote the decomposition of dietary fibre and bounded polyphenols to release free phenolic compounds [89].

5.2 Probiotics

Probiotics are microbial cell components or microbial cell preparations that have a favourable influence on the host's health and well-being. They have associated antimicrobial activity with a positive influence on the digestive tract and immune system of humans. Functional effects of probiotic bacteria include the ability to tolerate bile salts and their adherence to the intestinal cell wall for colonization with the capacity to prevent pathogenic adherence or activation. Beneficial strains, which can be used as probiotics, mostly belong to the genera *Bifidobacterium* and *Lactobacillus* [13, 104]. Fermented bamboo shoots are rich in microbes like LAB, and species like *L. plantarum* and *L. brevis* that reflect their potential to be used as functional and healthy foods, as medicines, and as a source of bioactive compounds. Various lactic acid bacteria present in fermented bamboo shoots were reported to have putative probiotic as well as antagonistic properties against the selected pathogenic bacteria [90]. *L. plantarum* found very frequently in most fermented bamboo shoots, provide them with probiotic effects along with cholesterol-lowering feature [59]. *L. plantarum* along with *L. brevis* also exhibit high hydrophobicity, which indicates the ability of bacterial culture to adhere epithelial cell layer of the digestive tract for good colonization [43]. Do et al. [35] identified a novel exopolysaccharide generated from fermented bamboo shoot-isolated *L. fermentum* having molecular mass in the range of 10^4–6×10^6 Da. These exopolysaccharides exhibit good rheological properties, such as viscosity, emulsion stability, and gelling, as well as act as probiotics [63].

5.3 Antimicrobial Activity

Various antimicrobial studies of fermented bamboo shoots have shown great potential as a preservative, antibiotic and disinfectant in the food and pharmaceutical industry. Angeline et al. [6] investigated the antimicrobial activity of acetone and methanol extracts of fermented *D. hamiltonii* shoots against *Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa* and *Fusarium* sp. using well diffusion technique. The results showed that 10 mg/ml concentration of acetone extract has a zone of inhibition for S. *aureus, E. coli* and *P. aeruginosa* are 14 ± 1.73 mm, 13 ± 0 and 11.6 ± 0.57, respectively. Methanol extract at 10 mg/ml concentration showed a zone of inhibition only for *P. aeruginosa* with 10.6 ± 1.15 mm. *L. plantarum* in *Ekung* and *Soibum*, shows a mechanism of action by conferring antifungal and antimicrobial properties [14]. Maximum zone of inhibition was produced by *L. plantarum* against *L. monocytogenes* and followed by *L. brevis* against *L. innocua*. Alemu et al. [4] identified *E. faecalis* as one of the dominant LABs present in the fermented bamboo shoot item of Thailand and it displayed desirable bacteriocin activity by inhibiting food spoilage microorganism including *L. mesenteroides* and *L. sakei*. Likewise, Hata et al. [42] isolated an *E. faecalis* strain from fermented bamboo shoots and showed that it can produce bacteriocin and inhibited the growth of pathogenic bacteria. *Lactobacillus* isolated from the fermented bamboo shoot (*Khorisa*) had shown anti-bacterial activity against *S. aureus* [7]. The lactic acid bacteria such as *Lactiplantibacillus fermentum, L. plantarum, L. amyloliquefaciens, L. brucei,* and *L. brevis* are used in fermentation to improve the palatability of shoots, owing to volatile flavour substances, organic acids and bacteriocins production. Hartayanie et al. [40] reported LAB identified as *Lactobacilli* isolated from bamboo shoot pickles fermented at 15 °C showed antibacterial activity against *E. coli* and *S. aureus*. Pickled bamboo shoot products can be a beneficial source of xylooligosaccharides (XOS)-fermenting probiotics and possess resistance under gastrointestinal tract conditions and display antimicrobial activity against foodborne pathogens [50].

6 Industrial Importance of Fermented Bamboo Shoots

Fermentation is one of the oldest forms of food processing technology and fermented food products like *Sauerkraut* (Europe), *Kimchi* (Korea), *Oncom* (Indonesia), *Tsukemono* (Japan), *Suan cai* (China), and *Atchara* (Philippines) are very popular in different parts of the world [78]. Various investigations have reported their pharmacological importance as a source of bioactive compounds attributed to either increased activity of beneficial cultures or increased bioactivity of certain compounds during fermentation. Fermented soybean products, such as *Cheonggukjang* (Japanese *natto*), *Doenjang* (soy paste), *Ganjang* (soy sauce), and *Douchi*, are reported as major sources of bioactive compounds including isoflavones such as genistein, daidzein, biochanin A, and formononetin, which possess the ameliorative potential to manage neurodegenerative diseases [48]. Fermented bamboo shoots can also be used in different industrial applications including the production of pharmaceuticals, nutraceuticals, dietary supplements and functional food [28, 73]. The bioconversion ability of *microbes* found in fermented succulent shoots of bamboo makes them an ideal source for nutraceuticals and bioactive metabolites such as phytosterols, bacteriocins, exopolysaccharides, etc. Sarangthem and Singh [75] showed that the fermented shoots of *B. tulda* and *D. giganteus* being a rich source of phytosterols, can be used as a potent source in the production of many pharmaceutically active steroids. In addition, owing to their high antioxidant and antimicrobial activities, fermented bamboo shoots have great potential to replace chemical preservatives in the food industry. Chavhan et al. [19] mentioned that the incorporation of paste, powder and extract forms of fermented bamboo shoots in pork has both antibacterial and antilipolytic effects. The shelf-life of all the products increased, with a maximum up to 90 days for products fortified with paste and extract formulation. Fortification of pork nuggets with 8% fermented *B. polymorpha* shoot mince increased their storage life by two weeks along with improved sensory, nutritional and microbiological characteristics [96]. Das et al. [31] prepared fortified chicken nuggets using fermented bamboo shoots, which results in enhanced physicochemical, microbial and sensory qualities of nuggets as well as increased shelf-life. The reduction of fat absorption due to the use of fermented bamboo shoot dietary fibre (BSDF) during deep fat frying of battered and breaded fish balls (BBFBs) [105]. It was revealed that a 6% addition of BSDF to the batter significantly reduced the oil penetration into fried BBFBs with improved sensory quality, textural characteristics, and other quality parameters.

7 Conclusion

The production of various fermented bamboo products is generally traditional and limited largely to local markets. However, due to numerous nutritional and health benefits, fermented bamboo shoots have already attracted the interest of the scientific community and hold great prospects as value-added ingredients in the food, nutraceutical and pharmaceutical industries. Improvement of crude traditional methods by employing modern scientific techniques to upgrade the quality and nutritional richness while keeping intact their unique natural flavour, taste and aroma technologies is the need of the hour. Therefore, keeping in mind about profitable and high economic future of fermented bamboo shoots, there is a need to document the traditional methods of fermentation and conduct detailed studies on microbial biodiversity, nutrients, anti-nutrients and bioactive compounds along with the development of techniques for profitable extraction of industrially important active metabolites. The awareness among the public about the nutritional and health benefits of fermented bamboo shoots and the development of modern fermenting techniques based on modified traditional methods will help accelerate the production of safe fermented bamboo shoots on a larger scale.

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Therapeutic Aspects of Bamboo for Wound Healing

Nikita Kalyan, Oinam Santosh, Aribam Indira, Anurag Kuhad, and Nirmala Chongtham

Abstract Bamboo has been an integral part of the traditional medicinal system worldwide. Traditionally, almost every part of bamboo has been used for medicinal purposes to treat skin infections, joint pains, bleeding gums, injuries, fever, and many more. Pastes of tender bamboo shoots are applied to injuries and skin infections. Bamboo is used in Ayurveda for paralytic complaints, inflammatory disorders, and external skin disorders. Several bioactive compounds like phenols, phytosterols, and flavonoids are present in young bamboo shoots and leaves which have putative health benefits and show antioxidative, anti-bacterial, anti-fungal and anti-viral properties. Several drugs derived from plants are described in Ayurveda as possessing wound-healing properties. *B. vulgaris* is used for skin problems in Trinidad and Tobago. The tribes of Raisen, Madhya Pradesh use leaves and stems of bamboo to treat skin injuries topically. Several bamboo extracts of leaves and shoots show potential anti-bacterial, anti-inflammatory and wound-healing properties. Antioxidants have been reported to play a substantial role in improving the wound-healing process and protecting tissues against oxidative damage. Flavonoids are known to promote the wound-healing process due to their antimicrobial properties, which appear to be responsible for wound contraction and increased rate of epithelialisation. *P. edulis* leaf extract has shown a potential role in preventing inflammation in persistent inflammatory conditions. Ethanolic extract of *D. asper* leaves has shown antimicrobial and anti-diarrhoeagenic properties, which is an important clinical aspect in wound-healing. Diabetes mellitus-associated impaired wound-healing severely affects patients' life quality, leading to prolonged hospitalisation and lower limb amputations. Herbal medicines and plant extracts are used by about 80% population around the world for primary health care as they show efficacy, safety, cultural acceptability, and lesser side effects. Natural accelerators of cutaneous tissue repair with simultaneous anti-inflammatory and antimicrobial activities are of great interest for various dermatological disorders, and bamboo is one of the potential plants.

N. Kalyan · O. Santosh · A. Indira · N. Chongtham (✉)
Department of Botany, Panjab University, Chandigarh 160014, India
e-mail: cnirmala10@gmail.com

A. Kuhad
University Institute of Pharmaceutical Sciences, Panjab University, Chandigarh 160014, India

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1 Introduction

Plants have been extensively used since ancient times to treat a wide range of ailments and diseases as they are a rich source of phytochemicals. The most common phytochemicals include polyphenols, carotenoids, flavonoids, coumarins, isoflavones, phenolic acids, saponins, anthraquinones, ginsenoside, and many more. The pool of plant-derived phytochemicals has garnered considerable interest in the clinical, pharmacological, cosmetic, and food industries as they are useful for a multitude of applications. According to World Health Organisation (WHO), approximately 80% of the world's population depends on traditional practices for primary health care due to their safety, cultural acceptability, efficacy, and lesser side effects [79]. The plant constituents play a part in the physiological functioning of living flora, and thus they have better compatibility with the human body [74]. Bamboo, apart from being an important part of day-to-day life is also an integral part of traditional medicinal systems across the globe (Table 1). It is the fastest-growing evergreen perennial giant woody grass belonging to the family Poaceae and subfamily Bambusoideae. It has played a very significant role in traditional Asian medicine, and its medicinal potential has been well described in ancient pharmacopoeias of the world [23]. All parts of bamboo, being it rhizomes, culms, shavings, resins, shoots, leaves and seeds, have clinical applications. In ancient Indian medicinal systems including Ayurveda, Siddha and Unani medicinal systems, bamboo has been used to treat several diseases. Leaves and shoots of bamboo have great therapeutic potential and can be an alternative to natural and eco-friendly ways of healthcare in a sustainable manner [93]. Bamboo shoots are used as an ingredient in food and traditional medicine [106]. Bamboo silica, also known as Tabasheer is considered the most potent remedy for bone and skin-related problems. In traditional Persian medicinal systems, Tabasheer is used for the treatment of diabetes [42]. Chyawanprash, 'the household remedy,' is a formulation of 'bamboo manna' which is used as an effective energizer, vitalizer, and immunity booster [105]. Ancient ayurvedic text 'Sushruta Samhita' described several medicinal benefits of various bamboo parts like culms, rhizomes, culm-sheath, and seeds [32]. In Unani medicinal systems, the powder of burned bamboo rhizome is often used to cure skin infections caused by ringworm, joint pains, premature hair loss, and bleeding of gums. The paste of tender shoots is applied on bites and injuries [124]. In China, the shoot decoction of bamboo has been used for treating infections, maggot-infected sores, cleaning wounds, and ulcers [12]. In traditional Chinese medicine, bamboo is generally considered cooling, calming, and phlegm resolving, and is incorporated in many traditional formulas to treat lung and stomach heat, febrile disease, and correct up-flowing qi (qi is a fundamental concept in traditional Chinese medicine referring to the energy flow in a living being). In Java, the sap from shoots is used for curing jaundice [12]. The decoction of tender shoots of

Bambusa nutans is applied to wounds and poisonous bites. The shoots are also boiled in water and the soup is taken to treat stomach ulcers. The soup made of boiled tender shoots of *B. tulda* is consumed in cases of poxes, and other skin diseases by the Naga tribe in the Kiphire District of Nagaland and the paste is applied on poisonous bites and injuries. The Karo people in North Sumatra, Indonesia, traditionally use bamboo to treat diabetes. Bamboo vinegar is used in the treatment of various skin-related allergies in Japan [25]. The bamboo shoot sap has been found to contain hydrocyanic acid lending to anti-septic and larvicidal properties. The poultice of the shoots is often used for cleaning wounds and healing infections [101]. Flavonoid-rich bamboo leaf extract has multiple biological effects, such as anti-free radical, antioxidation, anti-ageing, anti-fatigue, anti-bacterial, antiviral, and prevention of cardiovascular diseases. Bamboo leaves have been used as a remedy for several diseases, including burns, dog bite injuries, haemoptysis, uremia, fever, hypertension, atherosclerosis, detoxification, respiratory disorders, oedema, diarrhoea, and vomiting [55]. Each of the traditional systems offers a variety of medicines for wound management and is getting fast acceptance around the world. Currently, the wounds are mainly treated using silver products, advanced dressing, steroids, skin substitutes and growth factors. These therapies cause resistance and are costly. Whereas plant constituents including bamboo not only enhance wound-healing quality and closure rates but also act as an antimicrobial agent which is an important clinical property in wound-healing.

2 Wound-Causing Factors and Their Healing Process

(I) Factors

Wounds are physical, chemical, or thermal injuries caused due to disturbances in the normal skin anatomy and function resulting in a break of continuity of epithelium with or without the loss of underlying connective tissue [125]. Like other injuries, pressure, cuts, burns, diabetic, gastric and duodenal ulcers, wounds impose physical, mental as well as economic burdens on patients and healthcare professionals worldwide. Wounds can be a substrate for infection and can prolong or slow the recovery of injured patients. Depending upon the repair time, wounds can be acute, chronic, and complicated. Acute wounds can be superficial injuries involving both the epidermis and superficial dermis or full-thickness skin damage where a subcutaneous layer is compromised. Surgical incisions, abrasions, lacerations, and thermal wounds are examples of acute wounds. These wounds can heal only in a few weeks, and healing is regulated by cytokines and growth factors released nearby to the wound. Whereas chronic wounds fail to progress through normal stages of healing and are not repaired in a timely and orderly manner. These wounds frequently enter a state of pathologic inflammation due to an incomplete and uncoordinated healing process. Mostly, chronic wounds are ulcers that are associated with pressure, diabetes mellitus, ischemia, and venous stasis disease. Chronic wounds can lead to multiple organ failures or can even result in the death of the patient. Unhealed or chronic

Table 1 Traditional medicinal uses of bamboo

S. no	Species	Plant part used	Uses	References
1	*Bambusa arundinacea*	Root	Ringworm, bleeding gums, arthritis, diuretic, diaphoretic and emollient properties	[138]
		Bark	Skin Eruptions	
2	*B. arundinacea*	Leaves	Anti-leprotic, anti-coagulant (used in haemoptysis), infusion as eyewash, gonorrhoea, and fever, used to strengthen cartilage in osteoarthritis and osteoporosis	[113]
		Seeds	Laxative, beneficial in strangury and urinary discharges, anti-diabetic activity (like standard glibenclamide), enhance human fertility	
		Shoots	Cleaning wounds and healing infections, treating respiratory disorders Used to ease labour and expulsion of the placenta by inducing uterine contractions, increased faecal volume, and bowel movement frequency	
3	*B. bambos*	Stem, leaves, root, and bark	Cold, cough, inflammation, asthma, and leukoderma	[12]
4	*B. breviflora*	Culm shavings	Clears and transforms phlegm and heat in lungs with thick sputum, treats vomiting, pulmonary infections, chronic gastritis	[138]
5	Bamboo spp.	Bamboo shavings (Zhuru)	Clears heat and resolves phlegm, used in acute fevers, convulsions, bleeding due to heat, vomiting	[25]

(continued)

Table 1 (continued)

S. no	Species	Plant part used	Uses	References
		Tabasheer (Bamboo sap) (Tianzhuhuang)	Resolves phlegm, anti-convulsive, fever or loss of consciousness associated with phlegm heat, used in remedies for children's feverish disorders and epilepsy, for treating restlessness, palpitations, depression, heart stroke, migraine	
		Bamboo sap (Zhuli)	Eliminates phlegm heat, treats epilepsy, schizophrenia, hemiplegia, facial paralysis, numbness and tingling in limbs	
		Shoots	Reduces reproductive health-related problems in females like treatment of irregular menstrual cycle, heavy bleeding after delivery, infertility problems, reducing labour pain, and inducing puberty in young females	
		Leaves	To treat diarrhoea in cattle, remedy for cough and cold in horses	
6	*B.* spp	Bamboo sap	Used for treatment of tuberculosis, common cold, sore throat, sinus congestion, cough, for treating lung diseases	[138]
7	*B. spinosa*	Leaf bud	Used in leprosy, fever, and haemoptysis	[138]
		Root	To treat anuria	
8	*B. tulda*	Leaves	To treat tetanus	[117]
9	*B. vulgaris*	Leaves	Induces abortion, relieves labour pains, and postpartum cleanser for livestock	[25]
		Bark	To treat haemorrhage, nausea, vomiting	
		Fresh roots	Applied to hard tumours	

(continued)

Table 1 (continued)

S. no	Species	Plant part used	Uses	References
10	*Dendrocalamus giganteus*	Leaves	Production of steroid drugs	[117]
11	*D hamiltonii*	Stem	Invigorate medicine for kidney	[156]
12	*D. strictus*	Leaves	Abortifacient	[117]
		Leaves and gum	Tuberculosis and clearing the uterus	[12]
		Tender shoots	Wounds and injuries	[12]
13	*Indosasa pingbianensis*	Shoots	Common cold and headache	[157]
14	*Lophatherum gracile*	Stem and dried leaves	Used to treat urinary dysfunction to treat eczema due to damp-heat	[25]
15	*Phyllostachys bambusoides*	Leaves and stem	Anti-pyretic and used for haematuria	[138]
16	*P. edulis*	Leaves and bark	To treat arthritic inflammations, haemorrhage, nausea, vomiting Anti-inflammatory	[102, 138]
17	*P. glauca*	Leaves	Cough and lung inflammation	[157]
18	*P. heterocycla*	Sap of young culms	Cough and throat inflammation	[157]
19	*P. nigra*	Leaves	Anti-pyretic, diuretic, used for cold, pharyngitis, stomatitis, and nose bleeding	[138]
		Stem	Anti-pyretic, anti-tussive, expectorant, sedative, used for bronchial, catarrhal, and cerebral infections and lung infections	
		Bark	Antiemetic	
		Roots	Astringent, antipyretic, check blood flow, used for anxiety, fever, sleeping problems, general restlessness, and rabies	

(continued)

Table 1 (continued)

S. no	Species	Plant part used	Uses	References
20	*Pleioblastus amarus*	Dried leaves (Kuzhuye)	Used to treat febrile diseases, in treating fever, lung inflammation	[25]
21	*Pseudostachyum polymorphum*	Stem	To treat kidney problems	[156]
22	*Schizostachyum capitatum*	Infusion of leaves	Treatment of stomach pain	[117]
23	*Thyrosostachys siamensis*	Stem	Invigorate medicine for kidney	[156]

wounds constantly produce inflammatory mediators causing pain and swelling at the wound site.

Hyperglycaemia greatly hinders natural wound-healing in diabetics. Diabetes is a chronic disease manifesting delayed wound-healing and is a serious and prevalent issue in the public health care system. In diabetics, an orderly sequence of healing cascade is not followed, resulting in delayed wound repair. Higher concentration of proteases along with an imbalance between the production and degradation of collagen and lower levels of certain growth factors causes diabetic wounds to stall in the inflammatory state. Hyperglycaemia causes oxidative stress due to the production of reactive oxygen species, resulting in immune system dysfunction, neuropathy, cellular damage, and poor neo-vascularisation. In diabetic patients, high levels of pro-inflammatory cytokines such as TNF-α and IL-6 make them highly vulnerable to wound infections and inflammation. Also, delayed healing is caused due to lesser migration and proliferation of fibroblasts and keratinocytes, reduced accumulation of collagen and deferred re-epithelialisation. More than 6 million people, i.e., between 0.45% and 3.33% of the world population suffer from chronic wounds whose treatment costs around 25 billion dollars annually [92]. Foot and leg ulcer is a common disorders, and approximately 1% of the European population suffers from this chronic and recurrent ulceration. According to WHO, around 5 million people could die yearly due to improper wound-healing [145].

(II) **Healing Process**

Wound-healing is a dynamic, complex and well-orchestrated series of coordinated events that restore the skin's barrier function and mechanical integrity. Even though wound-healing is a familiar process, still its underlying biology is very complex [120]. The healing process consists of integrated cellular and biochemical events that starts with tissue damage and involves four time-dependent stages: haemostasis, inflammation, proliferation, and wound remodelling (Fig. 1). The haemostasis phase involves soluble mediators, blood cells, parenchymal cells, and extracellular matrix [74]. After the injury, in just a few minutes, the platelets aggregate at the injury site to form a fibrin clot and control the active bleeding. As the blood components fall into the injury site, the platelets move into contact with exposed collagen, releasing clotting

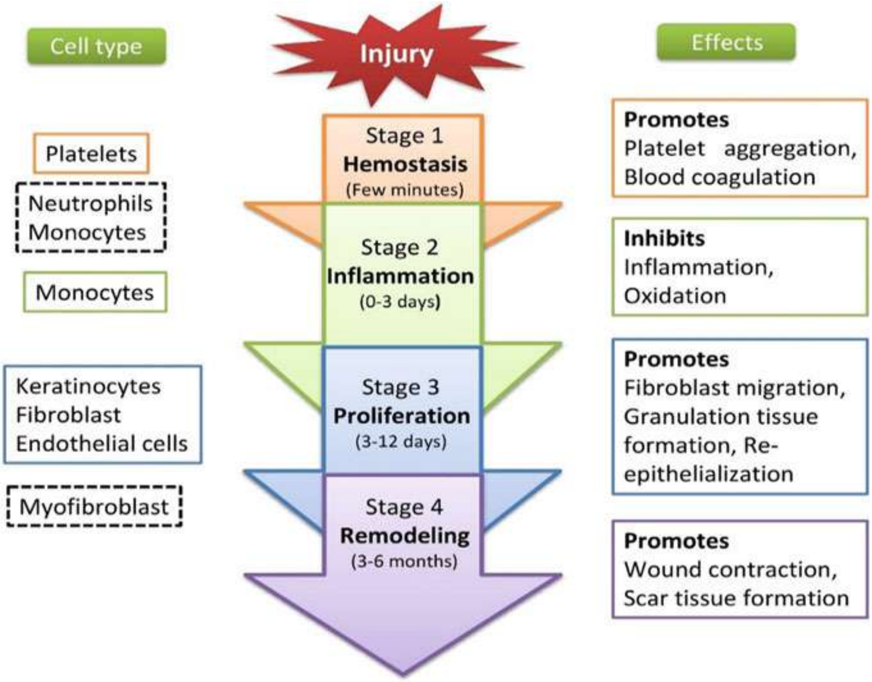

Fig. 1 Stages of wound-healing

factors and essential growth factors by the platelets. In haemostasis, neutrophils move to the wound site and phagocytosis begins to remove the foreign materials, bacteria and damaged tissue. The haemostatic phase and inflammatory phase have an overlapping role.

The inflammatory phase launches the haemostatic phase to stop blood loss. During the inflammation phase, increased amounts of superoxide anion radicals are produced by activated platelets, neutrophils, and macrophages as well as by the fibroblasts. These radicals are part of the innate immune system and are generated to destroy the invading microbes at the wound site. In the inflammatory phase, vasoconstriction takes place leading to inflammation at the wound site. Macrophages appear in the inflammatory phase and continue the phagocytosis process. After the wound site is cleaned out, the fibroblasts move to start tissue formation in the proliferative phase and deposit the new extracellular matrix. The new collagen matrix is organized by cross-linking through vitamin C-dependent hydroxylation during the final remodelling phase which leads to the regain of the injured tissue strength and the re-establishment of structural and functional integrity of the skin.

When a wound is inflicted, vascular disruption occurs in the wound and makes the microenvironment hypoxic, and leads to high oxygen consumption by metabolically active cells. Systemic conditions like old age and diabetes can impair vascular flow, which causes poor tissue oxygenation. This creates a hypoxic wound and can cause improper wound healing as proper oxygen level is crucial for optimum wound-healing. Hypoxia is important to stimulate wound-healing at initial stages like angiogenesis and release of growth factors while proper oxygenation is required to continue the healing process. If the phases of wound-healing do not proceed in an orderly and timely manner, then inappropriate healing will lead to either a chronic wound, like diabetic wounds, venous ulcers or pathological scarrings such as a keloid scar [135]. Inflammatory cells such as plasma cells, neutrophils, and macrophages migrate toward the wound area during the early inflammatory phase, and their presence after 20 days of wounding suggests that wound-healing is slow and incomplete.

Wound-healing is a normal biological process in the human body that can be adversely affected by many factors leading to impaired and improper wound-healing. Factors affecting proper wound-healing include site, size, and shape of the wound, foreign objects, injury method, haematoma or seroma, amount of oxygen, smoking, infection, nutritional factors, radiotherapy, and systemic diseases. Wound infection can stall the healing process. Diabetics are more prone to wound infection. Major organisms causing wound infection include *Staphylococcus aureus, Streptococcus pyogenes, Escherichia coli,* and *Pseudomonas aeruginosa* [61]. Proper blood flow and tissue perfusion are extremely important for appropriate wound-healing.

3 Medicinal Plants in Wound-Healing

Humanity has screened several medicinal plants for their biological activity throughout history. These plants have been used for their anti-coagulative, antioxidant, anti-infective, anti-cancer, and wound-healing activities while attempting to avoid their harmful properties such as cytotoxicity, neurotoxicity, cellular respiration inhibition, and alkylating DNA toxins. Archaeological discoveries have revealed that mankind has made profitable use of herbs since the Palaeolithic period. More than 70% of people living in developing countries, especially in Africa and Asia, depend on herbal medicines for their health needs, including wounds, and infectious and metabolic diseases. Contemporary science has acknowledged the active action of medicinal plants, and it has been incorporated into modern pharmacotherapy. World Health Organization (WHO) recognized the benefits of medicinal plants in 1978 and defined them as the best and largest source of drugs for humankind [92]. It is reported that three-quarters of the world's population use various herbal remedies for the treatment of diseases like rheumatism, asthma, cancer, Parkinson's disease, diabetes, infections and burns.

Medicinal plants are rich in phytochemicals which provide them with their specific medicinal properties. The main effects of the active constituents of plant extracts towards wound-healing include phytochemicals contributing to antimicrobial, anti-inflammatory, and antioxidant activities. Also, the active constituents show enhanced mitogenic activity leading to increased cell proliferation, angiogenesis, and enhanced collagen and DNA synthesis. Phytochemicals have shown significant promise in the prevention and treatment of microbial infections and wounds.

Medicinal plants rich in polyphenols are reported to possess remarkable wound-healing activity [145]. Extensive scientific explorations have been done on several medicinal plants with known traditional wound-healing properties (Table 2). These phytochemicals encourage blood clotting, fight infection, and accelerate wound-healing. Phenolics mainly promote wound-healing due to their astringent, antimicrobial, and free radical scavenging properties [24]. Polyphenols like flavonoids promote wound-healing mainly through antimicrobial and antioxidative properties, inhibiting lipid peroxidation, and hence, preventing cell damage and increasing the viability of collagen fibrils [121]. Several plant extracts contain polyphenolic flavonoids, proanthocyanins, and polyphenols which enable the healing process by the moderation of superoxide anions and later by enhancing the expression of vascular endothelial growth factor (VEGF), hence enhancing angiogenesis and blood flow as the repair proceeds.

4 Bamboo and its Wound-Healing Properties

For any agent to be classified as a good wound-healing agent, it should possess properties like the stimulation of fibroblast proliferation, keratinocytes proliferation, and differentiation, increased collagen formation, and exhibiting antimicrobial, antioxidant and anti-inflammatory properties. The common effects known of the active constituents of herbal extracts towards wound-healing include blood clotting, antioxidant, antimicrobial, and mitogenic activities and also enhance the expression of vascular endothelial growth factor (VEGF), leading to improving angiogenesis and blood flow as the tissue repair proceeds. In chronic wounds, the agents inducing keratinocyte differentiation play an important role [17]. Bamboo contains several compounds like phenols, flavonoids, and other antioxidants, showing promising wound-healing properties (Table 3) [159]. The presence of bioactive compounds like polyphenols, carotenoids, anthocyanin, phytosterols, dietary fibre, alkaloids, glycosides, saponins, anthraquinones, flavonoids, phenolics, tannins, phytosterols, and triterpenoids are reported by several researchers which indicate the therapeutic potentials of bamboo [9, 26].

Modern research has scientifically validated most of the health benefits of bamboo mentioned in traditional systems [7, 10]. Bamboo shoots and leaves show great therapeutic potential and can provide a natural and eco-friendly way of health care [23]. Bamboo possesses anti-bacterial, anti-fungal, and anti-viral activities due to the presence of lignans. The leaf extract has great potential to prevent inflammatory, cardiovascular, hypertension, detoxification, respiratory diseases, metabolic, and neurological/neuropsychiatric diseases [93]. Also, it has active constituents like flavonoids, polyphenols, and active polysaccharides, which possess anti-inflammatory, antioxidant, and lipid-lowering effects [118]. The potential health-benefiting properties of bamboo such as antioxidant, anti-inflammatory and antimicrobial (Table 4) are the major contributing factors for wound-healing which are discussed below:

Table 2 Wound-healing properties of some medicinal plants

S. no	Plant name	Plant part used	Family	Properties	Medicinal use	References
1	*Adhatoda vasica*	Leaves and stem	Acanthaceae	Antioxidant	Wounds	[144]
2	*Aloe vera*	Leaves	Liliaceae	Antioxidant and anti-inflammatory	Wounds	[69]
3	*Azadirachta indica*	Leaves	Meliaceae	Anti-inflammatory and antimicrobial	Wounds	[96, 100]
4	*Carapa guianensis*	Leaves	Meliaceae	Anti-inflammatory, anti-bacterial and pro-healing activity	Cuts and wounds	[86]
5	*Catharanthus roseus*	Flower and leaves	Apocynaceae	Antioxidant	Wounds	[87]
6	*Centella asiatica*	Whole plant	Apiaceae	Antioxidant	Wounds	[18]
7	*Commelina benghalensis*	Leaves	Commelinaceae	Anti-inflammatory and antimicrobial	Wounds	[11]
8	*Crocus sativus*	Flower (stigma)	Iridaceae	Anti-inflammatory and antioxidant	Burn wounds	[145]
9	*Curcuma aromatic*	Rhizome	Zingiberaceae	Anti-inflammatory and antimicrobial	Wounds	[59]
10	*Curcuma longa*	Rhizome	Zingiberaceae	Anti-inflammatory, anti-fungal and anti-bacterial	Wounds	[71, 145]
11	*Drymaria cordata*	Leaves and stem	Caryophyllaceae	Antioxidant	Cuts, burns and wounds	[11]
12	*Euphorbia hirta*	Whole plant	Euphorbiaceae	Anti-inflammatory	Wounds	[33]
13	*Glycyrrhiza glabra*	Root	Fabaceae	Anti-inflammatory and antioxidant	Gastric and oral ulcers, wounds	[145]
14	*Gymnema sylvestre*	Leaves	Asclepiadaceae	Anti-inflammatory	Wounds	[76]

(continued)

Table 2 (continued)

S. no	Plant name	Plant part used	Family	Properties	Medicinal use	References
15	*Hibiscus rosa sinensis*	Leaves	Malvaceae	Anti-inflammatory	Antioxidant and anti-inflammatory	[16]
16	*Moringa oleifera*	Leaves	Moringaceae	Anti-inflammatory, antioxidant and antimicrobial	Cuts, wounds, snake and dog bites and wounds	[11, 46]
17	*Ocimum sanctum*	Leaves	Lamiaceae	Antioxidant and antimicrobial	Wounds	[34, 121]
18	*Sesamum indicum*	Leaves and seeds	Pedaliaceae	Anti-inflammatory	Wounds	[56]
19	*Syzygium cumini*	Bark and leaves	Myrtaceae	Anti-inflammatory and antimicrobial	Burns	[80]
20	*Terminalia arjuna*	Stem bark	Combretaceae	Anti-inflammatory	Wounds	[20]

Table 3 Wound-healing properties of different bamboo species

S. no	Species	Effect	References
1	*Arundinaria gigantea*	Antioxidant	[44]
2	*Bambusa arundinacea*	Antioxidant	[83]
3	*B. arundinacea*	Antimicrobial	[165]
4	*B. balcooa*	Antioxidant	[38]
5	*B. balcooa*	Antioxidant	[44]
6	*B. bambos*	Anti-bacterial	[148]
7	*B. nutans*	Antioxidant	[137]
8	*B. rutila*	Antioxidant	[30]
9	*B. textilis*	Antioxidant	[73]
10	*B. tulda*	Antioxidant	[99]
11	*B. tuldoides*	Antioxidant	[128]
12	*B. vulgaris*	Antimicrobial	[98]
13	*Chimonobambusa quadrangularis*	Antioxidant	[160]
14	*Dendrocalamus asper*	Antimicrobial	[82]
15	*D. hamiltoni*	Antioxidant	[44]
16	*Dendrocalamopsis oldhami*	Antioxidant	[164]
17	*D. strictus*	Antioxidant	[37]
18	*Guadua angustifolia*	Antioxidant	[81]
19	*Indocalamus latifolius*	Anti-bacterial	[128]
20	*Phyllostachys bambusoides*	Antioxidant	[65, 163]
21	*P. bambusoides*	Anti-inflammatory	[64]
22	*P. pubescens*	Anti-inflammatory	[22, 102, 149]
23	*P. pubescens*	Anti-bacterial	[3, 133]
24	*P. pubescens*	Antioxidant	[130]
25	*P. pubescens*	Antioxidant	[49, 63]
26	*P. heterocycla*	Anti-bacterial	[134]
27	*P. humilis*	Antioxidant	[91]
28	*P. mannii*	Antioxidant	[91]
29	*P. nigra*	Antioxidant	[116]
30	*P. nigra*	Antioxidant and antimicrobial	[104]
31	*P. nigra*	Anti-inflammatory and antioxidant	[153]
31	*Sasa borealis*	Antioxidant and antimicrobial	[95]
32	*S. quelpaertensis*	Anti-inflammation	[54]
33	*S. senanensis*	Antioxidant	[78]
34	*S. veitchii*	Anti-inflammatory	[143]
35	Bamboo leaf extract	Anti-inflammation, antioxidant stress, anti-apoptosis	[161]
36	Bamboo leaf flavonoid extract	Antioxidant	[159]

Table 4 Phytochemical constituents of bamboo with wound-healing property

S.no	Species	Bioactive compounds	Properties	References
1	*Bambusa vulgaris*	Ascorbic acid	Antimicrobial effect against *Bacillus cerise, Escherichia coli, Lactobacillus* spp. and the fungus *Aspergillus niger*	[97]
2	*Phyllostachys edulis*	Isoorientin	Anti-inflammatory	[149]
	P. prominens		Anti-inflammatory and antioxidant	[151]
	B. textilis		Anti-inflammatory and antioxidant	[147]
	Sasa borealis		Antioxidant and cytoprotective	[104]
	S. coreana		Antioxidant and cytoprotective	[155]
	P. bambusoides		Antioxidant and cytoprotective	[62]
3	*Pleioblastus amarus*	Tricin, rutin, orientin, quercetin, luteolin, isoorientin, vitexin, isovitexin	Anti-inflammatory and antioxidant	[66]
	P. glauca			
	P. edulis			
	Indocalamus latifolius			
4	*B. vulgaris*	Flavonoids and phenolic compounds	Anti-inflammatory, antimicrobial, and antioxidant	[31]
5	*P. nigra* var. *henonis*	Orientin	Antioxidant and pro-oxidant	[162]
	B. textilis		Anti-inflammatory	[147]
	S. coreana		Anti-inflammatory	[155]
6	*P. nigra* var. *henonis*	Homoorientin	Antioxidant	[162]
	P. bambusoides		Anti-inflammatory	[62]
7	*P. nigra*	Tricin	Antioxidant, anti-inflammatory and inhibition of lipid peroxidation	[116]
8	*B. balcooa*	C-hexosyl-C-pentosyl-apigenin	Antioxidant	[44]
	D. hamiltonii			

(continued)

Table 4 (continued)

S.no	Species	Bioactive compounds	Properties	References
	Arundinaria gigantea			
	P. nigra			
	P. japonica			
9	*S. veitchii*	C-hexosyl-apigenin, Di-O,C-hexosyl-apigenin	Antioxidant	[44]
10	*D. hamiltonii*	C-hexosyl-apigenin	Antioxidant	[44]
11	*G. amplexifolia*	O-hexosyl-O-deoxyhexosyl-apigenin, Di-C-glycosyl-apigenin	Antioxidant	[44]
12	*P. prominens*	"isovitexin-2"- xylopyranoside	Antioxidant	[151]
13	*B. textilis*	Isovitexin	Antioxidant	[147]
14	*S. coreana*	luteolin	Anti-inflammatory	[155]
15	*P. nigra* var. *henonis*	orientin, homoorientin, vitexin, isovitexin, epicatechin, epigallocatechin-3-gallate, and catechins	Antioxidant	[35]
16	*S. veitchii*	Tricin-5-O-glucoside	Antioxidant	[44]
	F. robusta			
17	*S. veitchii*	O-hexosyl-tricin	Antioxidant	[44]
	P. nigra			
	P. japonica			
18	*S. veitchii*	C-hexosyl-O-pentosyl-luteolin	Antioxidant	[44]
	A. gigantea			
19	*S. veitchii*	O-hexosyl-C-hexosyl-luteolin	Antioxidant	[44]
	A. gigantea			
20	*A. gigantea*	C-hexosyl-O-pentosyl-luteolin	Antioxidant	[44]
21	*S. veitchii*	O-hexosyl-C-pentosyl-luteolin	Antioxidant	[44]
22	*P. japonica*	O-pentosyl-C-pentosyl-luteolin	Antioxidant	[44]
23	*P. edulis*	Ferulic acid	Antioxidant and inhibition of lipid peroxidation	[63]
	S. coreana		Anti-inflammatory	[155]
	P. pubescens		Antioxidant and inhibition of lipid peroxidation	[49]
	P. nigra var. *henonis*		Anti-inflammatory	[35]

(continued)

Table 4 (continued)

S.no	Species	Bioactive compounds	Properties	References
24	*P. nigra* var. *Henonis*	Caffeic acid	Antioxidant and inhibition of lipid peroxidation	[35]
	P. edulis		Antioxidant and inhibition of lipid peroxidation	[63]
	P. pubescens		Antioxidant and inhibition of lipid peroxidation	[49]
25	*P. edulis*	p-coumaric acid	Antioxidant	[127]
	P. pubescens		Antioxidant	[49]
	B. textilis		Antioxidant	[147]
	S. coreana		Anti-inflammatory	[155]
26	*P. pubescens*	protocatechuic acid	Antimicrobial and antioxidant	[104]
	Sasa borealis		Anti-inflammatory and antioxidant	[104]
27	*P. pubescens*	p-hydroxybenzoic acid	Antimicrobial and antioxidant	[104]
	Merostachys riedeliana		Anti-inflammatory and antimicrobial	[50]
	P. bambusoides		Antioxidant and antimicrobial	[51]
28	*P. pubescens*	Hydroxy-cinnamic acid	Antimicrobial, antioxidant and anti-inflammatory	[104]
29	*P. pubescens*	Syringic acid	Antimicrobial, antioxidant and anti-inflammatory	[104]
30	*P. pubescens*	Chlorogenic acid	Potential antioxidant and lipid peroxidation inhibition	[49]
31	*P. nigra* var. *Henonis*	Chlorogenic acid, 5-O-caffeoyl-4-methylquinic acid, 3-O-caffeoyl-1-methylquinic acid	Potential antioxidant	[35]
32	*P. prominens*	Xylitol 1-O-(6'- O-P-hydroxybenzoyl)-glucopyranoside (6 s,9 s)-drummondol-9-O-β-D-glucopyranoside	Antioxidant	[151]
33	*P. pubescens*	stigmasterol	Serum cholesterol lowering	[89]
	B.arundinacea		Anti-diabetic effect	
34	*B. arundinacea*	B-sitosterol glucoside	Anti-diabetic effect	[89]

(I) **Antioxidant properties**

Major phenolic compounds present in the bamboo are ferulic acid, p-coumaric acid, caffeic acid, protocatechuic acid, p-hydroxybenzoic acid, catechin, synergic acid, and chlorogenic acid [9]. Phenols are structurally simple aromatic hydrocarbons having either one (phenol) or more than one hydroxyl group substitution (polyphenols). p-coumaric acid (PCA) is a phenolic acid that has hepatoprotective, neuroprotective, antioxidant, cardioprotective, and anti-inflammatory activities [1]. It has also improved impaired glucose tolerance and suppressed neuronal cell death associated with inflammation, apoptosis, and oxidative stress in the hippocampus of diabetic rats [2]. Phenolic compounds are the largest group of natural antioxidants as they show strong hydrogen-donating properties of their hydroxyl group. They prevent the oxidative damage of various biomolecules such as DNA, lipids, and proteins by scavenging various reactive species such as hydroxyl radicals, superoxide radicals, hypochlorous acid, and peroxyl radicals, and by chelating metal ions and thus play an important role in preventing various chronic diseases such as gastric ulcers, cardiovascular diseases, cancer, and so on. Phenols act as antioxidants through mechanisms like free radical scavenging, ROS quenching, oxidative enzyme inhibition, chelation of transition metals or through interaction with biomembranes. Higher content of phenols and flavonoids have been found in *B. vulgaris* leaf extract that has shown higher antioxidative effect in DPPH antioxidant essay [165]. Phenolic compounds directly contribute to the antioxidative effect mainly due to their redox properties, playing a key role in absorbing and neutralizing free radicals, or decomposing peroxides [37].

Flavonoids are oxygen-containing aromatic compounds. Potent antioxidant properties of flavonoids extracted from black bamboo leaves (*P. nigra*) are documented by Hu et al. [45]. Among these flavonoids, flavone c-glucosides and p-coumaric acid reportedly have a long retention time in the colon and may contribute to free radical scavenging [162]. Gong et al. [35] suggested that bamboo flavonoids produced promising free radical scavenging activity. Antioxidants have been reported to significantly improve the wound-healing process and protect tissues from oxidative damage. The main role of antioxidants is to inhibit the oxidation of other molecules in the body and also scavenge the free radicals produced during oxidative stress. Antioxidant enzyme activities are suggestive of the overall oxidative stress at the site of inflammation and infection. Reactive oxidative stress impairs the healing process, and antioxidants are known to promote wound-healing by scavenging reactive oxygen free radicals [6]. Flavonoids and vitamin C present in *B. vulgaris* leaves' fractions showed strong antioxidant properties and promote an increase in collagen synthesis, support their cross-linking, and decrease the degradation of soluble collagen leading to its conversion to insoluble collagen by inhibiting the soluble collagen catabolism [74]. Collagen deposition is the most essential phase of wound-healing as it ultimately contributes to wound strength. It increases the tensile strength of the fibrous tissue and also promotes the adhesion of endothelial cells. Bamboo shoots are a rich source of vitamin C as reported by various workers [93] and ascorbic acid enhances neutrophil function, increases angiogenesis and functions as a powerful antioxidant. The effective healing process of skin wounds caused by cutaneous leishmaniasis using tabasheer from *B. vulgaris* is reported. *B. vulgaris* shows antioxidant, anti-inflammatory and antimicrobial effects due to the presence of ascorbic acid, vitamins, flavonoids, and phenolic compounds, which can be beneficial in the wound-healing process [31]. Butanol-soluble extract from the leaves of *P. edulis* contains derivatives of chlorogenic acid and has antioxidant activity [63].

The presence of niacin, thymine, and vitamins like A, C, B6 and E has been reported by Xia [150]. Shoots have a good profile of minerals such as potassium, calcium, manganese, zinc, chromium, copper, iron, phosphorus, and selenium [8]. Selenium incorporates into the protein to form selenoprotein which is an important source of antioxidant enzymes. The major antioxidants and nutrients of bamboo shoots that scavenge reactive oxygen radicals and provide an antioxidant defence system are vitamins C and E, phenolic compounds, and minerals like selenium, copper, iron, zinc and manganese [23]. Taxifolin and tricin obtained from bamboo culm sheaths are reported to show antioxidant properties [132].

Oxidative stress plays a crucial role in the cause of neurodegenerative disorders such as Alzheimer's and Parkinson's disease. Antioxidant therapy has been proposed for the prophylaxis and treatment of neurodegenerative diseases [154]. It also enhances the activity of aldose reductase and inhibits the formation of advanced glycation end products, and therefore may potentially have a role in the prevention of diabetic complications [52]. Orientin, another antioxidant obtained from the leaves of black bamboo, also prevents apoptosis induced by hypoxia and reoxygenation in myocardium and cardiomyocytes. The mechanism for this effect involves the inhibition of the activation of the mitochondrial apoptotic pathway [27, 72].

(II) **Anti-inflammatory properties**

Phenolic acids present in tender bamboo shoots have mild anti-inflammatory properties and are potent antioxidants that prevent cancer and blood vessel injury that can lead to atherosclerosis. Choi et al. [22] have reported that bamboo leaf extract reduced the adhesion of vascular epithelial factors, regulated endothelial cells to increase vascular mobility, and reduced the risk of atherosclerosis. Bamboo leaf extract has shown anti-inflammatory function in macrophages and inhibits adipogenic differentiation [118]. It has also been proved that there is a significant correlation between phenolic content and the antioxidant activity of bamboo shoots [23]. Leaves of kumaizasa bamboo have shown radical scavenging effects, immunopotentiating activity and suppression of tumour growth [82]. Anti-inflammatory and wound-healing effects of *B. vulgaris*, *Sasa quelpaertensis* and *P. edulis* leaves have been evaluated by several workers [23, 149]. Pro-inflammatory cytokines like IL-6 levels increase in the inflammatory phase of wound-healing. The hydroalcoholic extract of leaves and branches of *P. edulis* significantly reduced IL-6 overproduction under lipotoxic conditions in murine, Hepa6, 3T3-L1, and C2C12 cells mainly through activation of AP-1 and NF-κB pathways. Isoorientin, a major active flavonoid compound in leaf extract of *P. edulis*, contributes to moderate anti-inflammatory effects by the suppression of TNF-α-induced production of pro-inflammatory cytokines (IL-6), chemokines (IL-8), and VEGF factor [149]. The hot water extract of *Sasa quelpaertensis* leaves has ameliorated inflammation-related diseases by suppressing nitric oxide production in the pathological event [23]. Methanolic extract of *Bambusa* *vulgaris* has shown anti-inflammatory activity against various anti-inflammatory tests like acetic acid-induced vascular permeability, formaldehyde-induced paw oedema etc. [19]. Several flavonoids such as vitexin, orientin and isoorientin have been identified in the leaf extract of *Sasa coreana* and found to inhibit liposaccharide-induced nitric oxide production in macrophages. This indicates the therapeutic potential of *S. coreana* leaves for preventing inflammatory diseases [155]. The anti-inflammatory effect of *B. vulgaris* leaves has been studied by Lodhi et al. [74] and showed the decreased expression of inflammatory cytokines and increased levels of anti-inflammatory cytokines, further, this property is proved using carrageenan-induced oedema test.

Another important organic compound present in bamboo is phytosterol which has received attention because of its capability to lower the cholesterol level in humans [77], resulting in significantly reducing the risk of cardiovascular diseases. The phytosterols are the structural and functional counterparts of cholesterol in the plant kingdom. Recently, these have gained lots of acclaim due to their potential implications and benefits for human health. The phytosterols have several health advantages, including immunomodulation, anti-inflammatory, anti-cancer, anti-ulcer, and lowering serum cholesterol. Various phytosterols are reported in bamboo with their main concentration in the shoot and shell. The main phytosterols present in the shoots of bamboo (Fig. 2) are β-sitosterol, stigmastanol, campesterol, stigmasterol, cholesterol, and ergosterol.

(III) **Antimicrobial properties**

The antimicrobial and anti-bacterial activity of bamboo have been known since ancient times as the culm sheaths or bamboo shoot skin has been traditionally used for packing food. Several active compounds such as glycosides, coumarin lactones, anthraquinones and 2,6-dimethoxy-p-benzoquinone possessing antimicrobial properties have been isolated from bamboo leaves and shoots. Three major

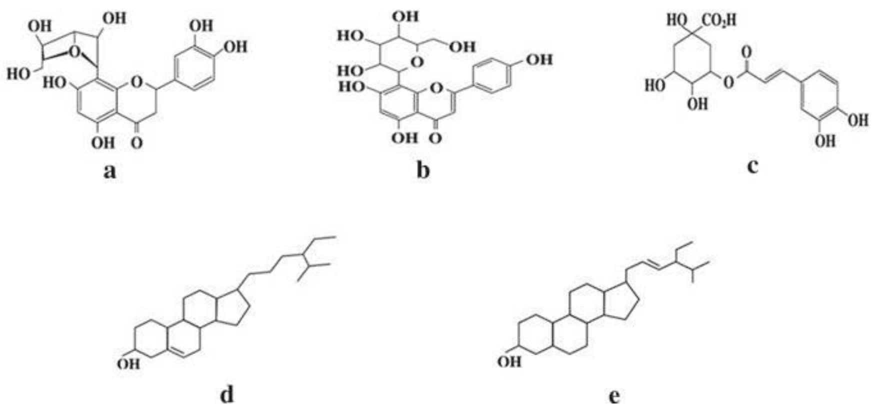

Fig. 2 Major bamboo bioactive compounds with wound-healing properties (**a** Orientin, **b** Vitexin, **c** Chlorogenic acid, **d** Sitosterol, **e** Stigmasterol)

components of essential oils i.e., tricosane, cedrol, and hexadecanoic acid extracted from leaves of *Phyllostachys heterocycla* var. *pubescens* have shown antimicrobial activity mainly against common food-related microorganisms such as *Bacillus subtilis*, *Saccharomyces cerevisiae*, and *Escherichia coli* [23]. Ethanolic extract of *D. asper* leaves has shown antimicrobial and anti-diarrheagenic properties mainly due to the presence of fatty acids and esters, which is an important clinical aspect in wound-healing. It also contained a phenol with similar antimicrobial activity to guaiacol. Several bioactive compounds like fatty acids, alcohols, esters and aldehydes are found in the extract which can be used to substitute conventional antimicrobial agents. Also, the methanol-ethanolic extract has a well-known antioxidant, namely butylated hydroxyanisole [82].

Some flavonoids present in bamboo leaves, such as orientin and vitexin, are reported to regulate gut microbiota responsible for maintaining whole-body functions, suggesting a possible interaction between the bamboo leaf extract and probiotics [55]. The antimicrobial effect of *B. vulgaris* leaf extract has been determined with respect to their inhibitory effect on the growth of *E. coli, Bacillus cerise, Lactobacillus spp.* and the fungus *Aspergillus niger* [97]. The leaves of bamboo are used as an astringent, ophthalmic solution, vulnerary, emmenagogue and febrifuge to heal wounds. According to Singh et al. [123] the fresh leaves of bamboo are more effective in inhibiting *Staphylococcus aureus* compared to penicillin. Also, leaves of *Bambusa arundinacea* are reported to inhibit *S. aureus*, *E. coli*, *Pseudomonas aeruginosa*, and *Bacillus* spp. An ethanolic extract from the leaves of *Phyllostachys edulis* contains high levels of polyphenols and flavonoids [70]. Essential oils of *P. edulis* extracted by steam distillation contain cis-3-hexenol and have antioxidant and antimicrobial activities [49]. 2,6-dimethoxy-p-benzoquinone extracted from the skin of *P. heterocycla* var. *pubescens* and some chitin binding peptides like Pp-AMP1 and Pp-AMP2 obtained from bamboo shoots have shown anti-biotic properties [28]. Dichloromethane extract of *P. pubescens* shoot skin has also been shown to have anti-bacterial activity against *Staphylococcus aureus,* which may be due to the presence of 2,6-dimethoxy-p-benzoquinone [132]. Anti-bacterial silver nanoparticles have been synthesized by Yasin et al. [158] using *P. aurea* leaves and were tested against *E. coli* and *Staphylococcus aureus* using the disc diffusion method. Flavonoids are known to promote the wound-healing process due to their antimicrobial properties, which appear to be responsible for wound contraction and increased rate of epithelialisation [5].

5 Conclusion

Proper wound-healing and its management have been a clinical challenge since ancient times. Modern medicinal systems, including allopathy-based medicines which use synthetic compounds may show allergy, resistance, and is costly, which has prompted wound care professionals and scientists to consider alternative approaches for wound treatment and to validate their use through modern technology. The perception towards alternative medicine such as Ayurveda, Siddha, Unani, and the Chinese medicinal system that mainly depends on plant constituents has changed. Bamboo is one such plant mentioned in traditional medicinal practice systems showing its potential in wound management. The wound-healing potential of bamboo is due to the presence of different active ingredients, and in recent times, it has been considered for the treatment of various diseases and chronic wounds because it shows properties like antimicrobial, antioxidant, and mitogenic activities and also enhances the expression of vascular endothelial growth factor thereby improving angiogenesis and blood flow as the tissue repair process advances. The rich therapeutic potential of bamboo has immense potential to develop a cost-effective, stable, sustainable, and efficient delivery system for the management and treatment of wounds.

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Bamboo: A Sustainable Alternative for Biochar Production

Mamta Lathwal, Mamta Rani, Aribam Indira, and Nirmala Chongtham

Abstract Biochar is a carbon-rich, heterogeneous, and chemically complex material produced by the thermal decomposition of biomass sources through the process of pyrolyzation. Research interest in biochar has grown recently due to its potential to improve soil microbial and enzymatic activity and soil properties, thus increasing agricultural yields along with contributing significantly to sustainable carbon sequestration, thereby mitigating climate change. With the continuous increase in food insecurity, soil pollution, greenhouse gas emissions and environmental safety demands, biochar in recent years has been linked to the development of sustainable agriculture and soil management as well as carbon sequestration. Due to the recent explosion of methods of large-scale synthesis of biochar, research relevant to biochar and biochar-based materials has increased exponentially. A wide range of biochar types is produced from feedstock, including woody residues, crop straws, animal manures, sewage sludge, and food wastes. Biochar made of woody feedstocks is of the highest quality but large production of wood biochar leads to deforestation and increased pressure on forests, thereby affecting the environment. Bamboo is a multipurpose plant with a wide range of uses, from construction, household items, food, biofuel, cosmetics, textiles, nutraceuticals and many more. It is an ideal precursor for biochar because of its significantly accelerated growth rate allowing harvesting of its culms every year, abundance, high biomass yield, low price, low ash content, alkali index and the possibility of propagation through tissue culture which makes it a sustainable alternate for biochar production. *Dendrocalamus* and *Phyllostachys spp* are some common bamboo species used for biochar production. This chapter will explore the feasibility of utilizing bamboo as biochar feedstock and as a suitable alternative for the remediation of environmental pollutants, soil conditioning, crop growth-boosting and carbon sequestration and will offer a perspective for future research and development of bamboo as biochar and its numerous uses.

Keywords Biochar · Bamboo · Carbon · Soil · Pyrolysis · Climate change · Green house gases · Soil amendments

M. Lathwal · M. Rani · A. Indira · N. Chongtham (✉)
Department of Botany, Panjab University, Chandigarh, 160014, India
e-mail: cnirmala10@gmail.com

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1 Introduction

With the unabated increase in atmospheric pollutants and green house gases (GHGs) in the Earth's atmosphere along with the rapidly dwindling carbon (C) budget, cost-effective emission technology need to be adopted to generate clean energy [9]. A recent report by the Intergovernmental Panel on Climate Change (IPCC) states that while steep and rapid emission reductions are critical, it is of utmost importance that C is pro-actively pulled out of the air and stored safely elsewhere. The pertinence of combining biological and engineering sciences-based intervention to reduce emissions is highlighted in recent literature [48, 54]. The whole world is facing different challenges posed by pollution, climate change, population and developing economy and their pressure on water, food and energy systems. The ever-increasing population is predicted to touch 9.8 billion in 2050 [66]. This increase in population will cause a surge in demand for water, food, land and energy which is already constricted in many parts of the world. The increasing demand for food has led to excessive use of inorganic fertilizers and pesticides in agriculture for high yield resulting in soil and water pollution [101]. Moreover, in the last decade, pollution of surface water and soils by pesticides, antibiotics and inorganic pollutants like arsenic, lead and mercury has become a major environmental problem threatening food security and risk to the ecosystem and human health. Significant steps are being taken up to develop eco-friendly and cost-effective technologies to remediate contaminated water and soils [56].

Waste management is another challenge the world is facing due to the release of a high amount of waste every year. The present trend of waste management is crucial based on recycling and the revival of waste as new materials. In India, on average, 500 million tons of crop residues has been generated every year and around 92 million tons of biomass are burnt which contributes to air pollution [16]. A number of processes have been explored for the effective management of solid waste and biochar technology is one potential method for managing the organic nutrient residues originating from agricultural residues, as it is biodegradable and C sequester for a long time [103]. Biochar plays a dual role in the environment; firstly, it can be derived from waste materials which are widely available and, secondly, it enhances soil quality to improve crop production and mitigate climate change by C sequestration and checking on GHGs emissions. Thus, biochar can benefit agriculture, the environment and the economy simultaneously. The application of biochars and engineered biochars converted from various types of biomass has emerged as a promising approach.

Biochar is a carbon-rich material produced through pyrolysis by means of the thermochemical conversion of biomass under O-limited conditions and is an emerging, efficient, environmentally friendly and cost-effective approach for achieving sustainable developmental goals [154]. For a sustainable agriculture system, agro-resources such as rice husk, wheat straw, coffee husk and sugarcane bagasse are considered popular sources for biochar synthesis [62]. Generally, the C content in biochar is 50–80% of the total content. Other than C, biochar is composed of nitrogen (N), O and other elements. Chemically, it contains aromatic and alkyl compounds which provide stability for hundreds of years and the potential to reduce carbon dioxide (CO_2) concentrations and store C for a long time [72, 153].

In the last decade, the interest in biochar is increasing for its prospects and applications for environmental management and sustainable agriculture. Although biochar is produced from various raw materials such as agricultural crops and remnants, agro-forestry, industrial, and municipal wastes, wood biochar is of high quality and more favoured. However, the uncontrolled use of wood as feedstock for biochar production will lead to deforestation at a great level. Bamboo could be a great alternative to wood feedstock as it produces high biomass and takes 4–5 years to get mature which is very less time in comparison to hardwood trees which take around 50 years to produce high-quality wood. Also refer to as the 'green gold' bamboo are distinguished by their diverse root system, vigorous rhizome system and woody culms [22, 111]. Moreover, it has characteristics of growth habits, like faster growth rate, rapid biomass accumulation and interwoven system of rhizomes and roots that helps in soil erosion control, stream bank protection, and increasing soil fertility by the addition of litter-fall and water conservation [14, 108]. Worldwide, the area under bamboo forests covers was 31.5 × 106 ha which is approximately 1.0% of the world's total forest area with around 1482 species under 121 genera [137]. By 2022, the bamboo forest area has reached about 36 million ha, approximately 3.2% of the world's total forest area [140]. Bamboo is exceptionally adaptive in different ecological and climatic conditions as it grows well in tropical, subtropical and temperate regions [28]. Different species of bamboo can absorb more than 62 tons of CO_2 per hectare per year and can play a major role in C sequestration and acting as a C sink that can be converted into durable products which can be used for construction, floor panels, furniture, mats and baskets [119]. Characteristics of bamboo like high biomass, fast growth and high C sequestration capacity make it an ideal choice as raw material and a sustainable alternative to wood. Further, it is supplemented by bamboo biochar's properties like a highly porous structure, four times more sorption capacity and ten times greater surface area as compared to other biochar [138].

This chapter provides insights into the use of biochar in soil management, waste water management as well as climate change mitigation through C sequestration and reducing GHGs emissions. Also, the history, production and properties of different biochar and benefits of biochar as wellas the use of bamboo as a sustainable option for biochar production as feedstock and its role in different applications are discussed.

2 History of Biochar

The term 'biochar' was first coined in 2003 but the concept of biochar is not new [18, 93]. There are various shreds of evidence which indicate the use of biochar for soil nutrient retention originated over 2,000 years ago in the Brazilian Amazon. It has been discovered that this region is rich in '*Terra Preta* soils' (Portuguese for 'dark land') where the soil up to two meters in depth is dark in colour, and highly fertile for agriculture for centuries. The nutrient-enriched soils created by human activity are found in patches throughout the region of the Amazon. The high amount of organic matter and char and its pore structure provides the soil in *Terra Preta* with high nutrient retention quality and neutral pH which makes this region highly productive as compared to its adjacent regions [70]. There are different theories regarding *Terra Preta* soil. Some believe that techniques similar to the slash and burn in modern times are responsible for the formation of the *Terra Preta* region [15]. The human habitation near *Terra Preta* suggests that this region was created by human activity. It is believed that people in Amazon produce biochar by igniting them, burying and smouldering biomass to create the low oxygen conditions necessary for production. Charcoal is considered an integral component of this black soil and has existed in soil for 1,000 years and longer [145].

Similar to the *Terra Preta* region, other regions are also found in Europe known as '*Plaggen*' soils and in New Zealand, known as '*Maori gardens*' [21, 39]. The ancient Japanese agriculture texts also refer to biochar, which is known as '*Miyazaki*' which means 'fine manure' [73]. There are records of charcoal use also in Bronze Age and Iron Age. Another piece of evidence is from China where a large amount of black pottery mixed with charcoal relics has been found at the Hemudu site which is 7,000 years old [25, 76]. Charcoal was used to mix with clay to reduce cohesion and increase the output of finished products [86].

Besides these physical pieces of evidence, biochar used in horticulture and agriculture is also mentioned in books dated back to the nineteenth century. In these texts, biochar was recommended for soil improvement by means of nutrition and water retention in soil, plants substrate and promoting seedling growth [6, 73, 105]. In modern times, the search for a suitable, low cost and environmentally friendly material drew attention to biochar when the *Terra Preta* soil characteristics and C content were published and properties of biochar are explored [43, 74]. Subsequently, the interest towards biochar grew tremendously due to its applications in different areas of energy, agriculture and the environment.

3 Type and Sources of Biochar

The biochar is produced by the thermochemical conversion of organic biomass including agricultural residues (on-field or off-field), bagasse, fruit pits, forestry wastes food and dairy wastes animal manures and sludge [30, 137]. The most common and suitable raw material for biochar is lignin and lignocellulosic-rich biomass. Lignin-rich biomass contains a higher content (>25%) of C as compared to lignocellulosic biomass that is primarily found in wood to form secondary cell walls [5]. But, the overuse of wood to produce biochar can lead to deforestation which is already increasing at an alarming rate. Bamboo can be a sustainable alternative for the production of biochar due to its characteristics like high biomass production and ability of C sequestration.

Table 1 Biochar type and raw material sources

Biochar Type	Raw biomass material
Bamboo biochar	Bamboo (culms and leaves) and bamboo sawdust
Straw biochar	Rice straw, wheat straw and residues, tea leaf and orange peel, forest residues
Shell Biochar	Corn stalk, cotton stalk, cottonseed hull, safflower seeds, peanut shell and giant reed, sugarcane bagasse
Sludge biochar	Municipal wastes, sewage sludge, pulp and paper mill wastes
Wood biochar	Woody material including pine needles, pine shaving, pine wood, oak wood, poplar wood, pepper wood, hickory wood, eucalyptus wood, hard wood, pitch pine, wood saw dust
Other Biochars	Dairy, turkey litter, swine solid and algae

The productivity of biochar and its type relies on biomass source and thermo-chemical conditions of production such as temperature, pressure and heating time. Biochar can roughly be categorized on the basis of biomass used as wood biochar, straw biochar, shell biochar, sludge biochar, bamboo biochar and other biochar [30] (Table1).

3.1 Bamboo as Feedstock for Biochar

Bamboo is a fast-growing, perennial, evergreen, arborescent and multipurpose member of the grass family Poaceae and subfamily Bambusoideae. While the forest coverage in tropical and subtropical is decreasing, the bamboo forest area is increasing as it can grow easily under different climatic conditions. It is estimated that the bamboo area increased by 1–2% annually in the world. Tree timber takes 20–50 years to harvest whereas bamboo timber can be harvested after 4–5 years which is very early compared to the trees. The annual increase in bamboo biomass is 10–30% in comparison to trees where the increase is 2–5% in the same area. Bamboo has very low S, N, and ash contents, which makes it suitable for many applications such as food, fencing, flooring, furniture, interior designing and especially in construction and scaffolding [29]. These applications of rapidly growing sustainable material have resulted in the production of thousands of tons of bamboo waste [91]. The thermal treatment to produce biochar can be a sustainable management of this waste. Furthermore, the lower ash content and higher alkali index of bamboo make it a suitable and more valuable feedstock in comparison to woody biomass [113].

Bamboo biochar has many advantages over other biochars. *Dendrocalamus spp* and *phyllostachys spp* are some common species used to produce biochars that can sequester up to 12 tons of CO_2 per hectare. The pore size of bamboo biochar is greater than other feedstocks biochar which is helpful in water holding and nutrient retention in soil [18]. The porosity and absorption capacity of bamboo biochar is five times and ten times greater than the porosity and absorption capacity of wood biochar

[149]. Hua et al. [50] observed that bamboo biochar is beneficial when applied as fertilizer incorporated with sludge composing thereby effectively reducing N loses in the soil. Bamboo biomass is a potential feedstock for the reduction of a diverse range of fuels and chemicals, such as bioethanol, butanol and lactic acid due to its higher cellulosic content in comparison to other woody biomass [38].

Bamboo biochar can be an ideal amendment for nutrient conservation and heavy metal stabilization due to its excellent properties which can be enhanced by physical and chemical modifications. Research on the mechanism of bamboo biochar amendment in soil and improvement in enzymatic activities are in their infancy and need extensive investigation and explore the potential of bamboo biochar.

4 Biochar Production

Biochar production involves drying, grinding and pyrolysis of organic biomass. The organic biomass used as raw material is commonly known as feedstock such as agricultural residues, wood, sewage sludge and municipal wastes. Pyrolysis is one of the most desirable and favourable techniques for the production of biochar in which organic materials are decomposed thermally under partial presence or total absence of oxygen on a temperature scale of 200–700 °C [147]. The biomass comprised of cellulose, hemicelluloses and lignin undergo different reactions involving cross-linking, depolymerization, fragmentation, gasification and condensation to produce syngas, bio-oil and biochar (Fig. 1). In an experiment conducted by Zhang et al. [148], the stem of *Phyllostachys edulis* contains a higher content of holocellulose (70.51 wt%), cellulose (47.29 wt%,), hemicelluloses (23.21 wt%) and lignin (20.13wt%) compared to the rice husk that is 59.88 wt, 40.19 wt, 19.69 wt, 14.43 wt% respectively indicating that bamboo stem can be a good raw material for biochar production.

In process of pyrolyzation, the moisture of biomass is removed at a temperature below 200 °C and some inorganic gases like CO_2 and N_2 are released into the pores [147]. As the temperature rises (300–500 °C), the decomposition of hemicelluloses followed by celluloses (long C chains) started and a large amount of bio-oil is precipitated from the biomass, including aromatic hydrocarbons, organic acids, methanol, acetone, tar, acetic acid etc. accompanied by the release of saturated gaseous hydrocarbons (CH_4). The solid mass at this time is known as coke which is an indirect indicator of bio-oil yield. When the temperature is increased (500–700 °C), the biomass further decomposes due to the breakdown of lignin content and the release of syngas and volatile organic compounds. The yield of biochar depends on pressure, temperature range and residence time etc. [153]. Based on temperature, heating rate and residence time, different methods used for biochar production are gasification, fast pyrolysis and slow pyrolysis (Table 2).

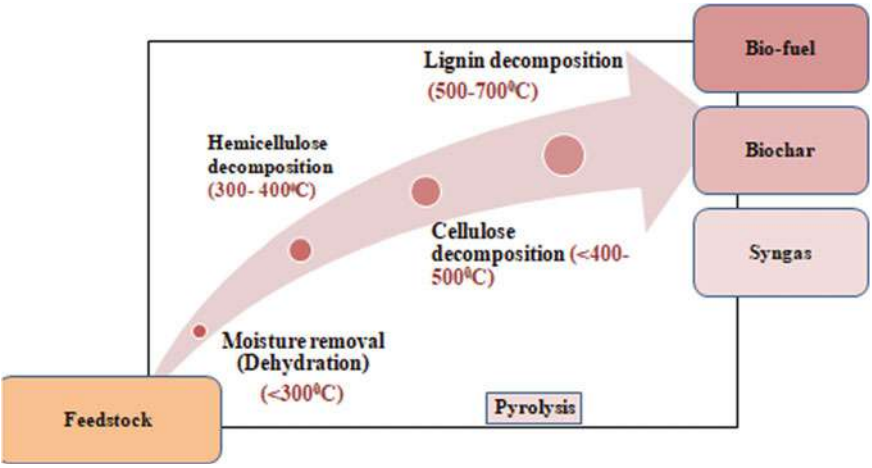

Fig. 1 Pyrolyzation process and its products

Table 2 Temperature, residence time, heating rate and biochar yield for different production processes

Biochar production process	Biochar yield (wt%)	Temperature (°C)	Vapour residence time (h)	Heating rate
Fast pyrolysis	15–35	400–600	0.5–10 s	300–800
Slow pyrolysis	35–50	300–800	>1 h	5–7
Gasification	10–20	750–1000	10–20 s	–

4.1 Slow Pyrolysis

The biomass is heated at the temperature of up to 300–500 C at the rate of 0.1–10 °C min^{-1} in an oxygen-free or limited environment. Slow pyrolysis yields 30–35 wt% biochar, 30–35 wt% syngas and 30 wt% bio-oil [67]. Though slow, this type of pyrolysis produces the highest yield and quality of biochar due to the slow heating rate and long residence time. The reactors used for this process are fixed-bed pyrolysis reactors, and auger pyrolysis reactors [97]. According to Lee et al. [69], the biochar produced at 500 °C contains about 68% of the raw material's energy content and is also good for soil application for nutrient retention. The biochar from *Dendrocalamus giganteus* produced by slow pyrolyzation with temperatures ranging from 300 to 600 °C and heating rate of 10 °C per min revealed simultaneous production of biochar and bio-oil that shows improved properties i.e., high porosity and C content of the biochar. A maximum biochar yield of 80 wt% was also observed at [46].

4.2 Fast Pyrolysis

The heating temperature range is 600–1000 °C with a rate of 10–1000 °C per min in the total absence of oxygen in a bubbling fluidized bed, ablative reactor and rotary cone. The major product is bio- oil with biochar and pyrolysis gas [99]. Fast pyrolysis changes the solid biomass into liquid bio-oil that has the potential for use in energy applications. The process conditions can be described as: (i) fast warming of biomass particles, (ii) short time of biomass particles and pyrolysis fumes at high temperature, (iii) pyrolysis treatment at moderate temperature. According to Wright et al. [133], fast pyrolysis of corn stover yields about 70 wt% bio-oil, 15 wt% biochar and 13 wt% syngas. In another study, biochar, bio-oil and syngas yield by fast pyrolysis using bamboo as feedstock in a fixed-bed reactor were reported to be 32, 48 and 20 wt% which indicate that fast pyrolysis resulted in low biochar yield [61].

4.3 Gasification

Gasification is a special form of combustion and pyrolysis that requires high temperatures (800–1000 °C) in a limited amount of oxygen to convert solid/liquid organic biomass into a solid phase (biochar) and gas/vapour phase (syngas) [90, 98]. Syngas has a high heating power and can be used for biofuel production and power generation. The steps of the gasification process are oxidation, drying, pyrolysis and reduction [90]. The reactors used for the process are known as gasifiers and it differs depending on the rate of heat transfer, feed material and gasifying agent and residence time of fed material into the reaction zone. As gas is the main product of this process, safety issues are a major concern.

4.4 Biochar Engineering

Biochar can be modified with other materials to produce engineered biochar with enlarged surface areas and abundant surface functional groups and can perform better in environmental remediation with desired qualities [56]. Engineered biochar is derivative of conventional biochar modified to improve its biological, chemical and physical properties such as pH, specific surface area, porosity, cation exchange capacity, surface functional group etc. [125]. The three common ways to produce engineered biochar are physical, chemical, and biological (Fig. 2). The physical modification affects the physical structure of biochar and is achieved by temperature, gaseous, plasma, ultrasound and electrochemical treatment [107]. Chemical modifications are achieved by acid/alkali treatment, metal salts, impregnation and oxidation [7]. Bioengineered biochar can be produced by biological modifications

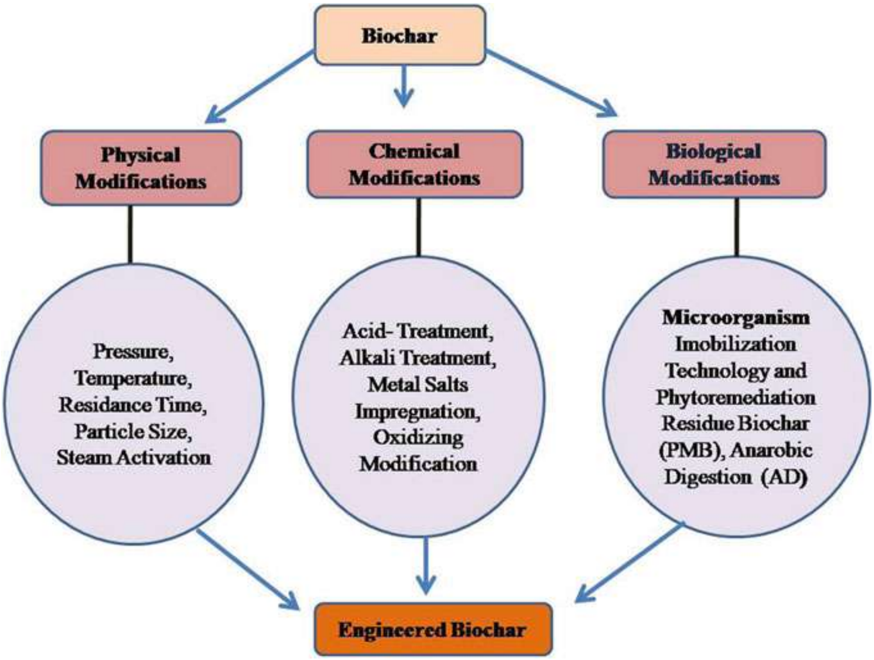

Fig. 2 Different modifications of biochar engineering

that use anaerobic digestion of biologically pretreated feedstocks [44]. The bamboo biochar produced by in situ pyrolysis with urea and potassium bicarbonate ($KHCO_3$) doped with nitrogen adsorbed 499 mg per gm methylene blue and 169 mg per gm phenol indicating that N_2-doped bamboo biochar can efficiently remove the organic pollutant from soil and water [79]. Bamboo biochar modified with chitosan when used to adsorb Cd(II) shows that modification significantly improves the surface properties of biochar and adsorption of Cd(II) possibly by the mechanism of electrostatic adsorption, ion exchange and surface adsorption [51]. Although conventional biochar is beneficial for several applications, engineered biochar with high specific areas, aromatic surface and multiple functional groups can efficiently remove pesticides, synthetic dyes and heavy metals from water and soils.

5 Biochar Properties

Biochar is a phenomenal adsorbent on account of its distinctive properties like large surface area, high porosity, hydrophobicity, unique chemical structure and high content of C. Different parameters such as biomass type, the process of production and heating temperature during the process defines the properties of biochar [150]. The pyrolyzation of *P. edulis* culms with temperatures ranging from 200 to 700 °C resulted in a difference in biochar yield and its elemental composition. Maximum temperature i.e., 700 °C resulted in the least yield (21.45 wt%) whereas the maximum yield (95.89 wt%) was observed when pyrolyzed with minimum temperature (200 °C) [23] (Table 3). pH plays an important role in the binding of inorganic compounds such as heavy metals with biochar and in decreasing their bioavailability. The characteristics of biochar make it a favourable amendment to the soil. Biochar is known for raising cation exchange capacity (CEC), changing the pore size distribution of soil, reducing bulk density and salinity and changing the availability of nutrients in soils. It also alters the water retention capacity of the soil, water and air transportation in the soil and the leaching of nutrients [52]. Due to the presence of particles with low density, biochar reduces the soil bulk density and increases the soil terrene [87].

5.1 pH Value

Biomass materials and their preparation conditions are detrimental to the pH of biochar. Generally, the pH value of raw biomass ranges from 5 to 7.5 which is typically acidic or slightly basic in nature [130]. During the process of pyrolysis, the predominantly acidic functional groups such as hydroxyl, carboxyl and formyl groups get detached making biochar basic in nature [42]. The increase in the degree of carbonization and ash content which is of basic nature is responsible for the increase in pH value. The temperature during the pyrolyzation is crucial for the pH of the final product. Generally, the pH value of biochar ranges between 8.82 and 12 when paralyzed at a temperature above 500 °C. The liming nature of biochar helps in reducing CO_2 and N_2O emissions further reducing the use of nitrogen fertilizers and regulating GHGs emissions from acid soils [135].

5.2 Cation Exchange Capacity (CEC)

Cation exchange capacity (CEC) is defined as the ability of a material to adsorb cations (Mg^{2+}, Na^+, Ca^{2+}, NH^{4+}, K^+) in their exchangeable forms [68]. The adsorption of cations depends on the charge of surface area which is imparted by a functional group (carboxyl and phenolic carbon) attached to it. The CEC indicates the nutrient-holding capacity of the material. A low temperature (250 °C) during pyrolyzation provides biochar with a high CEC value (51.9 $cmol_c$ per kg) compared to a higher temperature (400 °C) that provides biochar with a lower CEC value (16.2 $cmol_c$ per kg) [92]. Biochar produced under suitable conditions can change the overall CEC of the soil which plays an important role in nutrient retention in soil and their availability to plants.

Table 3 Various elements, ash content and biochar yield of bamboo at different temperatures

Temp (°C)	Biochar yield (wt%)	C (wt%)	H (wt%)	N (wt%)	O (wt%)	S (wt%)	O/C	H/C	Ash (wt%)	References
700	21.45	86.34	1.59	0.93	6.87	0.12	0.06	0.22	4.15	[23]
600	22.79	82.45	1.92	0.94	10.44	0.12	0.09	0.28	4.13	
500	25.31	79.59	2.83	0.91	12.59	0.13	0.12	0.43	3.95	
400	31.87	72.26	3.52	0.83	19.73	0.14	0.20	0.58	3.52	
300	53.62	64.38	3.79	0.87	27.53	0.12	0.32	0.71	3.31	
450	34	67.3	3.48	2.99	24.6	–	3.65	1.61	13.2	[142]
500	33	69.3	2.91	2.80	22.7	–	3.68	1.44	14.2	
200	95.89	48.56	6.11	0.16	45.17	–	0.93	0.13	1.74	[150]
800	26.3	89.63	1.44	0.47	8.46	–	0.09	0.02	4.56	

5.3 Elements Composition

The elemental composition majorly depends on the type of feedstock used. The chemical composition of raw biomass used for biochar production changes during pyrolyzation especially, the C content that increases due to the detachment of functional group containing O and H [130]. The elemental composition is affected by reaction temperature as the increase in temperature results in a low content of O, N and H and an increase in C content. An increase in C content is due to a higher degree of polymerization as an increase in pyrolyzation temperature leads to a more condensed C structure of biochar [35]. The biochar with a more aromatic structure has proven to be resistance to microbial degradation. The high C content of biochar is also advantageous in terms of maximizing the amount of C storage and could be used as an energy resource or for soil adsorption of pollutants [69]. Higher C content is observed in wood (60–85% dry weight (d wt)) and bamboo biochar (38–88% d wt) as compared to other agricultural residue biomass suggesting that the raw material biomass plays a significant role in the elemental composition of biochar (Table 4) [57, 129]. The carbon content increased from 64.38 to 86.34% in bamboo biochar as the pyrolyzation temperature increased from 300 to 700 °C suggesting that temperature has a great effect on the elemental composition of biochar (Table 2) [23].

Table 4 Element composition of biochar based on biomass

Biomass	Total C (% d wt)	Total O (% d wt)	Total N (% d wt)	Total H (% d wt)	References
Bamboo	86.34	6.87	0.93	1.59	[23]
Bamboo	82.1	14.6	0.54	2.72	[46]
Bamboo	77.63	18.32	1.07	2.81	[33]
Bamboo (Different particle sizes)	38.1–69.5	19.3–32.3	0.3–0.6	4.0–5.1	[123]
Bamboo	83.2	13.9	2.28	2.28	[152]
Bamboo	62.61	16.91	0.75	0.02	[40]
Bamboo	83.2	–	0.006	0.023	[34]
Corn straw	63.5	21.62	0.71	3.77	[45]
Corn straw	29.5	7.9	0.6	1.6	[20]
Organic waste	41.38	52.37	2.92	1.72	[146]
Rice straw	44.9	50.26	1.02	3.04	[84]
Rice straw	61.02	34.85	2.29	1.84	[85]
Safflower seed cake	70.43	22.39	3.36	3.49	[8]
Wheat straw	69.1	26.5	–	3.1	[134]

5.4 Particle Size

The biochar particle size has a significant role in determining the application of biochar products and the method of application. The particle size majorly depends on feedstock biomass, pyrolysis process, temperature and reaction time. The biochar produced from manure and crop residues has brittle and fine structures whereas biochar generated by using wood-based biomass is predominantly xylemic and coarser [36, 122]. The process of pyrolysis and its condition (residence time, pressure and heating rate) also affects the particle size of biochar. Generally, slow pyrolysis generates large particles whereas, fast pyrolysis produces fine powder [120]. The small fragmented and porous powder structure of biochar produced through fast pyrolyzation and gasification is probably due to rapid devolatilization [19]. Biochar with small particle size increases the water holding capacity by improving porosity, and total C content and decreasing the bulk density of soil [122].

5.5 Ash Content

The ash content of biochar increases after pyrolyzation with the increase in temperature and depends on the raw material used as feedstock. The gradual increase in the concentration of organic matter combustion residues and inorganic constituents results in high ash content of biochar. In addition, a rise in temperature gradually detaches the acidic functional group (–COOH) and attaches to the basic functional group by increasing ash content [151]. Hardwood biochar has low ash content and high C content as compared to agricultural residue-derived biochar. Straw biochars have the highest ash content ranging from 10.4 to 34.2 wt%. The biochar prepared from bamboo sawdust and walnut has 2.5 and 10% high ash content respectively in comparison to raw material [115]. The ash content of biochar should be minimal for more productivity and it depends on the feedstock biomass used for pyrolyzation.

5.6 Porosity

The retention of water and nutrients in soil depends on the porosity of biochar. The biochar originated from the vascular bundles of the raw biomass with large pore sizes is advantageous. The larger pore size may be the result of the decomposition of organic matter leading to the formation of micropores [151]. Pores are important for improving soil quality as they can provide habitats for symbiotic microorganisms [118]. They can also act as release routes of pyrolytic vapours generated in the process [69]. The biochar from bamboo develops high porosity, presenting longitudinal pores with sizes ranging from micro to macro pores (10–200 μm). Tan et al.

[116] reported that bamboo biochar has high porosity which presents good performance as an adsorbent for elemental mercury removal from coal combustion. The porosity of biochar can be improved by physical or chemical activation processes.

6 Applications of Biochar

The low-cost, eco-friendly and easy preparation method from a wide range of biomass by thermochemical techniques for addressing the surplus waste problem and vast environmental applications make biochar an area of interest among researchers. The different applications such as soil amendment, energy storage, wastewater treatments, and plant growth enhancer as mentioned in Fig. 3. Biochar are known to remove pollutants and contaminants from water and soil system depending on pyrolysis temperature and type of biomass. Biochar produced at low temperatures has oxygen-containing functional groups, low porosity and high dissolved organic carbon content making it a best-suited option for the removal of inorganic pollutants, whereas carbon-rich biochar produced at high temperatures is ideal for the removal of organic contaminants [139]. Biochar can increase income sources due to its environmental and energy implications.

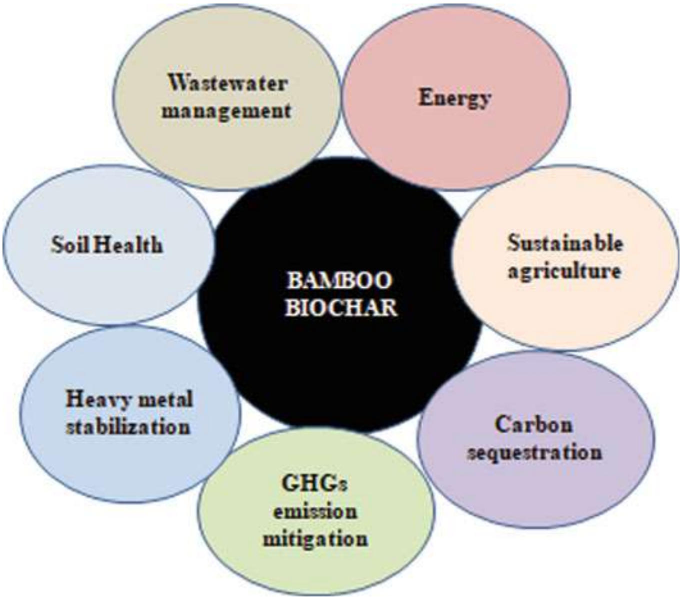

Fig. 3 Different applications of bamboo biochar

6.1 Soil Amendments

Biochar act as an excellent soil conditioner due to its high C content which mitigates the contamination and degradation of soil and helps in reforestation thereby addressing the problems of climate change [154]. The physical health of soil enhanced by biochar application includes texture, structure, aeration, density and temperature and chemical properties like pH, electrical conductivity, cation exchange conductivity, solubility, sorption, water holding capacity and nutrient composition [59, 82] (Table 5). The inclusion of biochar elevates the organic content of the soil which ultimately increases the water retention capacity of the soil [3]. According to a report from The Natural Resources Conservation Service, an acre of land can store 20,000 gallons of more water if the organic content increases by 1% [94]. Therefore, the application of biochar can help to achieve the sustainable use of available water and promotion of responsible consumption and production. Biochar increases the ability of soil to retain nutrients by increasing the cation exchange capacity of the soil. In addition, biochar has a liming effect which neutralizes the acidic soils and thus enhances the productivity of plants.

Furthermore, biochar boosts the microbial activity of soil [75]. The large surface area of biochar provides additional habitat to microbes which increases the microbial population and activity [100]. Cheng et al. [27] studied the effect of biochar on microorganisms and found out that the O content increase by 24% and C content decreased by 71% due to the oxidation of biochar surface by microorganisms. Oxidation leads to an increase in oxygen-containing functional groups which ultimately enhance the cation exchange capacity of biochar and nutrient retention by soil.

Table 5 Effects of different types of biochar as an amendment on the properties of soil

Feedstock	Application rate	Soil properties	References
Bamboo	5% (w/w soil)	pH declined by 7% compared to the control; EC increased in comparison to control	[129]
Rice straw	3% (w/w soil)	EC was 4.6 times of control	
Corn stove	7%	Water holding capacity increased by 25–36%; increased soil porosity	[65]
Cow manure	15 t ha^{-1}	Increase N and P uptake by 111 and 220% respectively	[121]
Rice straw	2.5 and 5%	pH increased from 4–4.5 to 6–6.5; significant liming ability; high pH and high conc. of basic cations	[13]
White lead tree	2.5 and 5%	Soil porosity increased by 24.3 and 26.8% in case of 2.5 and 5% application respectively; Cation exchange capacity increased from 7.41 to 10.8 cmol/kg; increased pH from3.9 to 5.1; soil loss decreased significantly by 50 and 64% at 0.5 and 5% application rate respectively	[59]

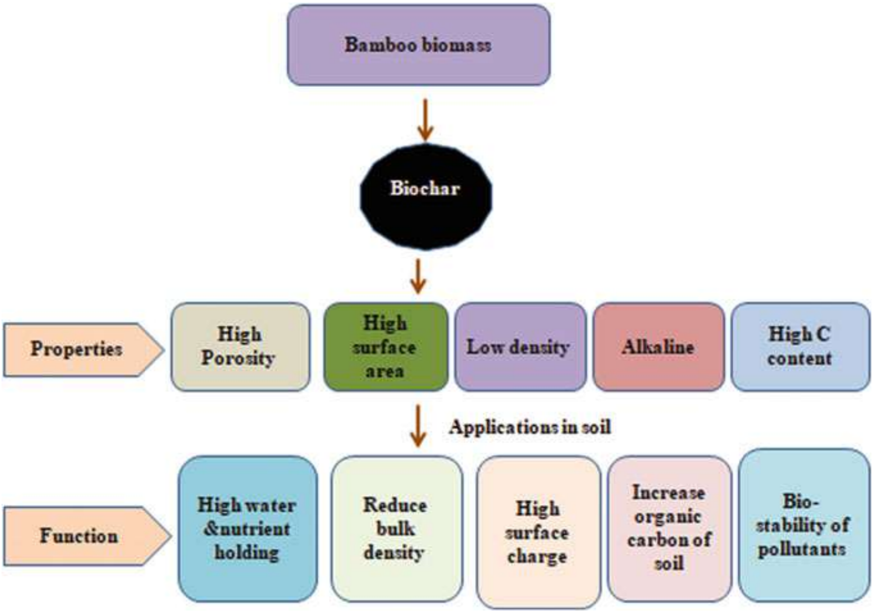

Fig. 4 Bamboo biochar: Properties and function as soil amendment

Biochar addition to a rice paddy increase soil pH, and soil organic C leads to increased rice productivity [144].

Biochar application also reduces the emission of CO_2 by altering the soil's physiological properties. CO_2 emission increases as the microbial activity in soil increases but biochar check the emission of CO_2 while increasing microbial activity [24, 49]. Tarin et al. [117] reported that bamboo biochar application in red soil exhibited a substantial ability to increase fungal diversity and richness. The properties and function of bamboo biochar as a soil amendment are depicted in Fig. 4. In another experiment, Prayogo et al. [102] reported that willow biochar application increased the total bacterial population by 28% possibly by affecting the net N mineralization process.

6.1.1 Contaminants Remediation of Soil

Heavy metals have the potential to cause harm to humans and the environment. Some of the heavy metals are necessary to complete basic functions in various plants and other organisms but harmful above the critical concentration [124]. The sources of heavy metals are natural as well as anthropogenic such as weathering of rocks, mining, smelting, waste disposal, industrial disposal and agriculture [88]. Over the past few decades, biochar has gained numerous attention as a soil additive to immobilize the toxic heavy metal in soil [83, 127].

The mechanism by which biochar absorption inorganic elements are the ion exchange mechanism, co-precipitation, adsorption of cationic ions, and complexation with oxygenic functional groups on biochar surface to form stable metal complexes [26]. Characteristics such as porosity and surface area of biochar influence the absorption of heavy metals. The dosage of biochar also plays a critical role in the interaction of biochar with heavy metals. Some applications and the results of different biochars in the absorption of heavy metal from the soil are given in Table 6.

Kim et al. [64] observed a decrease in phytoavailable concentration of Cd, Pb, and Zn after the application of biochar at the treatment rate of only 1% (W/W). Pb, Cr and Cd were reduced by 79, 78 and 61% with the application of 4% biochar as compared with the control [55]. Moreover, biochar reduced the concentration of arsenic (As) by 72% in rice grain, which led to a 66% reduction of incremental lifetime cancer value for arsenic associated with the consumption of rice [144]. This proves the phytoremedial effects of biochar on heavy metals contaminated soil.

Wang et al. [129] conducted a pot experiment to investigate the effects of bamboo biochar (5%), wood biochar (5%), Chinese walnut shell biochar (5%) and rice straw

Table 6 Effects of different types of biochar on the availability of heavy metal in soil

Biochar	Heavy metal	Effects	References
Bamboo	Cu, Zn	Cu Uptake reduced by 15% and Zn uptake increased by 5%	[129]
Rice straw	Cu	35% reduction in Cu uptake	
Chinese walnut shell	Cu	26% reduction in Cu uptake	
Bamboo	Cd	Decreased the bioavailability of Cd content by 54% and improve the micronutrient availability and biomass	[12]
Bamboo	Pb, Cr, Cd	Adsorption of Pb, Cr and Cd decreased by 42, 38 and 55% respectively	[142]
Bamboo	Pb, Cu, Cd	Pb, Cd and Cu concentration decreased by 48, 20 and 18 and by 55, 29 and 21% with the application of 10 and 15% respectively	[126]
Miscanthus	Cd, Pb, Zn	Removal of Pb, Cd and Zn by 92, 71 and 87% respectively	[48]
Oakwood	Pb	Bioaccessibility and bioavailability decreased by 12.5 and 75.8%	[4]
Rice straw	Cu	Reduce Cu uptake by 60% in roots	[104]
Sewage sludge	Zn, Cu, Pb, As, Cr, Cd, Ni	Cu, Zn, Cd mobilization; As, Cr, Co, Ni, Pb immobilization	[63]

biochar (5%) on soil properties, the solubility of heavy metals in soil and growth and accumulation of heavy metals in moso bamboo. The results showed a significant increase in the dry weight of moso bamboo with different biochar treatments. Rice straw biochar is most effective in enhancing the plants' biomass i.e. 113, 111 and 157% in roots, stems and leaves respectively. The addition of 0.2% bamboo biochar decreases the bulk density of the soil, while an increase in organic matter and cation exchange capacity (CEC) increases in the soil [29]. The electrical conductivity also increased significantly with the applications of biochar. In addition, biochar application enhances soil fertility which leads to an increase in net primary production and thus minimises the pressure of converting the native land into agricultural land.

The application of biochar in soil with the mixture of other soil additives like compost from agricultural residues and arbuscular mycorrhizal fungi prove to be an effective way to stabilize the heavy metal in polluted soil by limiting their bioavailability. A study conducted by Liang et al. [80] reported that the application of rice husk biochar in combination with compost reduced the concentration, mobility and bioavailability of Cd and Zn in soil. An Increase in the pH of the soil is also observed after the application of biochar with compost which enhances the binding of heavy metals on the surface of biochar.

6.2 Sustainable Agriculture

Biochar can be a boon to farmers as the new approach to modern agriculture practices for sustainable food productivity [47, 96]. Organic agriculture is sustainable as it improves the quality of land and reduces air and water pollution and biochar could be a great additive to agriculture. As different biomass such as crop residues, wood and bamboo are used for the production of biochar, it can be a sustainable soil conditioner in organic agriculture. The biochar amendment is able to tackle the problem of drought, salinity and heat stress on the soil. Due to its high water holding capacity, biochar can be a great soil additive in rice fields as an adequate supply of water is needed during the growth phase. The use of biochar in rice fields also advocates as a potential strategy to reduce N retention, and GHGs emissions from soils and enhance soil C stocks with improvement in soil health and crop productivity and increase rice yield by 16% as compared to control [10]. The plant shows a much better response to biochar as compared to other commercial potting or rooting media.

Several investigations reported that biochar can be an excellent choice for plant growth that enhances crop production as compared to chemical fertilizers. It enhances the supply of nutrients to the growing plants by increasing cation exchange capacity, nutrient and water holding capacity and ultimately preventing the leaching of nutrients [114]. Bamboo biochar increases the dry weight of mustard (10.80 g) by 60% when compared without the treatment of biochar (6.75 g) with the application of 9 tons per hectare which may be due to the enhancement of nutrient supply [109].

6.2.1 Crop Production

Several studies have been conducted to observe the effects of biochar on crop yield and found a positive effect on it. The major challenge in the soil-water-plant system is soil fertility management which can be controlled by biochar. Various pot studies and field trials have reported the use of different biochar at different application rates in various plants like maize, watermelon, tomato, cucumber, wheat, strawberry, rice, and sweet pepper [31]. The amendment of 20 and 40 t/ha biochar significantly increased the rice yields by 166 and 180.3% under the contamination of cadmium [17]. The biochar obtained from the stem of *Guadua angustifolia* was used as an amendment with the application rate of 1, 2.5 and 5% (dry mass) and observed an increase of 350 and 151% in tomato yield in sandy soil and silt loam soil respectively with the application of 5% biochar [123] (Table 7). In another experiment, the application of 15% of bamboo biochar obtained from bamboo waste with arbuscular mycorrhizal fungi (AMF), an increase in dry weight by 9.5% in leaves, 16.6% in stems, 26.5% in fine roots dry weight was observed. AMF inoculation and biochar amendment prove to be the potential alternatives that could improve the growth and survival of plants in acidic and nutrient-deficient soil [2]. The application of 10 t/ha of bamboo biochar increases crop production by 44% as compared to control in pak choi plant [110]. Biochar not only improves the vegetative growth and productivity of plants but also helps in protecting them against abiotic stress, i.e., drought, and salinity [11].

6.3 Climate Change Mitigation

According to the IPCC report, climate change is a threat to the well-being of humans and the planet's health. Human-induced climate change is affecting the ecosystem and billions of people's lives around the world. Over the next two decades, global warming will reach a hazardous level with an increase of 1.5 °C. The report evidently states that there is an urgent need to take enthusiastic and expedited steps to enable climate-resilient development as strengthening and safeguarding nature is the only key to a livable future [54]. Biochar produced from organic biomass can be a viable option to provide resilience against climate change. Biochar technology is known as a 'geo-engineering solution' which is imminent to quench the atmospheric GHGs concentration actively. These geo-engineering technologies have the potential to trim down the atmospheric concentrations of GHGs and contribute to sustainable agriculture [31]. Overall, biochar can be a good C sink as the agricultural crop biomass can be converted into biochar by pyrolysis which can then be applied back to the soil. Biochar incorporation into soil cut down the N_2O effectively from different kinds of soils. Biochar can be considered as a measure to mitigate the climate change impact due to the fact that the GHGs can be removed from the environment. About 2/3rd of total C remains at site bamboo plantation site for a longer time as compared to other rapidly growing trees such as Chinese fir when grown for 5 years proving bamboo to be a potential plant for carbon sequestration [143].

Table 7 Illustration of the effects of different biochars on crop yield

Biochar feedstock	Application rate	Crop	Effects	References
Bamboo (*Guadua angustifolia*)	2.5% w/w	Tomato	Tomato yield increased by 350% and 151% in sandy soil and silt loam soil respectively as compared to the control	[123]
Bamboo	0, 7.5 and 15% w/w	Cocoa	Improved the height and stem diameter of plant in all concentration	[2]
Bamboo	0.5%, 1% and 1.5% w/w	Chinese cabbage	Enhance growth by 64.23%, 47.31 and 34.93% in soil treated with Cd at 0, 5 and 50 mg per kg	[89]
Silkworm excrement	1% w/w	Rice	Increase in the number of tillers and a 55.43% increase in rice grain under heavy metal contamination	[106]
Sugarcane bagasse	3% w/w	Maize	Improved plant root length, height, leaf area and fresh shoot biomass by 80.80, 81.11, 80.11 and 85.50% respectively	[11]

6.3.1 GHGs Emission Reduction

The fundamental cause of climate change is the increase in GHGs emission and global warming but CO_2 emission alone contribute above 77% of it. Biochar is proposed as a sustainable technology to mitigate the emission of GHGs and climate change. Production of biochar by using C-rich feedstock offset the GHGs emission from the burning of biomass and stores it in the form of biochar [82]. The addition of biochar in the soil helps to bind the GHGs in soil bodies in the form of stable C [32]. The biochar remains in the soil for many years and sequesters the C and reduced the CO_2 present in the air and improving the liveliness of the soil over the years [37]. Liu et al. [81] reported that the emission of N reduced from 0.17 to 0.07 kg and N_2O-N by 0.10 kg in paddy soil after applying 40 and 20 t/ha biochar respectively. Biochar was applied in combination with four different fertilizers and conventional chemical-based fertilizers in a rice field and observed that biochar-based fertilizers improved N efficiency and reduced GHGs emissions by 35–44% during rice production [53].

The GHGs emission by burning fossil fuels is reduced by 2–5 times though the applications of biochar [41].

6.3.2 Carbon Sequestration

Biochar has the potential to deal with the menace of climate change through the process of carbon sequestration. As much as 0.50 billion tons of CO_2 could be sequestered by the annual production of around 339.4 tons of biochar which is equivalent to 1.5% CO_2 emissions annually. One ton of biochar in the ground is equivalent to 3 tons of CO_2 permanently sequestered from the atmosphere [131]. Liu et al. [82] estimated that annually, 0.3 billion tons of CO_2 emission can be stored by biochar in a more stable form of C. Application of 10,000–100,000 kg biochar to 1,411 million hectares of cropland stored around 7–110 Giga tons of C proving biochar as an effective remedy to the problem of climate change [71]. A field experiment for 24 months was conducted to observe the change in carbon stocks and soil GHGs emissions in a forest of moso bamboo with the application of bamboo leaf biochar pyrolyzed at the temperature of 500 °C to observe that the vegetation carbon stock increased by 66.79 and 59.85% and soil organic carbon stocks increased by 26.60 and 0.07% with application of 5 and 15 mg per ha, respectively. This study implies that the carbon sequestration capacity of moso bamboo forests can be enhanced by the application of biochar and it can be an effective forest management option to increase carbon stocks and reduce GHGs emissions in forests [136]. The surface area of bamboo biochar was increased after activation with KOH and helped to adsorb 1.50 mmol per gm of CO_2 at 25 °C which reveals that KOH-activated bamboo biochar can be a potential solution to capture carbon [58].

6.4 Wastewater Treatment

Inorganic pollutants in wastewater including heavy metals (Cr, Cu, Pb, Cd, Hg, Fe, Zn, and As ions) and compounds like nitrate (NO_3), nitrite (NO_2), ammonium (NH_4), phosphorus (P), and hydrogen sulfide (H_2S) cause significant risk to public health and environment. Biochar could be a promising technique for wastewater treatment at different stages due to its efficiency by the mechanism of co-precipitation, physical adsorption, complexation and electrostatic interaction as mentioned in Fig. 5. In wastewater, biochar application governs the mechanism of buffering, adsorption, and immobilization of microbial cells. Biochar can efficiently absorb byproducts such as N and P which can be used as enriched material.

In the active sludge treatment process, biochar could improve the treatment and setting ability of the sludge and provide the surface for the movement of microbes. Li et al. [77] observed that polar insecticide and herbicide like 1-naphthol, norflurazon, and fluridone were removed from the water by the interaction mechanism of functional groups of biochar with pollutants. It is observed that the pH of biochar is

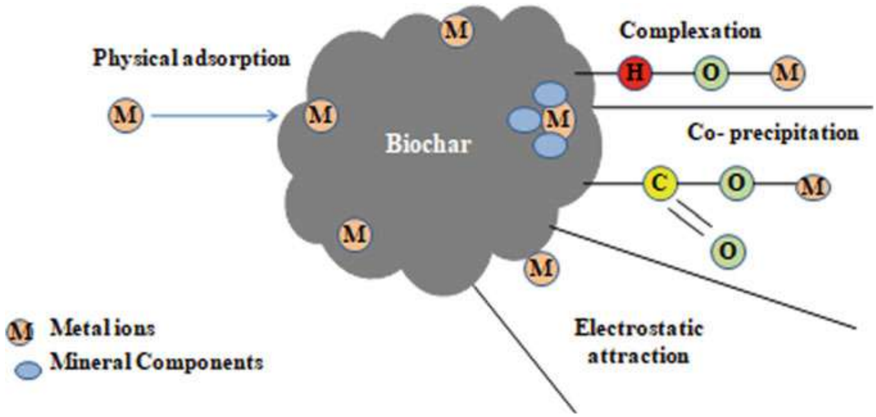

Fig. 5 Mechanism of sorption of contaminants by biochar

the most important factor for the interaction and removal of organic pollutants. The removal efficiency increased with increasing biochar dosage in wastewater systems which is due to increased pH and surface area to absorb more pollutants. Wang et al. [128] investigated the removal ability of bamboo biochar for the removal of fluoroquinolone antibiotics and they obtained 99% removal of the antibiotics from waste water. In another study, Yang et al. [141] concluded that bamboo biochar has a great potential for the removal of metal and complex dye from the water. This study revealed that bamboo biochar is a highly cost-effective adsorbent for metal complex removal from aqueous solution due to its high porous structure and high surface area.

6.5 Energy Production

Power generation technologies based on biomass might be more economically feasible than fossil fuels because of the high availability of lignocellulosic-rich biomass sources [78]. Biochar production systems can potentially adjust the energy structure of India and can come up with a promising green sustainable development strategy. Biochar could be used as an energy-producing and storage material. Biochar produces energy and electricity from gasification and can be used as storage material in supercapacitors and rechargeable batteries system and enhancing energy recovery from anaerobic digestion.

The direct combustion of biomass to produce heat has limitations of low energy efficiency and smoke emission. Whereas biochar set out to be a high-energy–density solid fuel with lower O/C and H/C ratios and lower emission of smoke under thermo-chemical processing [1]. Biochar could be used as feedstock to produce extra gaseous fuel in the process of gasification. Co-firing technology with biochar can reduce the dependency on fossil fuels and increase the diversity of fuel for coal-fired thermal power systems. For instance, coal could be blended with biochar for pelletizing and combustion in a single pellet furnace which leads to easy ignition and long-lasting combustion [78]. In addition, biochar could store energy in energy storage systems such as rechargeable batteries and supercapacitors. Primarily, C electrode material decided the performance of energy storage devices. As biochar contains high C, electrical conductivity and C-O groups and a large specific surface area, it has great potential to serve as a supercapacitor and an electrocatalyst. Various investigations illustrated that bamboo residue can be utilized as feedstock for bioenergy generation. The use of biochar in energy will improve the economics of biochar production systems.

7 Future Prospects

Industrialization, urbanization, modernization and rapidly increasing populations have led to an increase in food demand which ultimately became a burden on agriculture land with the over use of fertilizers. This problem of over-exploitation and contamination of soil can be solved by the use of bamboo. Bamboo helps to restore degraded soil and wasteland as it grows in a wide range of habitats with minimal requirements. It has emerged as a potential energy source and biomass feedstock due to its high availability, biomass production capacity and quality of biochar.

The socio-economic value of bamboo which is more confined at the local level can be brought up to a higher level as it can ameliorate the degraded and waste lands. The waste materials from bamboo furniture and handicraft can be utilized for the production of biochar. Hence, besides the popular use of bamboo in construction, other aspects like food, nutraceuticals, phytoremediation and biochar production should also be popularized in society. Biochar has also been proven to control the bad odour of wastewater treatment plants and landfills [112, 132]. However, there is no enough literature to identify the public opinion on biochar. The opinion of farmers on biochar is critical because they are the ones who work at the field level. A recent survey on farmers' views about biochar in Thailand revealed disagreement on the utilization of biochar in their fields as they were not aware of its benefits and usefulness [95]. Positive opinions of the general public about the use of biochar can promote the application of biochar on large scale. Hence, further scientific studies on the social benefits of biochar and its application in the case of different crops and changing public perception are important to explore the full potential of biochar at the field level. Biochar-based technology can generate more jobs and revenue for the country. However, a better selection, production and promotion strategy should be implemented. Recent studies indicated that the application of biochar in fields can be a cost-effective solution for soil amendment. A cost–benefit analysis of wood biochar application on avocado farms culminated that the application of a metric ton of biochar gives a net benefit of US$ 8581 per hectare [60]. Similar benefits from biochar utilization in the paddy field have been reported in a rise in benefit-to-cost ratio from 1.79 to 2.23$ per unit in non- amended soil to 2.65–3.64$ per unit in amended soil [126]. This shows that biochar could make profitable outcomes for farmers. However, the transfer of the proper scientific knowledge of biochar applications from pilot scale to field is a short-coming due to higher cost in its production. The cost of biochar depends on the type and availability of feedstock. Therefore, the development of a better cost-effective strategy for the production and application of biochar is a crucial step.

The use of bamboo as feedstock should be promoted on a commercial level due to its high biomass production capacity and quality of biochar. The production plants of biochar should be set up in the vicinity of biomass sources so the cost of biochar production can be minimized and in turn, benefit the locals. Studies on the application and dose of biochar according to species and variety of crops should be encouraged. Biochar application on soil microbiota as well as on other soil fauna needs to be carried out in the field analysis. Moreover, the government needs to drive attention towards the agricultural and environmental implications of biochar by implementing policies that improve the socio-economic condition as well as the environment.

8 Conclusion

The production of biochar is gaining attention due to its promising potential in energy production and environmental applications. Biochar has made a substantial breakthrough in reducing soil nutrient leaching losses, GHGs emissions and global warming, sequestering surplus atmospheric carbon into the soil, reducing the bioavailability of environmental contaminants in soil and water, increasing agricultural productivity and subsequently becoming a value-added product of sustaining circular bio-economy. Bamboo has many potential if it is harvested, managed and planned properly. Incorporating bamboo as feedstock could remarkably decrease the burden of waste generated from different conventional applications of bamboo. Properties of bamboo such as wide availability, fast-growing, versatility in many applications, ability to grow on degraded lands, excellent fuel properties and quick storing and sequestering of carbon make them an excellent biochar source. Biochar is a marketable bio-product due to its profitable uses such as bio-oil and bio-gas production which can be widely used in industries, the energy sector and agriculture. Additionally, this chapter urges us to explore the ways to produce and use this abundant resource to contribute to economically sustainable growth. Furthermore, research and management of bamboo resources and the involvement of locals in the biochar industry are required.

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Bamboo-Based Lignocellulose Biomass as Catalytic Support for Organic Synthesis and Water Treatments

Omar Ginoble Pandoli, Druval Santos de Sá, Mario Nogueira Barbosa Junior, and Sidnei Paciornik

Abstract Bamboo is an exciting raw material as a lignocellulose source due to its high mechanical resistance, low cost, fast harvesting, and large abundance in all tropical and subtropical zones worldwide. Considering the industrial applications of renewable, biodegradable, and low-cost natural support for heterocatalysis reactions and water remediation, bamboo-based lignocellulose biomass can implicate new insight in these research fields. The chemical and thermal stability, biocompatibility, different catalyst immobilization strategies, reusability, and recovery of the lignocellulose biomass as catalytic support for metal ions, metal nanoparticles, and enzymes are presented. Bamboo, as a 3D microarray of channels with properly regioselective coating with conductive silver ink is presented as a microfluidic heater for potential continuous flow organic synthesis. Bamboo-based lignocellulose biomass can be used as a natural absorbent for metal contaminates in solution (Pb^{+2}). Much more studies are demonstrated using bamboo charcoal (BC) as bioadsorbents for several heavy metals in solution (Pb^{2+}, Cu^{2+}, Cr^{3+}, Cd^{2+}, Hg^{+2}, Zn^{+2}) or in the gas phase (Hg^0). BC and bamboo activated carbon (BAC) have been investigated as efficient adsorbents for nitrogen aromatic compounds, organic dyes, and pharmaceuticals active products. The first bamboo 3D bio template was demonstrated as a solar

O. Ginoble Pandoli (✉) · D. Santos de Sá
Department of Chemistry, Pontifícia Universidade Católica do Rio de Janeiro (PUC-RIO), Rua Marquês de São Vicente, Rio de Janeiro, Brazil
e-mail: omarpandoli@puc-rio.br; omar.ginoblepandoli@unige.it

D. Santos de Sá
e-mail: drdruval@gmail.com

O. Ginoble Pandoli
Dipartimento di Farmacia, Università degli Studi di Genova, Viale Cembrano 4, Genova, Italy

M. Nogueira Barbosa Junior · S. Paciornik
Chemical and Materials Engineering Department, Pontifícia Universidade Católica do Rio de Janeiro (PUC-RIO), Rua Marquês de São Vicente, Rio de Janeiro, Brazil
e-mail: contatomariojr@gmail.com

S. Paciornik
e-mail: sidnei@puc-rio.br

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vapor generation for water desalinization. This overview points out the potential use of bamboo-based derivatives for industrial bio-economy.

Keywords Analytical platform · Catalytic microreactor · Heterocatalysis · Biocatalysis · Bio-adsorbent · Waste treatment · Lignocellulosic support · Pyrolyzed bamboo

1 Introduction

"Green Engineering" is the design and fabrication of chemical products and processes that reduce and eliminate the utilization and generation of hazardous substances to be safer and more efficient. Environmental and human health are associated with resource and energy consumption. The U.S. government reported that the cost associated with safety and environmental regulation consumes a very significant part of the domestic product across all the manufacturing sectors. Because of that, it has been recognized as a transition time to a sustainable society with safer, renewable, and reusable materials. An initial motivation for redesigning chemical processes came from the pollution prevention legislation in the early 1990s by the Environmental Protection Agency (EPA) that articulated safer and sustainable chemicals as the best pollution prevention strategy.

Green chemistry has 12 basic principles: prevention, atom economy, less hazardous chemical syntheses, designing safer chemicals, safer solvents, and auxiliaries, design for energy efficiency, use of renewable feedstocks, reduce derivatives, catalysis, design for degradation, real-time analysis for pollution prevention, inherently safer chemistry for accident prevention.

Organic catalysis, metal catalysis, or enzyme catalysis are masterpieces in improving the efficiency of organic synthesis. One of the aims of heterocatalysis is to find out a chemical strategy to immobilize a selected catalyst on a biobased material such as a lignocellulosic biopolymer extracted from a wood or bamboo biomass. The big challenge is to maintain the catalytic efficiency of the catalyst for the intensification process of the chemical transformation in batch or in flow mode.

All these challenges can be faced with the use of lignocellulose biomass as a multifunctional tool for sustainable catalysis [1]. In this regard, bamboo is rich in cellulose, lignin, and hemicellulose that can be modified with different types of organic and inorganic agents to obtain immobilizing functional groups for different types of catalysts for heterogeneous catalysis. Bamboo vascular bundles, bamboo slices (BS), or bamboo powder (BP) bring similar or better chemical and physical characteristics of wood presenting high mechanical resistance, thermal stability, insoluble in solvents, modifiable surface, and easy handle, which makes them an excellent alternative as heterogeneous catalytic supports.

Lignocellulose support from bamboo powder (*Bambusa multiplex* and *Dendrocalamus giganteus*), bars (*Phyllostachys pubescens*), and bamboo shoot shells (*Dendrocalamus Latiforus*) have already been used to immobilize different enzymes, respectively, *lipase Candida* [2, 3], *neutral protease* [4], α-*amylase* [5], and *L-glutaminase* [6]. The biocatalytic transformations in the batch mode were demonstrated for the esterification of fatty acid, hydrolysis of olive oil, proteolysis, and hydrolysis of α-1,4-glycosidic bond in carbohydrates. For the first time, the kinetic resolution of a racemic solution of 1-phenylethanol was applied in flow mode in a packed bed column reactor [2].

The pioneer bamboo-based analytical device as a passive absorbent for analytical colorimetric detections is described [7]. More recentlyd an easy chemical functionalization of the lignocellulose biopolymer was disclosed that allowed anchoring copper nanoparticles (Cu-NPs) [8], or copper ions (Cu^{+2}/Cu^{+1}) [9] to catalyze cycloaddition click-chemistry reactions in batch mode or flow mode, respectively. Additionally, Ag-NPs were immobilized in microchannel vascular bundles to create a high-efficiency catalytic capillary microreactor for nitroaromatic reduction and water purification [10]. For other purposes, the immobilization of a commercial conductive silver ink paste allowed the fabrication of the first microfluidic heater for potential applications in organic flow synthesis [11].

Carbon-based functional materials from low-cost, abundant, and sustainable resources have shown great interest as adsorbents for water remediation [12]. Natural Bamboo biomass, bamboo charcoal (BC), or bamboo activated carbons (BAC) are presented for water treatment applications. A bamboo-based biotemplate as a porous absorbent was used to remove Pb(II) from the aqueous mixture [13]. Bamboo and its residues were transformed into bamboo charcoal (BC) in high temperatures, and low oxygen atmospheres are environmentally friendly sorbents and can be cost-effective for removing heavy metals in aqueous solution [14–18] or gases [19]. BC and BAC have presented for the removal of heterocyclic aromatic compounds [20], organic dyes [21, 22], pharmaceuticals active products [23–25], and nitrogen derivatives [26–28] from water waste. Finally, a 3D bamboo structure is presented as an excellent solar vapor generation for water desalinization [29].

In this present overview, we focus on the applications of bamboo-based lignocellulosic polymers as support for sustainable heterogeneous catalysis and bamboo charcoal as bio-adsorbent for water remediation, which can pave the way for new bio and circular economy solutions.

2 Bamboo Carries for Biocatalytic Reactions

Among the wide use of enzymes for biocatalytic transformation, lipases are the most widely used biocatalyst in enzyme technology. They recognize a wide variety of substrates with high enantioselectivity, and high stability in organic solvents, and with several applications for pharmaceutical production, biodiesel, and food modification. Figure 1 illustrates the most important organic reactions catalyzed by lipases, and triacylglycerol hydrolases for hydrolysis, esterification, and transesterification, among others. They could hydrolyze a triacylglycerol (TGA) into glycerol and free

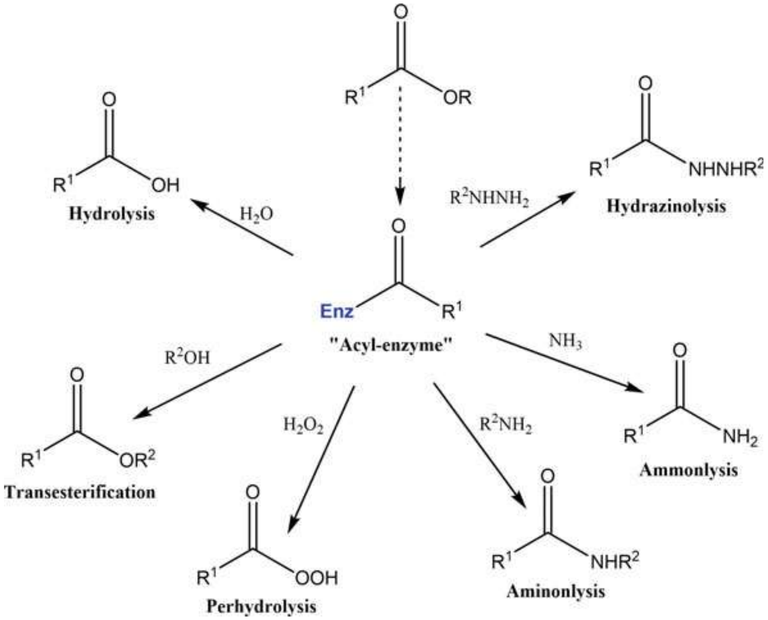


Fig. 1 Illustration of the wide applications of the lipases for several organic syntheses is water and non-aqueous media

fatty acids in water. In organic solvents, these enzymes can catalyze hydrazinolysis, ammonolysis, aminolysis, perhydrolysis, transesterification, and glycerolysis. The versatility of the lipases gives them wide applicability for several industrial sectors. Among the commercially available enzymes, Novozym® 435 (lipase B from *Candida antartica*—CalB) is the most applied in esterification reactions due to its advanced properties, such as a wide range of operating temperature of 20–110 °C, good recyclability, and high activity [30].

As illustrated in Fig. 2 there are different techniques for enzyme immobilization: physical methods (adsorption and entrapment into gel, membrane matrix, or metallic-organic framework) and chemical methods (covalent attachment and cross-linking).

The aims of the enzymatic immobilization on an inert substrate are to find out an improvement of the enzyme conformation preservation, catalytic activity, specific activity, immobilization efficiency, recovery of the enzyme activity (reusability), thermal and chemical stability to improve its stability toward denaturation by heat or organic solvent. The solid support must be insoluble in water, thermally and mechanically stable, able to support the enzyme, resistant to the enzyme, suitable for a large-scale application, inexpensive, and easy to functionalize. Lignocellulose biomass from bamboo could fullfill all these requirements considering that it is a cheap and fast-grown resource.

The enzyme immobilization is necessary for the separation, recovery, and reusability of the biocatalyst for industrial economic impact overall the process.

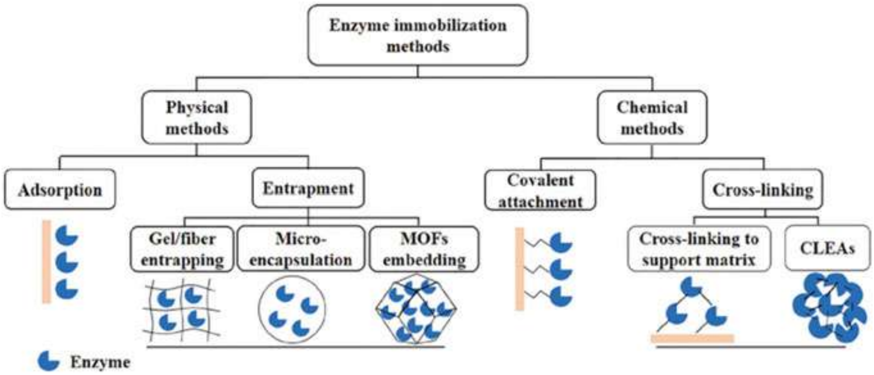


Fig. 2 Different protocols for enzyme immobilization (Abbreviations: MOF, metallic-organic framework; CLEA, crosslinked enzyme aggregates)

From the industrial point of view, if the reusability of the enzyme is important, at the same time is relevant to the costs of the support and the chemical modification steps necessary for the immobilization of the enzyme onto the carrier. All these aspects should be balanced to decide the favorable approach to scale up production through the biocatalytic process in continuous mode or in batch. If we consider only the lignocellulosic from bamboo biomass as carriers, only one study was carried out with a packed-bed reactor (PBR), while the others are all executed with a classical batch stirred tank reactor (BSTR) (Table 1). However, in the literature, flow bioreactors for biocatalytic process intensification have been presented with new configurations and immobilization techniques. The transition from batch to continuous flow micro- and mesoreactor involves important green chemistry and process intensification aspects [31]. The influence of the immobilization methodology and relative chemical pretreatment on the pristine bamboo carrier or its extracted biopolymers (lignin and lignocellulose) plays a crucial role in the biocatalytic activity, stability, and reusability.

The pretreated chemical methods allow the cleaning of the bamboo's inner cavities, and the elimination of the impurity, ions, starch, and natural metabolites. As well as the chemical activation process could improve the adsorbing capacity by changing the roughness of the surface, and the porosity of the biomass matrix, or adding new chemical functionalities for selective chemical binding of the enzyme. Acid or alkali pretreatments or oxidative attach have been executed with different results depending on the chemical composition of bamboo biomass and the structural protein of the enzyme. Considering the varieties of bamboo species and the enzyme is far from the establishment of a standard method for enzyme immobilization steps. In Table 2 we have summarized the different pretreated methods used for each method indicated in Table 1. For example, with acid treatment, hemicellulose and cellulose can be partly hydrolyzed, while during an alkali treatment, the lignin polymer could partly dissolve, and more hydroxyl groups can be exposed for better interaction with the protein surface of the enzyme (Fig. 3).

Table 1 Summary of biocatalytic reaction with immobilized enzyme on bamboo derivatives

Bamboo species (morphology)	Source of enzyme	Method of immobilization	Reaction (substrate and solvent)	Reactor configuration	References
Pristine Lignocellulose Bamboo Powder (BP) (*Dendrocalamus giganteus*)	Lipases (*Candida Antarctica* Lipase B—CalB and *Rhizomucor miehei—RM*) from Novozymes	Physical Adsorption and covalent binding with APTS and glutaraldehyde (*lipase*@BP)	Esterification of Palmitic acid with ethanol in heptane, hydrolysis of olive oil, kinetic resolution of a racemic solution (±)-1-phenylethanol with vinyl acetate in cyclohexane	BSTR and PBR	[2]
Lignocellulose Bamboo powder (BP) (*Bambusa multiplex*)	*Candida Antarctica* Lipase B	Core–shell immobilized lipase onto bamboo carrier with alginate core–shell structure *lipase*@core–shell-alginate	Esterification of lauric acid with isooctanol into n-hexane	BSTR	[3]
Lignin from Bamboo Bar (BB) (*Phyllostachys pubescens*	Neutral protease (NP)	covalent binding between a quinone group of oxidized lignin and an ammine group of NP (*neutralprotrase*@BB-lignin)	Proteolyisis of Casein	BSTR	[4]
Lignin powder from Bamboo Shoot Shell (BSS) (*Dendrocalamus Latiforus*)	*α-amylase* from *Bacillus subtilis*	Adsorption binding onto BSS lignin (*α-amylase*@BSS-lignin)	Hydrolysis of a-1,4-glycosidic linkages in starch and other related carbohydrates	BSTR	[5]
Lignocellulose Bamboo Sticks (BS) from the commercial market	*L-glutaminase* from *Escherichia coli*	Covalent immobilization with glutaraldehyde on cellulose polymer of BS (*L-glutaminase*@BS)	Hydrolytic deamidation of L-glutamine (L-Gln) to ammonia and L-glutamic acid	BSTR	[6]

Abbreviation Batch stirred tank reactor (BSTR) and Packed-bed reactor (PBR)

Table 2 Chemical treatment for the immobilization protocol of the enzymes

Carrier substrate	Chemical pre-treatment	Enzyme@Carrier	Protein loading	Recycling activity
Pristine Lignocellulose Bamboo Powder (BP) (*Dendrocalamus giganteus*)	Washing in water, SDS or hexane	Lipase@BP-lignocellulose	CalB 14.0 mg/g of bamboo and for RM 11.0 mg/g of bamboo powder	10 cycles with a constant enzyme activity of 53% for CalB and 86% for RM of esterification conversion
Lignocellulose Bamboo Fiber (BF) (*Bambusa multiplex*)	With 2 wt% NaOH solution at 120ºC for 1 h, 1.2 wt% sodium alginate (core), and 0.69 wt% calcium alginate (film shell) with a calcification time of 100 min at 30 °C	*Lipase*@core–shell-alginate	Not reported	17 cycles with a constant 80% of esterification conversion
Lignin from Bamboo Bar (BB) (*Phyllostachys pubescens*	16% NaOH and 2% Na_2SO_3 (1:5 v/v) for 30 min at 160ºC and left in distilled water for 12 h at 50ºC	*Neutralprotrase*@BB-lignin	5 mg/g of BB	6 cycles with a constant loss of the activity till 37%
Lignin powder from Bamboo Shoot Shell (BSS) (*Dendrocalamus Latiforus*)	Extraction of lignin from BSS with acetic acid (87%), HCl (36%) for 80 min, filtration and washing with hot water, and finally, lyophilization	*α-amylase*@BSS-lignin	19.0 mg/g	10 cycles with a constant loss of activity till 62%, and after 14 cycles, the residual activity fell to 53%
Lignocellulose Bamboo Sticks (BS) from the commercial market	Chemical modification of cellulose with 50% (v/v) THF/APTS (12 h) and (20%) H_2O/glutaraldehyde (12 h) then washed with sodium acetate solution (5 mM), the BS modified was stirred with L-*glutaminase* enzyme	*L-glutaminase*@BS	Not reported	5 cycles with a maintained activity of about 60%

Abbreviations SDS, sodium dodecyl sulfate, APTS, 3-aminopropyltriethoxysilane, THF, tetrahydrofuran

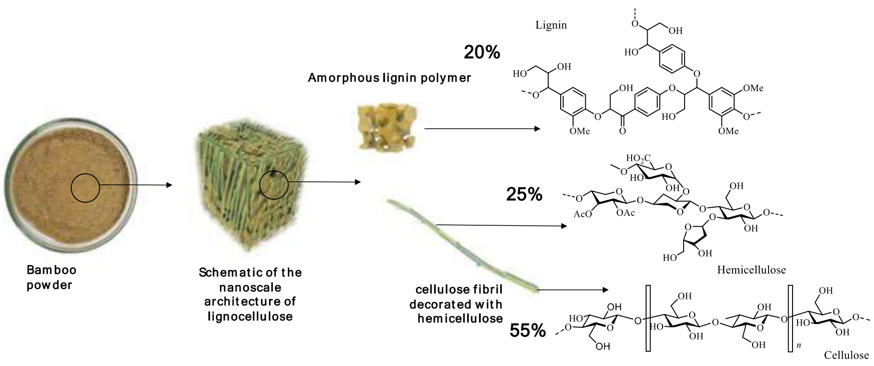
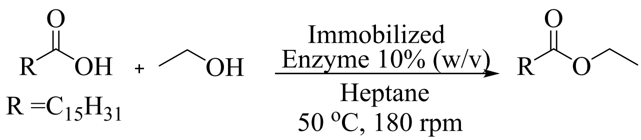


Fig. 3 Lignocellulose bamboo derivates as support for enzyme immobilization

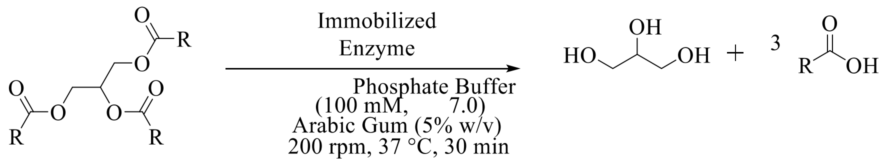


Scheme 1. Esterification performance of CalB immobilized on pristine bamboo powder (IB-CalB) by covalent attachment and physical adsorption

B. Palma and co-workers tested the esterification of ethyl palmitate to determine the immobilization efficiency of CalB and RM, physically absorbed or covalently attached to pristine bamboo powder into BSTR [2]. The covalent attachment method resulted in a non-effectiveness with a conversion of 75% compared to the 92% of physical adsorption when 3 mL of a 100 mM solution (1:1 palmitic acid/ethanol) in heptane and 30 mg of immobilized biocatalyst (IB-CalB), at 50 °C were let 6 h under orbital stirring (Scheme 1).

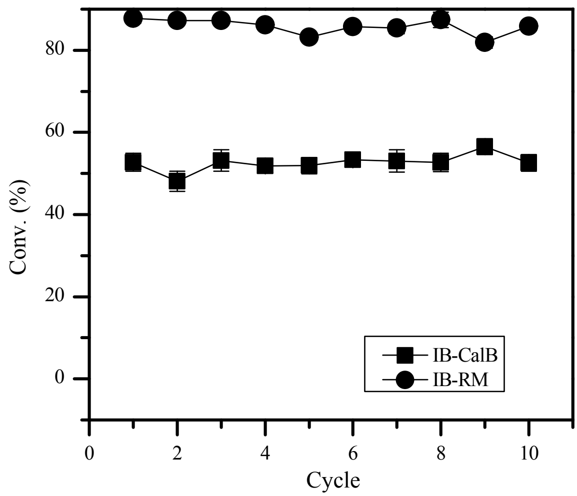
To improve the enzyme immobilization efficiency by physical adsorption, hydrolysis of olive oil was carried out as a reaction model (Scheme 2) with a pre-treatment of the powder to remove impurities and increase the interactions between the protein and the lignocellulosic surface. The reaction model was tested with 3 different powder carriers: (a) pristine bamboo without pre-treatment, (ii) washed with hexane, and (iii) washed with a solution of sodium dodecyl sulfate (SDS). None of the washing treatments allowed an increase in the catalytic performance of the olive oil hydrolysis.

After determining the lowest protein loading on the support carrier (14 mg of CalB.g^{-1} of bamboo and of 11 mg of RM.g^{-1} of bamboo), the batch operation stability of the biocatalyst is another important test to evaluate the recovery and reusability of the immobilized biocatalyst. Figure 4 shows the operational stability



Scheme 2 Evaluation of carrier pre-treatments on the catalytic performances of the immobilized biocatalysts (IB-CalB and IB-RM) for olive oil hydrolysis

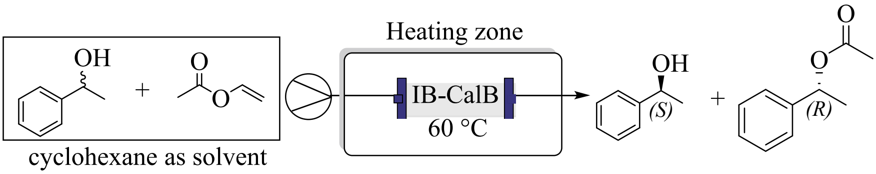
Fig. 4 Batch operational stability of ethyl palmitate reaction conditions: 3 mL of a 100 mM solution (1:1 palmitic acid/ethanol) in heptane and 30 mg of immobilized biocatalyst, at 50 °C for 2 h under orbital stirring (14 mg of CalB.g^{-1} of bamboo and of 11 mg of RM.g^{-1} of bamboo). Esterification conversions were determined by GC-FID from the relative peak areas. Reprinted with permission from [2] Copyright 2021, Elsevier



of ethyl palmitate synthesis in successive batch reactions for the immobilized biocatalysts. The esterification conversion of about 86% and 53% for IB-RM and IB-CalB, respectively, evidence the stable interaction between the enzyme and lignocellulose surface without leaching of the enzyme.

After optimizing the best kinetic resolution of a racemic (±)-1-phenylethanol in batch condition with the immobilized biocatalyst CalB (IB-CalB), the same was packed into a glass column of 1 cm diameter and 4.3 cm height containing 1 g of IB-CalB for the kinetic resolution of rac-1-phenylethanol in the presence of acyl donor (Scheme 3 and Fig. 5). With the continuous-flow protocol was observed an enhancement of the product conversion (45%) of the product with a reduction of reaction time (2 h).

The internal illustration of the immobilized lipase onto a lignocellulose bamboo carrier into a core–shell alginate structure [3]. The authors have reported an important and hard investigation for the optimization of the chemical parameter conditions to obtain the most stable core–shell carrier to increase the thermal stability and the reusability of the immobilized enzyme up to 18 cycles maintaining the esterification



Scheme 3 Kinetic resolution of rac-1-phenylethanol applying IB-CalB as a biocatalyst in continuous flow into a packed-bed flow reactor containing 1 g of IB-CalB, flowing at 60 °C a rate of 0.056 and 0.028 mL · min^{-1} cyclohexane, rac-1-phenylethanol (0.3 M), acyl donor (0.3–0.6 M). Reprinted with permission from [2] Copyright 2021, Elsevier

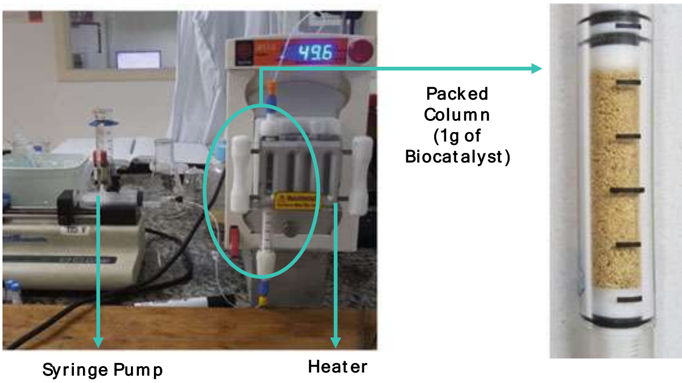


Fig. 5 The packed-bed reactor of 1 cm diameter and 4.3 cm height containing 1 g of IB-CalB for the kinetic resolution of rac-1-phenylethanol. Reprinted with permission from [2] Copyright 2021, Elsevier

conversion of lauric acid with isooctanol above 80%. Considering the potential application for the industrial esterification processes, it is important to consider the time consumption for the optimization process of this kind of bamboo-derivative carrier.

Yu-Huan Liu et al. reported a neutral protease (NP) immobilized on oxidized lignin with a chemical binding between a quinone group and an amine group of the enzyme. The bamboo bar was treated with an oxidant solution containing 16% NaOH and 2% of Na_2SO_4 (1:5, v/v) for 30 min at 160 °C and left in distilled water for 12 h at 50ºC followed by a UV light treatment. The oxidant treatment allows the break of the α-O-4 and β-O-4 bonds of lignin into a phenolic hydroxyl group and finally obtains a quinone group with a UV photoreaction. The quinone-amine condensation reaction allows the chemical immobilization of the enzyme. The maximum enzyme activity was reached after the optimization condition of the procedure at 7 pH, 4 h of contact at 40ºC, with an enzyme loading of 5.0 mg. The reusability of the immobilized enzyme was tested up to 6 cycles with a constant drop of the protease activity to 37%. The loss of protease activity might be due to the enzyme active site's conformational change, or the enzyme's leakage from the matrix during the reaction and washing steps.

W. Gong et al. proposed a simple adsorption immobilization of α-amylase onto lignin powder from bamboo shoot shell (BSS). The extraction of lignin from bamboo (*Dendrocalamus latiforus*) was described by the same authors elsewhere [32].

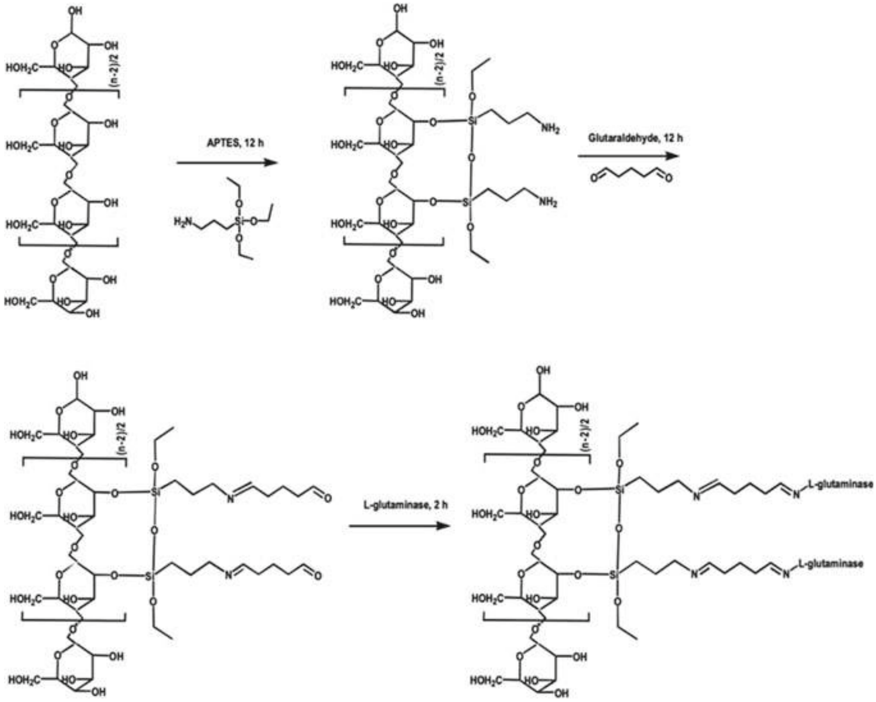
BSS was suspended in a hot water bath for 2 h at 95ºC, filtered, and dried overnight in an oven at 60ºC. The residual BSS was treated with aqueous acid acetic (87%), added with concentrated HCl (36%), and kept under stirring for 80 min. The contents of the flask were filtered and washed with distilled water and acetic acid (87%). The filtrate was purred in water and centrifugated at 4000 rpm for 10 min, then lyophilized to obtain the desired lignin pellet from BSS. For the adsorption of the enzyme onto the carrier, 1 g of BSS lignin powder was suspended with a commercial crude α-amylase in a buffered solution for 30 min at 30ºC under stirring. The immobilized *α-amylase*@BSS-lignin was characterized in terms of protein loading (19.0 mg/g), catalytic activity (92.4 U/mg of protein), storage stability (60ºC and pH of 6.5), and operation stability (62% after 10 cycles).

Li qi et al. proposed an *L-glutaminase* enzyme immobilized onto the bamboo stick (BS) through a glutaraldehyde modification of the cellulose for covalent binding (Scheme 4). *L-glutaminase*@BS has been developed for inhibitor screening applications. The cellulose surface was chemically modified with 3-aminopropyltriethoxysilane (APTS) and aqueous glutaraldehyde to immobilize the enzyme through the condensation reaction between the aldehyde and an amino group of the *L-glutaminase*. *L-glutaminase*@BS system was tested, promoting the hydrolytic deamidation of L-glutamine (L-Gln) to ammonia and L-glutamic acid (L-Glu). The operation stability (reusability) of the *L-glutaminase*@BS was tested for up to 5 cycles maintaining a hydrolytic activity of about 60%.

3 Bamboo as Support for Analytic Colorimetric Sensor and Metal Catalytic Organic Synthesis

3.1 Lignocellulose-Based Analytical Devices (LADs)

The first work to explore the capillarity of bamboo vascular bundles to create high-detection analytical devices was carried out in 2015 by Kuan et al. [7] The authors developed one-dimensional, low-cost, and easy-to-handle lignocellulose-based analytical devices (LADs) with passive transport based on passive capillary flow. Firstly, bamboo and wood stirrers were pre-treated with deionized water at 100 °C for 5 h to remove chemicals and starch granules, then dried at 50 °C for 8 h. The LADs were made using only a drill press and colorimetric reagents and colorimetric reagents for detection. Figure 6 shows the sequence: (I) creating a groove



Scheme 4 Immobilization of L-glutaminase onto lignocellulose Bamboo Sticks (*L-glutaminase*@BS). Reprinted with permission from [6] Copyright 2019, Elsevier

as a reaction zone on the surface of bamboo stirrers with a drill press, (II) immobilizing detection reagents (colorimetric reagents) with a micropipette into the reaction zone, (III) immersing the SMLADs into the target samples, (IV) recognizing the colorimetric results on the surface of the reaction zone.

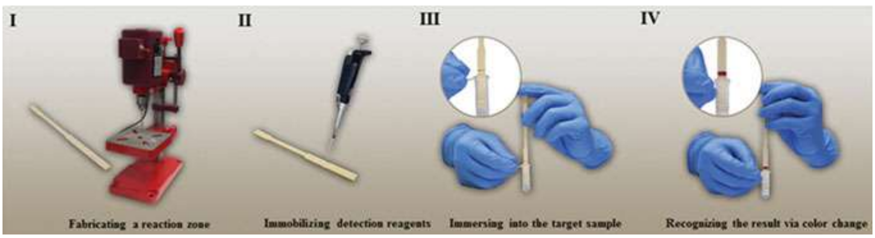


Fig. 6 Schematic of the fabrication process of LADs: (I) fabrication of a reaction zone; (II) immobilization of the colorimetric reagents; (III) immersion of the LAD into the target sample; (IV) colorimetric recognition of the results into the reaction zone. Reprinted with Creative Commons CC BY license [7]

After optimizing the manufacturing process of the LADs and adjusting the detection signal, it was observed that the position of the reaction zone and the immersion times influenced the sensitivity of colorimetric assays. As a result, the optimized set-up was chosen as a device with a reaction zone of 3 cm from the end zone absorption and a 7 min solution immersion period. The images of the reaction zone were captured with a digital camera, and the color intensity was analyzed by ImageJ Software to create a calibration curve and to determine the limit of detection (LOD) for each analysis. The LADs were applied in assays of nitrite with deionized water and hot-pot soup, resazurin in milk, PMS-MTT in water and nitrite, urobilinogen, and pH in human urine for urinalysis. The detection of nitrite followed the principle of the Griess reaction, where a reagent solution (3 μL of sulfanilamide, citric acid, and N-(1-naphthyl)-ethylenediamine dihydrochloride) was immobilized in the reaction zone (Figure AA). Bacterial (*E. coli*) detection was based on oxidation–reduction indicator (MTT) conversion. The detection of urobilinogen and glucose was based on the principles of the Ehrlich and glucose oxidase- and hydrogen peroxidase (HRP)-mediated couple reactions, respectively. The schematic representation of the PMS-MTT assay for bacterial detection in water is shown in Fig. 7. The bamboo LADs devices results indicated a nitrite detection limit with sensitivity compatible with the actual paper analytical device (PAD) [33]. The LODs for urinalysis of nitrite and urobilinogen were 0.06 mM and 160 mg/dL, respectively. The bacteria detection indicated LOD in the range of 1.8×10^4–9.3×10^4 CFU/mL which is ideal to monitor meat safety. As the authors projected, the lignocellulosic properties of longitudinal microfluidic channels, the passive capillarity, and the resistance of organic solvents may be significant to advance microfluidic research.

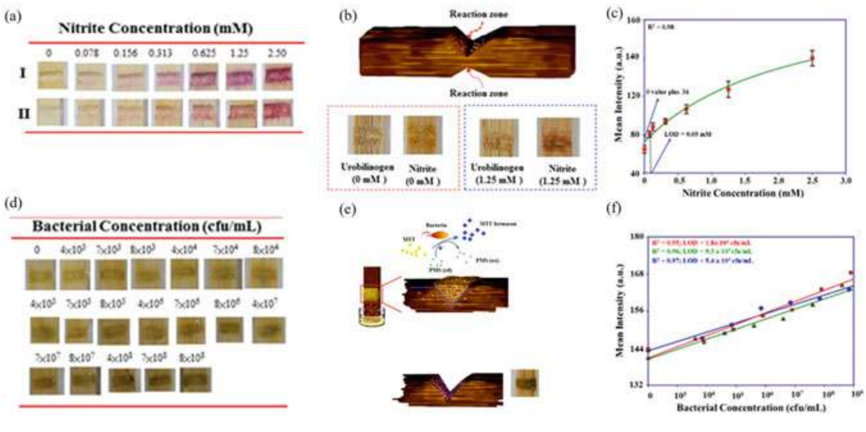


Fig. 7 **a** Colorimetric results for nitrite assay. **b** Multiple detections of nitrite and urobilinogen on two sides of the LDA with the colorimetric results into red and blue boxes. **c** A nitrite calibration curve **d** Colorimetric results for bacterial detection in drinking water (PMS-MTT assay). **e** schematic representation of the PMS-MTT assay and **f** Bacteria (*E. coli*) calibration curve. Reprinted with Creative Commons CC BY license [7]

3.2 Copper-Functionalized Lignocellulosic Microreactor (Cu-LµR) in Flow Mode

The unprecedented fabrication of a copper-functionalized lignocellulosic microreactor (Cu-LµR) from bamboo culms wacs carried out in 2019. de Sà et al. [9] explored the 3D structure and vascular channels of giant bamboo (*Dendrocalamus giganteus* Munro) to develop a microreactor applied as a catalytic microfluidic device. The biomicrofluidic device (LµR) showed easy prototyping and quick functionalization of internal channels with copper (II) ions. The manufacturing process of LµR involves a sequence of cuts followed by gluing connectors and pumping fluid through the device. Figure 8 shows the following phases to manufacture LµR: (i) cut an internode sector of bamboo culm into a suitable segment length of 3 and 6 mm diameter, using three different types of rotary saws; (ii) clean the internal vascular bundles with water by vacuum-induced penetration and dry in a standard convection oven; (iii) reduce the diameter size of the segment to 4.2 mm; and (iv) glue two syringe needles as inlet and outlet of the microreactor with connections to polyethylene tubes. The device showed excellent microfluidic performance at both low and high flow rates (from 0.1 to 2.0 mL min^{-1}), with a backpressure of 5 psi at 2.0 mL/min^{-1} and without any type of leakage.

To immobilize Cu(II) ions in LµR, the cellulose of the microchannel inner walls was modified via chemoselective oxidation of the hydroxyl carbon 6 with carboxylate formation. Figure 9 shows the process of cellulose oxidation and functionalization

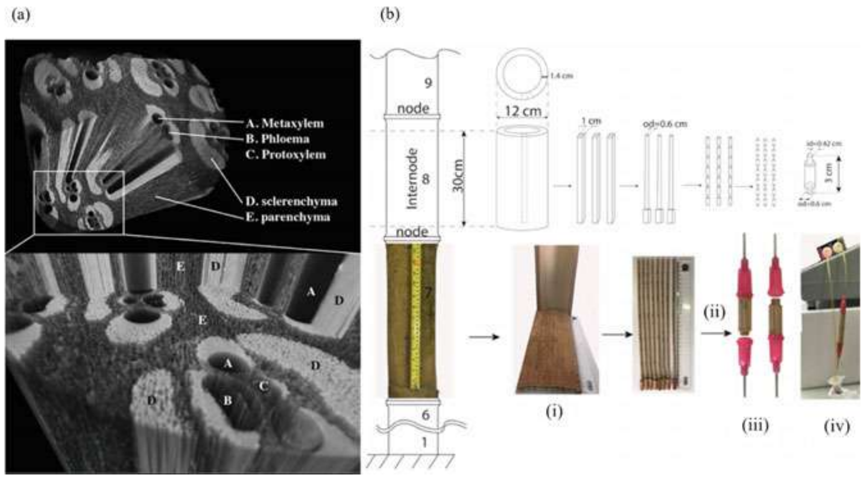


Fig. 8 **a** µCT image of the internal structure of bamboo with its vascular bundles (metaxylem, phloem, and protoxylem), sclerenchyma, and parenchyma tissue; **b** fabrication of lignocellulose-based microreactors (LRs) from bamboo internode 7. A tutorial video for the fabrication process is available in the supplementary information of Ref. [9]. Reprinted with permission from ACS Sustainable Chem. Eng. 2019, 7, 3, 3267–3273. Copyright 2019 American Chemical Society

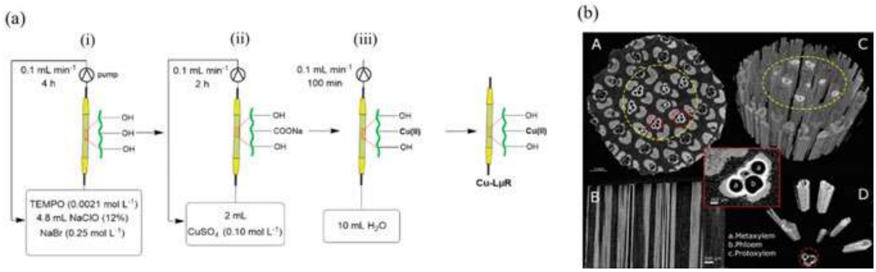


Fig. 9 **a** Functionalization with copper ions of LμR. **b** μCT images of Cu-LμR: transversal and longitudinal cross sections of bamboo culm (A–B); 3D image with and without the vegetal biomass (C–D). The dotted circular yellow line with an internal diameter of 4.2 mm corresponds to the internal area of flow injection. Insight into the metal depositions onto microchannels (metaxylem, phloem, protoxylem) are highlighted with red lines. Reprinted with permission from ACS Sustainable Chem. Eng. 2019, 7, 3, 3267–3273. Copyright 2019 American Chemical Society

with Cu(II). (i) An oxidative solution containing TEMPO/NaClO/NaBr was recirculated through LμR by a peristaltic pump for 4 h at 0.1 mL min^{-1}. Subsequently, (ii) a solution of $CuSO_4 \cdot 5H_2O$ 0.10 mol L^{-1} was pumped into the functionalized microreactor (2 h at 0.1 mL min^{-1}) for complexation between Cu(II) and the carboxylate group. Finally, (iii) 10 mL of ultrapure water was injected to wash and remove unbound copper from the polymer matrix (100 min to 0.1 mL min $^{-1}$). Figure 9b shows μCT de-LμR images that show the coating of vascular bundles (metaxylem, phloem, and protoxylem).

As a proof-of-concept study, the continuous-flow copper(I)-catalyzed 1,3-dipolar cycloadditions (CuAAC) was selected as the benchmark to test the effectiveness of the fabricated bamboo-based microreactors. The continuous flow click chemistry reactions within Cu-LμR were performed from the injection of a solution containing 0.12 mol of aryl azides, 0.14 mmol of phenylacetylene, and 5 mg of sodium ascorbate at a rate of 0.1 mL min^{-1} for 6 h. A series of 1,4-disubstituted 1,2,3-triazole derivatives were obtained under a flow regime with good efficiency (60–96%) and leaching minimum copper (5 ppm) (Fig. 10a). The contribution of copper leached during the reaction to the formation of product 3aa in homogeneous catalysis was evaluated by the following experiment (Fig. 10b). The reaction mixture was pumped through Cu -μLR for 2 h with a product yield of 16%. Then, the system was stopped, and the reaction mixture was kept under stirring for 6 h without Cu-μLR contact with a small yield increment of about 2%. Finally, the reaction mixture was recirculated through Cu-μLR for 6 h with a final product yield of 80%. This result indicated that in the formation of 3aa, the heterocatalytic contribution of the complexed copper inside the LμR channels is much higher than the contribution of the leached copper in the medium reaction. The device maintained good catalytic yield for 3aa formation (80–73%) until the fifth reuse (Fig. 10c). Maintaining process efficiency demonstrates the long-term operation of the new copper lignocellulosic microreactor. The simple, rapid and more sustainable prototyping of LμR has contributed to a new class

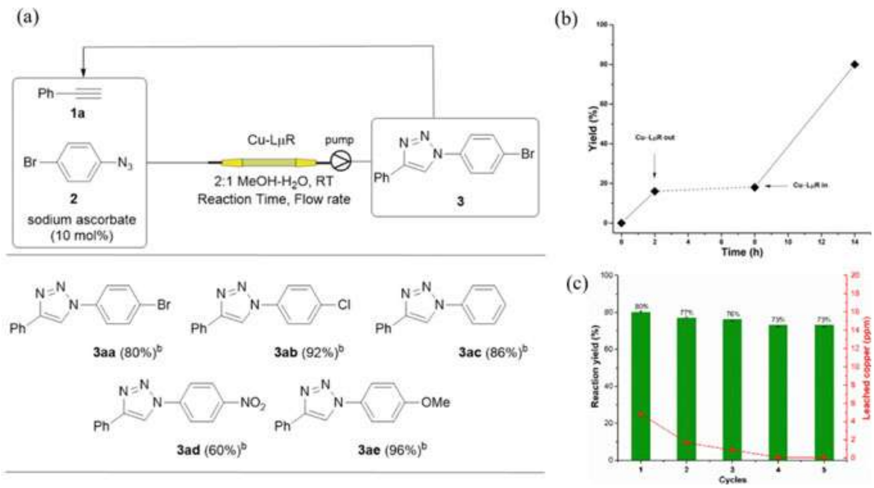


Fig. 10 **a** Scope of the CuAAC flow procedure with Cu-LmR. [a]**1a** (0.14 mmol), **2** (0.12 mmol), sodium ascorbate (10 mol%), 2:1 MeOH-H_2O (3 mL). [b]Isolated Yield. **b** Evaluation of the contribution of homogeneous catalysis (leached copper) to the reaction outcome of the optimized flow process with Cu-LμR. **c** Reusability of Cu-LμR and quantification of leached copper (ICP-MS analysis).Reprinted with permission from ACS Sustainable Chem. Eng. 2019, 7, 3, 3267–3273. Copyright 2019 American Chemical Society

of biomicrofluidic devices with potential applications in the area of heterogeneous catalysis or biocatalysis.

3.3 *Copper Nanoparticle-Functionalized Bamboo Slice for Batch Organic Reaction*

In 2022, De Sà et al. disclosed a lignocellulosic bamboo (*Dendrocalamus giganteus Munro*) catalytic support using a sustainable heterocatalytic organic reaction in batch mode [8]. The first step consisted of the unprecedented one-pot synthesis of copper nanoparticles (CuNPs) capped by carboxymethylcellulose (CMC) in the presence of NaOH at 60 °C, without the use of traditional reducers (Fig. 11a). In the second step, the bamboo slices (BS) (10 mm × 10 mm × 1 mm) were subjected to oxidation mediated by the reagent TEMPO/NaClO/ NaBr for 4 h (Fig. 11b). Subsequently, BS was immersed in 2 mL of CuNPs-1 mM-60 °C, CuNPs-3 mM-60 °C, and CuNPs-5 mM-60 °C and left in contact for 8 h, to obtain the catalytic charges of 0.3, 1.8 and 2.5 mol% Cu, respectively (Fig. 11c), indicating a good capacity for functionalization of the bamboo surface. The functionalization capacity of the support is an important factor in heterogeneous catalysis as it allows different catalyst loads on the solid support according to the needs of the reaction used.

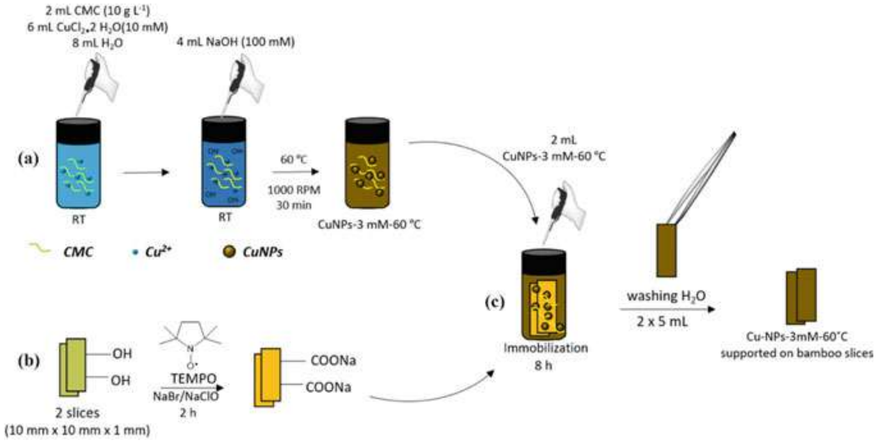


Fig. 11 Schematic representation of the experimental steps for the synthesis of CuNPs (**a**); oxidation of bamboo slice (BS) (**b**) and immobilization of CuNPs on BS (**c**). Reprinted with permission from [8] Copyright 2022, Springer Nature

The last step consisted of the catalytic application of CuNPs-3 mM-BS (1.8 mol%Cu) in the CuAAC reaction to form 1,2,3-triazoles 1,4-disubstituted. Several triazole compounds were synthesized in water at 70 °C with yields ranging from 78 to 98% and leaching of 1.14 ppm (Fig. 12a). The evaluation of the contribution of CuNPs leached in the reaction medium (1.14 ppm, ICP-OES analysis) in the formation of product 3ab was studied according to the following experiment (Fig. 12b). The mixture of reagents in the presence of the CuNPs-BS was initially stirred for 90 min to detect a product yield of 52% by ^{1}H-NMR analysis. Then, the catalyst support was removed, and the reaction mixture was stirred for 90 min more, observing a 6% increase in yield. Finally, the reaction mixture was put in contact again with CuNPs-BS for another 90 min reaching a yield of 90%. These results indicate that the leached copper contributes minimally to the conversion of the reaction, which mainly proceeds under heterogeneous conditions. CuNP-3 mM-60 °C showed good recyclability with a small drop in catalytic performance after the seventh reuse (from 90 to 73% 3aa yield) and a negligible increase in copper leaching was observed (from 1.14 to 1 0.31 ppm) (Fig. 12c). Compared to the copper-functionalized lignocellulosic microreactor (Cu-LμR) [9], the detected copper leaching was much lower, thus demonstrating the utility of CuNPs-BS in long-term catalytic applications.

3.4 Silver Nanoparticle-Functionalized Bamboo Capillary Microreactor (BCMR)

Another application of biomimetic design inspired by the water transport system in vascular bundles of bamboo is the creation of a bamboo microreactor functionalized

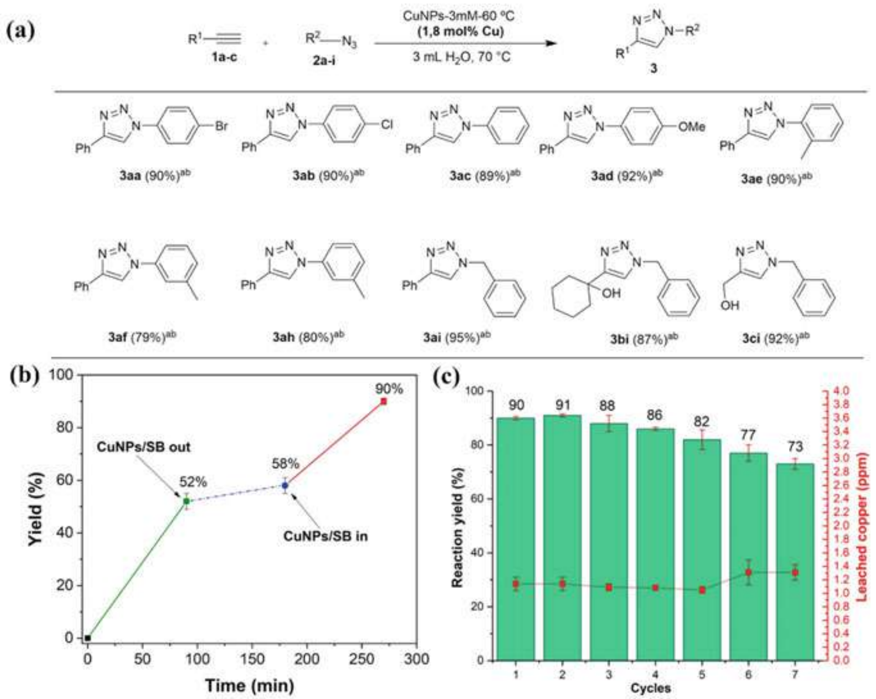


Fig. 12 **a** Scope of the CuAAC batch procedure with CuNP-3 mM-60 °C supported on bamboo slice. [a]1a–c (0.14 mmol), 2a–h (0.12 mmol), [b]Isolated Yield, [c]3ah, 3bh, and 3ch were synthesized by one-pot methodology: benzyl chloride (0.24 mmol) and terminal alkyne (0.24 mmol), NaN_3 (15.6 mg, 0.24 mmol) and Cu-NPs-bamboo (1.8 mol%) in 5 mL of H_2O. **b** Evaluation of the contribution of homogeneous catalysis (leached copper) to the reaction outcome with CuNP-3 mM-60 °C on a bamboo slice. **c** Reusability of CuNP-3 mM-60 °C supported on Bamboo slice and quantification of leached copper (ICP-EOS analysis). Reprinted with permission from [8] Copyright 2022, Springer Nature

with silver nanoparticles (AgNPs) generated in situ to reduce aromatic nitrocompounds [10]. In this type of device, the 3D structure and the growth direction of Moso bamboo (*Phyllostachys edulis*) are preserved, and AgNPs play the role of a heterogeneous catalyst. With the aid of a peristaltic pump, the vascular bundles were explored, mimicking the natural process of pumping water by bamboo. The fabrication of the device went through the step of processing the bamboo into sticks 200 mm in length and 10 mm in diameter using a drawing machine (Fig. 13a–b). The SEM images (Fig. 13c–d) allowed the identification of the vascular bundle system with mean channel diameters of 126, 131, and 42 μm for the metaxylem, phloem, and protoxylem, respectively. Prototyping this type of device was simple and fast. For the construction of the flow system, the ends of the bamboo sticks were connected to silicone tubes, and the surface was coated with 3 M tape to prevent leakage. The functionalization of the microchannels of the bamboo microreactor with AgNPs occurred in situ without the addition of reductants or stabilizers from the continuous pumping of an $Ag(NH_3)_2NO_3$ solution through CMR at a flow rate of 0.3 mL/min (Fig. 13a–d). Samples treated with 8, 20, and 50 mM concentrations of $AgNO_3$ produced the devices Ag-1/B CMR (0.15 wt %), Ag-2/B CMR (0.36 wt %), and Ag-3/B CMR (0.56 wt %), respectively (Fig. 13e–g). The $Ag(NH_3)_2NO_3$ solution flow method with silver reduction by lignin, cellulose, and hemicellulose from bamboo was suitable for the homogeneous formation of AgNPs with an average size of 2.9 nm (Fig. 13h–i), mainly on the surface of bamboo microchannels along with flow routes with good dispersion.

The evaluation of the catalytic performance of CMRs was made from the reduction reaction of nitroaromatics (4-nitrophenol, 4-NP; 2-nitrophenol, 2-NP; 4-nitroamine, 4-NA and 2-nitroamine, 2-NA) in the presence of $NaBH_4$. The $NaBH_4$ and nitroaromatic solutions were mixed and immediately pumped through the three Ag-1/B CRM microreactors under different flow rates (60–420 μL/min) (Fig. 14a–c). The reaction was monitored by observing the decrease of the 4-NP band at 400 nm and the formation of the 4-AP product band at 299 nm (Fig. 14d). The highest catalytic efficiency was achieved by Ag-3/B CMR (0.56% by weight), which achieved 99% conversion of 4-nitrophenol (4-NP) to 4-aminophenol (4-AP) at lower flow rates at 240 μL/min.

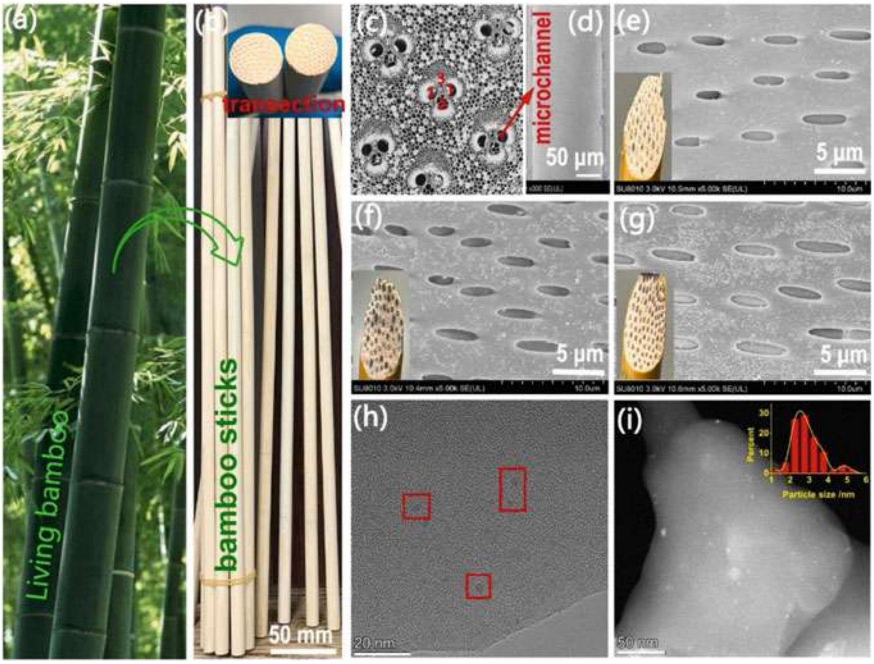


Fig. 13 CMR fabrication and characterization. **a** Moso bamboo culm. **b** Drawn bamboo sticks. **c** The mean diameters of (1) metaxylem, (2) phloem, and (3) protoxylem. **d** SEM image of a bamboo microchannel. **e**–**g** SEM images of bamboo microchannels Ag-1/B CMR (**e**), Ag-2/B CMR (**f**), and Ag-3/B CMR (**g**). **h** TEM image of an Ag-3/B CMR. **i** HAADF-STEM image of an AgNPs sample. Reprinted with permission from [10] Copyright 2022, Elsevier

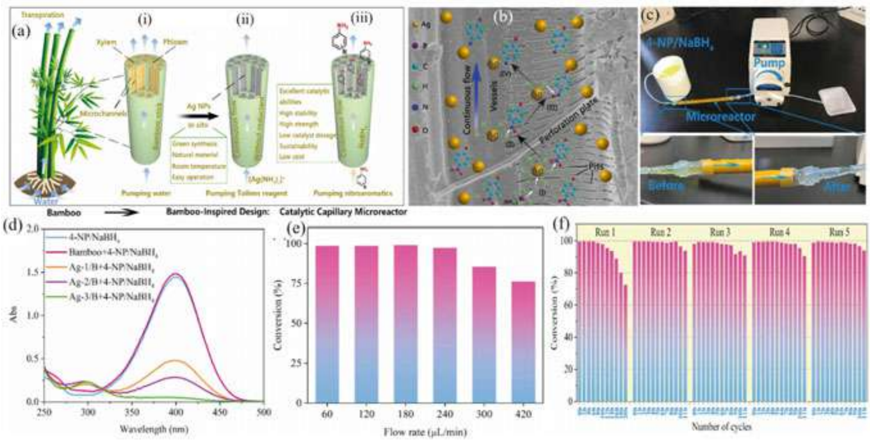


Fig. 14 **a** Bamboo-inspired CMR design. (i) live bamboo–water transport; (ii) functionalization of CMR microchannels with AgNPs in situ; (iii) Reduction of nitroaromatics in the microfluidic channels of AgNPs-CMR. **b** The proposed mechanism for 4-NP reduction in Ag-3/B CMR. **c** CMR flow system set-up. **d** Effect of Ag/B CMR catalytic charge on 4-NP/$NaBH_4$ reduction at 240 μL/min. **e** Effect of the flow rate on Ag-3/B CMR. **f** Long-term stability and reusability of the bamboo-inspired CMR. Reprinted with permission from [10] Copyright 2022, Elsevier

Rates above 240 μL/min showed that the catalytic efficiency of the device decreased significantly, reaching 76.2% at 420 μL/min, due to the reduction in residence time (Fig. 14e). To study the scope and generality of Ag-3/B CMR, other nitroaromatics with different substituents (2-NP, 2-NA, and 4-NA) were also subjected to a reduction reaction at a rate of 120 μL/min (residence time of 0.79 min) and showed total conversion in a short time. Fig. 14f shows that Ag-3/B CMR achieved catalytic performance of 90% in continuous flow for 11 h for five cycles, showing excellent stability and high efficiency. The Ag-3/B CMR microreactor was also applied to ambient water samples and showed high catalytic capacity. The simple manufacturing process steps, long-term stability, recyclability, and application diversification of a lignocellulosic microreactor are essential features to achieve future industrial applications.

4 Bamboo as a Template for Electrothermal Microfluidic Heater Device

Nowadays, 3D fabrication, such as controlled folding, 3D printing, and 3D electric and electrochemical devices, have been attracting attention because of all the energy storage potential. Processed cellulose-based fibers as papers and raw cellulosic materials are the two leading classes of cellulose-based materials that have been used to fabricate devices with high electrical conductivity. Bamboo has been standing out as the best raw biomass to be explored as a lignocellulosic natural resource due to its scalable production, eco-friendly, sustainable, low-cost, and portable electronic and electrochemical devices.

In the work of O. G. Pandoli et al., we could see for the first time a room temperature fast prototyping method to fabricate an ultrahigh conductive array of microchannels employing a *Dendrocalamus Giganteus*anisotropic lignocellulosic structure bamboo such as a new bio-template [11]. With the application of silver ink into the bamboo microchannels, a conductivity of 9.3 (±4.0) × 10^5 S m^{-1} was achieved. The Ag-coated bamboo device (d = 6 mm and L = 20 mm) demonstrated a high conductivity along the microchannels' direction however, a very high resistivity perpendicular to them shows an anisotropic internal structure of bamboo. In the direction of channels, the electrical resistance between the top and bottom surfaces consisted of the approximate value of $R_{\parallel} = 20\ \Omega$. Opposite of that, the electrical resistance increases by 10^6 in order of magnitude when measuring orthogonally to the lateral surface, reaching a value of $R > 20\ M\ \Omega$.

The method used in this reference article overshadows other state-of-art methods from three points of view. The first of them is the achieved high conductivity; the second is the possibility to create greener and more sustainable functional devices from nature and the last one is the production stability of the proposed device. A functional 3D electrical device was fabricated through an electric circuit in which the current flows from the bamboo's bottom face to the top in a microchannel array. These hollow conductive microchannel arrays make it possible to flow liquids (water, for instance) through the bamboo device metaxylem vessels with an efficient transfer of heat and increase the temperature of it. Due to the joule heating effect, it is possible to increase the temperature of bamboo when applying an electric current from 0.5 to 1.5A, as illustrated through infrared thermography images (Fig. 15a–d). Figure 15e–f show the entrance of water in bamboo and the steady state water outlet temperature for different flow rates at different current values, respectively. The water outlet temperature could be increased from 25 to 55 °C by controlling both the flow rate and electric current. In the bar graph of Fig. 15g, we observe an internal heating system achieving energy efficiency of 55%. This EE is notably higher compared to 30% for the external heating system, which presents higher resistance to deliver energy to warm up water (inside the microchannels) and faster heat dispersion to the external environment. In conclusion, the unique anatomic structure and the anisotropic conductive of bamboo microchannels made possible a complex three-dimensional electronic circuits fabrication and a microfluidic heater with notable potential applications where fluid heating is demanding.

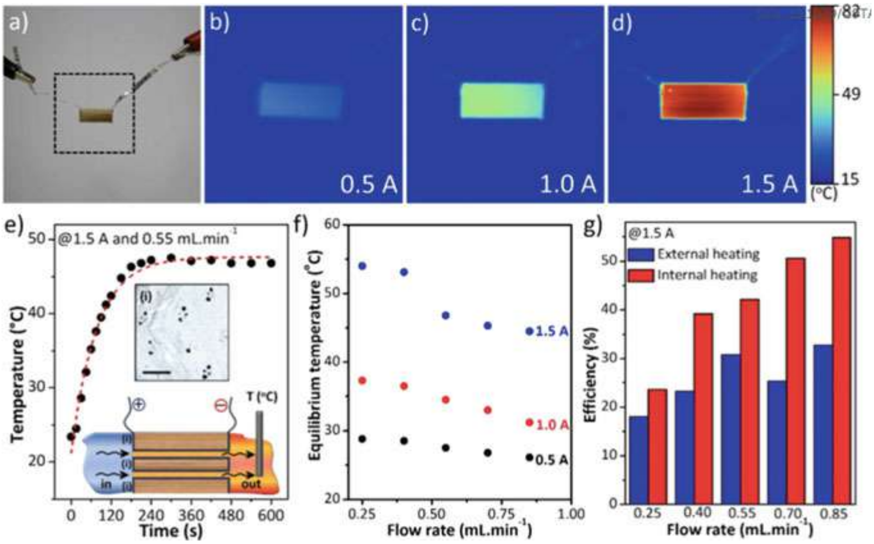


Fig. 15 **a** Photo of a multi-channel bamboo-based microfluidic heater (d = 6 mm and L = 20 mm) with electric contact; **b–d** Infrared thermographic images of bamboo under different currents (0.5–1.5A); **e** outlet water temperature vs time at fixed current and flow rate. Inset **i** shows an optical microscopy image of the Ag-coated bamboo surface presenting open channels (scale bar is 1 mm); **f** Out-let water temperature in function of flow rate and different applied currents; **g** Joule heating efficiency with internal and external conductive walls of bamboo. Reprinted with permission from [11] Copyright 2022 Royal Society of Chemistry

5 Bamboo Biomass for Water Treatment Applications

5.1 Hydrolyzed Bamboo as a Porous Bioadsorbent for Removal of Pb (II) from an Aqueous Mixture

Another major concern of environmental and health agencies is the big amount of industrial water with high levels of Pb(II) that is discarded into the oceans, contaminating several species of fish that will be consumed by human beings around the world. Knowing the high toxicity of this chemical element for humans, traditional methods of removing heavy metals are already widely used, such as chemical precipitation, oxidation, or reduction. However, these methods can produce new residues or pollutants and new toxic materials. Another method already used is adsorption with activated carbon, which has a very high cost and ends up limiting its application. As adsorption is a method with high efficiency, there is a demand for studies and the generation of green and sustainable adsorbent products capable of adsorbing Pb(II) in the presence of high concentrations of amino acids and salts. The ability to adsorb heavy metals from a solution comes from a key factor which is the functional groups present in the lignocellulosic biomass material. Carboxylic acid functionalities are

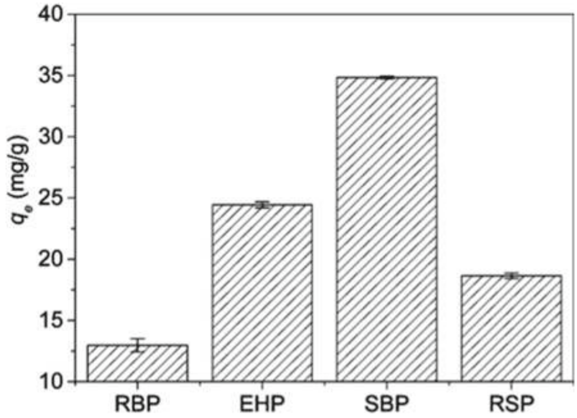


Fig. 16 Effect of different adsorbents on the adsorption capacity of Pb(II). The adsorption conditions were pH 5.0; contact time, 240 min; Pb(II) concentration, 50 mg/L; sodium chloride concentration, 4 mg/mL; arginine concentration, 20 mg/mL; adsorbent dosage, 0.05 g; and temperature, 303 K. Reprinted with permission from J. Agric. Food Chem. 2014, 62, 25, 6007–6015. Copyright 2019 American Chemical Society

effective for binding metal ions and can be introduced by the chemical modification of hydroxyl groups in the lignocellulosic biomass. The number of accessible hydroxyl groups determines the degree of biomass modification (e.g., by succinylation). In the work of Xiao-Kun Ouyang et al., the performances of raw bamboo powder (RBP) were investigated; enzymatically hydrolyzed bamboo powder (EHP); succinylated bamboo powder (SBP), and succinylated raw bamboo powder (RSP) [13]. As we can analyze in the graph of Fig. 16, the SBP method obtained the highest Pb(II) adsorption capacity, being chosen as the best method.

The efficiencies of the SBP method were analyzed under some factors that influence the adsorption capacity. Figure 17 shows that adsorption capacity increases with increasing pH (3.5–6) because of the proton competition and electrostatic repulsion effects decrease, and the carboxylic acid groups become deprotonated and easily attract Pb(II). The graph of Fig. 17b shows the decrease in the adsorption capacity of Pb(II) with the increase of its dosage, while Fig. 17c shows that the same adsorption capacity starts to have a stable and continuous behavior with increasing contact time between Pb(II) and the surface of the bioadsorbent. Finally (Fig. 17d), the adsorption capacity of Pb(II) with increasing sodium chloride concentration was studied. The capacity decreases considerably with increasing the NaCl concentration. To summarize, bamboo was used as an efficient Pb(II) bioadsorbent after enzymatic hydrolysis which allowed a significant increase in its porosity.

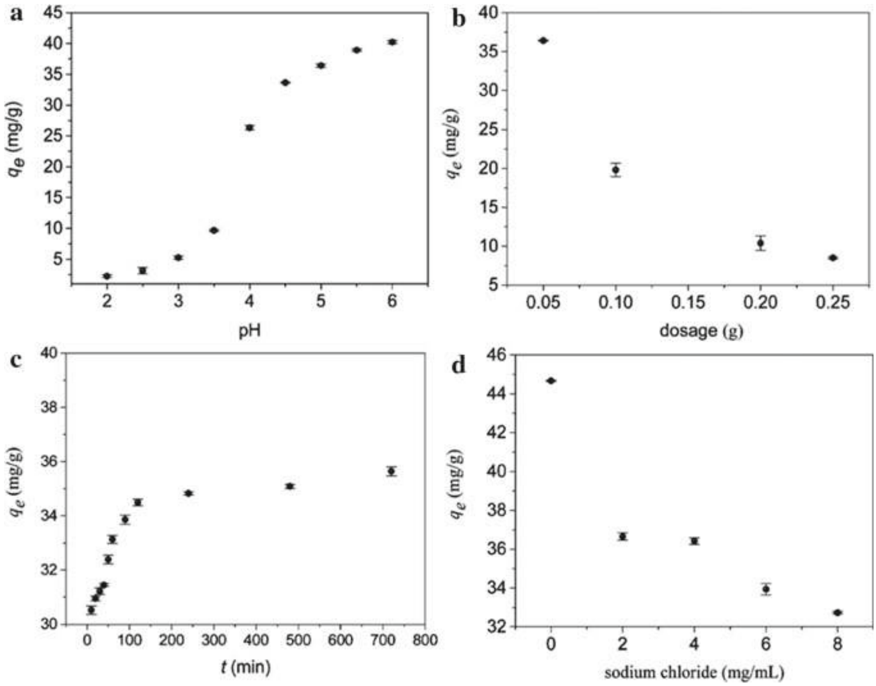


Fig. 17 Effects of experimental conditions on Pb(II) adsorption by SBP: (**A**) pH, (**B**) adsorbent dose, (**C**) contact time, and (**D**) sodium chloride concentration. Studies were conducted at pH 5.0; initial Pb(II) concentration, 50 mg/L; contact time, 240 min; adsorbent dosage, 0.05 g; and temperature, 303 K, unless otherwise stated. Reprinted with permission from J. Agric. Food Chem. 2014, 62, 25, 6007–6015. Copyright 2019 American Chemical Society

5.2 Pyrolyzed Bamboo Charcoal (BC) as a Porous Matrix for Water Remediation

Most of the studies exposed below are related to the transformation of the lignocellulose bamboo biomass into pyrolyzed bamboo charcoal (BC) in a nitrogen atmosphere. The BC, chemically treated with alkali, acid, and oxidant solutions, is defined as bamboo activated carbons (BAC) to increase the porosity and add a new chemical functional group. BC and BAC were used for metal removal in an aqueous solution or gas phase and adsorption of organic compounds, such as dyes, drugs, and aromatic compounds.

Batch adsorption experiments were conducted for the adsorption of Cd (II) ions from aqueous solution by BC [14]. The results showed that the adsorption of Cd (II) ions was very fast initially, and the equilibrium time was 6 h with an optimal pH 8.0 of Cd(II) removal with an adsorbed capacity of 18 mg g^{-1}. Similarly, the batch adsorption capacity of heavy metal ions by BAC was investigated by Sheng-Fong Lo et al. The optimum pH values for the adsorption capacity of heavy metal ions were

5.81–9.82 by bamboo-activated carbons. The optimum soaking time was 2–4 h for Pb^{2+}, 4–8 h for Cu^{2+} and Cd^{2+}, 4 h for Cr^{3+} by Moso BAC, and 1 h for the tested heavy metal ions by Makino BAC. The removal efficiency of heavy metal ions by various BACs decreased in the order: $Pb^{2+} > Cu^{2+} > Cr^{3+} > Cd^{2+}$. Depending on their interaction with anionic functional groups on the surface of activated carbon, the adsorption capacity varies from 0.68 to 0.19 mg g^{-1} [15, 16].

Mesoporous bamboo activated carbon (BAC) (surface area of 608 m^2/g) has achieved high efficiency in the removal of Cd(II), Hg (II), and Zn(II) ions from the water solution [17]. The proposed low-cost adsorbent was physically activated with water steam from the bamboo species *Bambusa vulgaris striata*. The batch studies suggested the highest adsorption capacities for an activated carbon dose of 0.6 g/L, solution pH of 9, and an equilibrium time of 16 h in static conditions, are 240, 248, and 254 mg/g of cadmium, mercury, and zinc, respectively. Figure 18 shows several adsorption capacities on conventional lignocellulosic-based adsorbents. Among them, other studies using bamboo derivates were mentioned with lower absorption capacities: 12.8 mg/g of Cd(II) on bamboo charcoal (BC) [14], and 40.5 mg/g of Zn(II) on BAC of *Melocanna baccifera* [18].

The bamboo charcoal, after chemical modification with $FeCl_3$ was demonstrated as an excellent absorbent for removing gaseous mercury [19]. The mercury removal performance of modified bamboo charcoal (BC) was investigated with a bench-scale fixed-bed reactor at a relatively high reaction temperature (140 °C) (Fig. 19). It can be assumed that Hg^0 reacts with Fe^{3+} to form the final oxidized mercury on the carbon surface with an adsorption capacity of 12.9 mg g^{-1}.

The removal of organic dyes, pharmaceutical compounds, and fertilizer from wastewater is an important environmental issue for the purification of industrial dye effluents and drinking water. The use of BC is an alternative strategy to the use of commercial activated carbons, advanced oxidation processes (AOPs), and biological treatments.

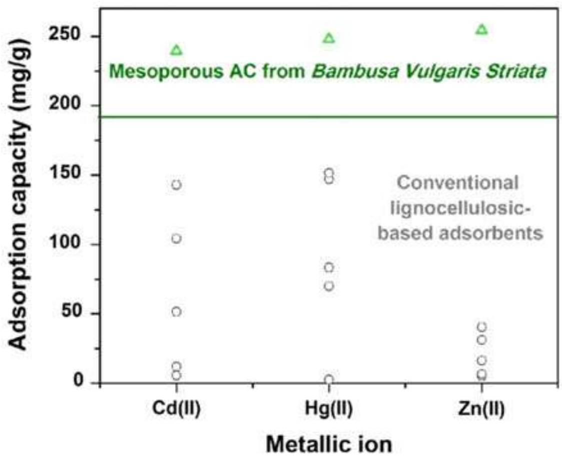


Fig. 18 Comparison of the adsorption capacities of Cd(II), Hg(II), and Zn(II) on various adsorbents. Reprinted with permission from [17] Copyright 2014, Elsevier

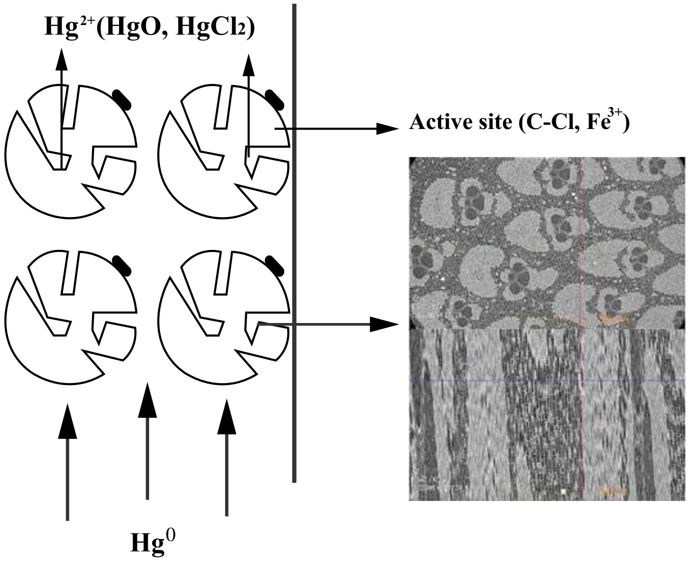


Fig. 19 Illustration of a bench-scale fixed-bed reactor filled $FeCl_3$-impregnated BCs for removing gaseous mercury (Hg^0). Reprinted with permission from [17] Copyright 2015, Elsevier

Peng Liao et al., have investigated the adsorption kinetics and thermodynamics of nitrogen-heterocyclic compounds (NHCs), pyridine, indole, and quinoline, in aqueous solutions on bamboo charcoal (BC) in batch, as well as the regeneration of spent BC by microwave radiation (Fig. 20). The BC obtained from Moso bamboo was able to absorb between 30 and 40 mg g^{-1} for up to 5 cycles [20]. The same authors applied a similar approach for the adsorption of organic dyes: methylene blue (MB, 35.3 mg g^{-1}) and acid orange 7 (AO7, 10.5 mg g^{-1}) [21]. Bamboo activated carbon (BAC) prepared with a physiochemical activation with potassium hydroxide (KOH) and carbon dioxide (CO_2) with heat treatment at 850 °C (BAC) presented an adsorption capacity of 454.2 mg g^{-1} for MB [22].

In Table 3 are summarized the adsorption capacities of bamboo charcoal for several heavy metals, and organic and inorganic adsorbates in an aqueous solution. Adsorptive removal of active pharmaceutical compounds from wastewater by bamboo charcoal was investigated for the following compounds: chloramphenicol (CAP) [23], tetracycline (TC) [24], and dibenzothiophene (DBT) [25]. As well, nitrogen derivatives, such as N-vinylpyrrolidone [26], and nitrate [27], and ammonia [28] were removed from aqueous solutions.

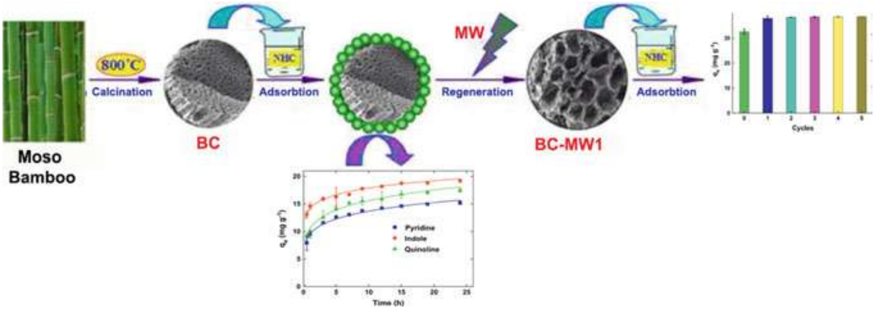


Fig. 20 Illustration for adsorption of nitrogen-heterocyclic compounds (NHCs) on bamboo charcoal and its regeneration with microwave for reuse up to 5 cycles. Reprinted with permission from [20] Copyright 2013, Elsevier

Table 3 Comparison of the adsorption capacity of several adsorbates on bamboo charcoal

Adsorbent	Adsorbate	Adsorption capacity (mg g^{-1})	References
BC	Cd^{2+}	18.2	[14]
BAC of Moso bamboo	Pb^{2+}, Cu^{2+}, Cr^{3+} and Cd^{2+}	From 0.68 to 0.19	[15, 16]
BAC of *Bambusa vulgaris*	Cd^{2+}, Hg^{2+} and Zn^{2+}	240, 248 and 254	[17]
BAC of *Melocanna baccifera*	Ni^{2+} and Zn^{2+}	52.9 and 40.5	[18]
$FeCl_3$-impregnated BCs	Hg^0	12.9	[19]
BC of Moso bamboo	NHCs	30–40	[20]
BC	MB and AO7	35.3 and 10.5	[21]
BAC treated by KOH and CO_2	MB	454.2	[22]
BC treated by NaOH	CAP	50.0	[23]
BC	CAP and TC	8.1 and 22.7	[24]
BC	DBT	425.5	[25]
BAC treated by NaOH and HCl	N-vinylpyrrolidone	833.3	[26]
BC	Nitrate	1.3	[27]
BC treated with H_2SO_4	Ammonia	9.5	[28]

Abbreviation Bamboo charcoal (BC), bamboo activated carbon (BAC), nitrogen-heterocyclic compounds (NHCs), methylene blue (MB), acid orange 7 (AO7), chloramphenicol (CAP), tetracycline (TC), dibenzothiophene (DBT)

5.3 Bamboo 3D Biotemplate for Desalinization of Water

Carbonized woods with 2D structures have already been reported as solar absorptance, confined heat, and quick vapor transportation, which made them very efficient vapor generation devices. Nevertheless, because of the energy loss via reflection and thermal radiation heat loss, the efficiency of the 2D structure achieves a limit of 90% or less. A solution to this problem is to increase the surface area to decrease the surface temperature of the absorber. Yue Bian et al., have found that the bamboo's 3D structures could be used as an excellent solar vapor generation [29]. The carbonized bamboo structure maintained good mechanical properties (the microstructure is not destroyed after carbonization as confirmed by SEM); natural hydrophilicity (because of the cellulose structure constructed from polysaccharide chains); aligned microchannels for rapid water transport and a reduced thermal radiation heat loss. The experiment was done with 1 sun illumination, and the bamboo device (carbonized at a temperature of 900 °C) evaporates water without any degradation after a 360-h cycle. The carbonized bamboo was put on a float polystyrene foam (for thermal insulation) which was wrapped with air-laid paper (for a 2D water supply). The water comes into the device due to capillary force and hydrophilic bamboo fibers that make a very important mechanism of absorption. An AM 1.5G solar spectrum equipment was used to compare the solar absorptance of 2D and 3D bamboo devices. The efficacy was 94.8, and 99.6% for 2D and 3D carbonized bamboos, respectively. The study also showed that 92% of the diffused light from the bottom surface can be reabsorbed by the device walls. The bamboo device was 4.4 cm high and needed approximately the 70s to wick water from the wet air-laid paper to its upper surface. That was possible by reason of branched diffusion. The water temperature has risen by 1.0 °C under one sun illumination proving the thermal radiation shielding performance, although previous works have demonstrated an increase of 5 °C in the case of direct bulk water.

Owing to the efficient recovery in thermal radiation heat loss from the 3D bamboo structure, and the gain in energy from the warmer ambient, the 3D device showed a rate of 3.13 kg m^{-2} h^{-1} and an efficiency of 132% compared with a rate of 1.547 kg m^{-2} h^{-1} and an efficiency of 62.3% of a 2D device. The work of Yue Bian et al., also analyzes the desalination of a 3.5%wt simulated seawater performing a solar water evaporation experiment consecutively. After desalination, the concentration of the ions existing in seawater as Na^{+}, Mg^{2+}, Ca^{2+}, K^{+}, and Zn^{2+} impressively decreased, turning water into a drinkable product following the standards defined by the World Health Organization (WHO) and the US Environmental Protection Agency (EPA). The evaporator was artificially illuminated to simulate a natural environment. The constancy of the 3D evaporator was also explored due to the fact that the salt crystals form on the inner and outer surface when the light is on but gradually dissolve back into water under darkness. So, a 3.11 kg m^{-2} h^{-1} evaporation rate was calculated for 15 cycles with 8 h in light and 16 h in the dark. As could be seen, bamboo can be used as excellent, low-cost, scalable solar vapor generation devices with great energy efficiency. Furthermore, the same device has an appealing industrial and domestic wastewater desalination application.

A real-life prototype using 3D carbonized bamboo for large-dimension solar vapor generation was proposed. The device consists of an evaporation chamber and a condensing chamber which are made of light transparent plastic walls. The carbonized bamboos are arranged in the evaporation chamber, floating on the water's surface. The vapor produced under natural solar light illumination by the carbonized bamboos condenses on the upper chamber wall and is collected along the inclined wall to the condensing chamber.

6 Conclusion

Bamboo is a renewable bioresource and environmentally friendly due to its short growth period, fast harvesting, and large production in many tropical countries in Asia, Africa, and Latin America. Due to the rapid development of the bamboo industry and the new technological applications of natural bamboo and its pyrolyzed derivatives in heterocatalysis synthesis and water remediation, respectively, it is reasonable to imagine an important impact on green chemistry and the new bioeconomy. Lignocellulose biomass with its natural porosity, supramolecular interactions with similar biopolymer or protein structures, or in the alternative, with the chemical modification of the bamboo surface, is possible to selectively immobility metal ions, metal nanoparticles, and enzymes. Bamboo charcoal (BC) or bamboo activated carbons (BAC) with a large surface area and increased porosity are considered great bio-adsorbent materials for water purification removing many heavy metals, and organic and inorganic contaminants in wastewater.

In this chapter, some of the solutions and applications using biomass from bamboo were presented so that we can have a transition time to a sustainable society with safer, renewable, and reusable materials besides a large-scale fabrication of these kinds of devices, which can pave the way for a greener economy solution.

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Bamboo-Based Forest Landscape Restoration: Practical Lessons and Initiatives to Upscale in Africa

Barnabas Neba Nfornkah, Arun Jyoti Nath, Rene Kaam, Cedric Djomo Chimi, and Karol Lavoine Mezafack

Abstract Studies suggest that the restoration of degraded land through planting bamboo could be a viable strategy for forest landscape restoration. As part of more extensive landscape restoration, planting bamboo in degraded and marginal landscapes have the potential to restore its productive use and ecosystem services, thus improving the adaptive capacity and resilience of such systems under the accelerated climate change phenomenon. However, using bamboo in landscape restoration has yet to receive significant attention primarily due to data scarcity, scattered or even missing in the literature, and general poor perception, thus contributing to less attention at policy and development planning levels. The lack of adequate information has hindered the potential usefulness of bamboo in landscape restoration and climate change adaptation and mitigation. Therefore, this chapter aims to review and assemble existing knowledge on bamboo resources related to its ability to restore the degraded forest landscape and its contribution to climate change mitigation and adaptation. The chapter, therefore, also aims to highlight promising practices deemed viable to inform decision-makers and to upscale in Africa, which has a bamboo potential of about 115 species covering 7.2 million ha. We highlighted specific key characteristics of bamboo in forest landscape restoration, such as rapid growth, soil binding, and erosion control properties, adaptive capability, nutrient and water conservation, and the provision of a continuous and permanent canopy. Furthermore, we examined its contributions to direct and indirect human well-being through ecosystem services.

B. N. Nfornkah (✉) · R. Kaam
International Bamboo and Rattan Organization (INBAR), Central Africa Reginal Office (CARO), Door 63, Road No. 1860, Behind Bastos Factory, Yaounde 1St District, PO BOX 17056, Yaounde, Cameroon
e-mail: barnabasneba@yahoo.com

B. N. Nfornkah · K. L. Mezafack
Fokabs INC, Tsinga Yaounde, 2500 St. Laurent Blvd, Ottawa, ON K1H 1B1, Cameroon

A. J. Nath
Department of Ecology and Environmental Science, Assam University, Silchar, India

C. D. Chimi
Institute of Agricultural Research for the Development (IRAD), PO BOX 136, Yokadouma, Cameroon

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It is concluded that bamboo has enormous potentiality in landscape restoration vis-a-vis climate change adaptation and mitigation. Finally, it is suggested to initiate an action call for good practices to restore degraded forest landscapes in Africa within frameworks of initiatives such as the REDD + strategy, Bonn Challenge, Afr100 initiative, and the Great Green Wall incorporating bamboo as one of the essential components.

Keywords Bamboo resource · Forest landscape · Restoration · Ecosystem services · Climate mitigation and adaptation · Practical lessons · Africa

1 Introduction

Deforestation and forest degradation continue to occur at alarming rates, contributing significantly to the ongoing loss of biodiversity and climate change exacerbation. Since 1990, it is estimated that some 420 million hectares of forest have been lost through conversion to other land uses. However, the rate of deforestation has decreased over the past three decades. Between 2015 and 2020, deforestation was estimated at 10 million hectares per year, down from 16 million hectares per year in the 1990s. As a result, the area of primary forests worldwide has decreased by over 80 million hectares since 1990 [34].

Degrading these forest landscapes (FL) creates a severe problem and reduces forests' capacity to provide goods and services [36]. Due to their negative impact on natural ecosystems, approximately 1 billion people live in degraded areas, representing 15% of the Earth's population, and one-third of the world's population is affected by land degradation [35, 108]. The degradation occurs on the landscape as the heterogeneous mosaic of different land uses (agriculture, forestry, soil protection, water supply and distribution, biodiversity conservation, pasture provision, etc.) across a large area of land or a watershed [41]. This has led to the "persistent decline" in providing an ecosystem's goods and services.

Land restoration is any intentional activity that initiates or accelerates the recovery of an ecosystem from a degraded state. It aims to re-establish ecological integrity by supporting human well-being [35, 108]. Forest and Landscape Restoration (FLR), according to the Global Partnership on Forest and Landscape Restoration [42], is "an active process that brings people together to identify, negotiate and implement practices that restore an agreed optimal balance of the ecological, social and economic benefits of forests and trees within a broader pattern of land uses". FLR seeks a balance between restoring ecosystem services related to wildlife habitats and biodiversity, water regulation, carbon storage, and more, and supporting the productive functions of land for agriculture and other related uses [69]. Landscape approaches are increasingly essential in developing sustainable land use and livelihood strategies in rural areas [37, 72] defined a world of opportunities for FLR opportunities as wide-scale (restore dense forests to the landscape), mosaic (integrates trees: scattered across the landscape or in patches), and remote (unpopulated and located far away from human settlements) restorations, with others like agricultural land, recent tropical deforestation, urban areas and forest without restoration needs.

Global commitments to the Bonn Challenge and the New York Declaration on Forests, as well as regional commitments such as Latin America's Initiative 20 × 20, Afr100 initiative and the Great Green Wall, is to bring a collective 350 million ha of degraded and deforested land under restoration by 2030 [71]. Investment in timberland and traditional forest plantations, both native and exotic species, requires patience, time, and illiquid capital [35, 103]. Adding degraded land into the equation further increases the timeline for productivity and financial returns [103]

Bamboos belong to one of 12 subfamilies (i.e., subfamily Bambusoideae) within the grass family (Poaceae). They represent the only major grass lineage diversifying in forests [135]. There are nearly 1,642 species in 128 genera globally [135], and extant species are classified into three tribes [135]. Bamboo's substitutability provides a fundamental way of dealing with current natural resource deficits. Bamboo reaches maturity within five to seven years and can be harvested yearly [88]. Moreover, it grows on marginal land and, under this production framework, does not compete with food production and requires little fertilizer or water in comparison to traditional sources of fibre [30]. By planting bamboo as part of a larger landscape, degraded lands could be restored to productive use, alleviating some of the pressure on forests from development uses and providing communities with secure incomes, reducing smaller-scale pressures that drive continued degradation [59].

Studies worldwide suggest bamboo is a fast-growing plant. For example, some species can grow up to 0.88 to 1 m a day [154]. At the same time, a culm can reach its full height in two to three months and is widely adaptable to temperatures as low as 5 °C and as high as 45 °C [120]. Bamboo is a perennial monocot plant. Soil binding and erosion control have extensive fibrous roots that stabilise loose soil to prevent soil erosion and act exceptionally in water filtration [73]. In terms of adaptive capability, it can thrive on degraded soils and steep slopes where many plants cannot grow [73, 104]. A continuous and permanent canopy enables selected and carefully chosen bamboo species to act as succession species to restore degraded land [35, 73, 103, 154]. Other studies show that the underground rhizomes and fibrous roots of bamboo can measure up to 100 kms (km) per ha of the bamboo stand, grow to a depth of 60 cm (cm) and live for a century [129] This underground biomass makes bamboo capable of surviving and regenerating exceptionally when several factors, including fire, destroy the biomass aboveground. Bamboo provides key ecological benefits: restoration of degraded lands [27, 33, 34, 102, 128] and, restoring soil health [22, 100], raising water levels [97, 112, 127], sequestrating exceptionally high carbon [3, 83, 85, 155] It can, therefore, revegetate and restore productivity to bare land over a short period but also provide livelihood benefits for human well-being [40, 47, 50, 89, 97, 98, 115, 118, 128, 136].

Bamboo also plays an important role in ecology and biodiversity conservation. It forms vast pure stands in many places providing essential habitats and food for wildlife. For example, the dense stands of *O. alpina* play a significant role in conserving the high mountains in Africa, such as the Virunga transboundary protected area that includes parks in the Democratic Republic of Congo (DRC), Uganda and

Rwanda and Mt. Kivu in Zaire [117], the Aberdares and Mau ranges, Mt Kenyain Kenya, the highlands of Ethiopia, Mt Uluguru in Tanzania, Mt. Mulanje in Malawi, and Cameroon in Cameroon [45, 117]. However, despite growing political support for using bamboo as a nature-based solution in certain parts of the Asian Pacific Regions in FLR to fight against desertification and mitigate and adapt to climate change, many concerns have been raised. These included scarcity, scattered, unavailability, and even missing knowledge on bamboo and FLR in literature, thus hindering policymakers and development planners in taking scientifically informed decisions to drive towards achieving the global commitment to FLR by 2030.

This study was undertaken to assess the literature and assemble available knowledge on (i) the status of bamboo on forest landscape restoration, (ii) the critical characteristics of bamboo supporting the restoration of the degraded forest landscape, and (iii) drawing lessons to upscale for Africa.

2 Methodology

This book chapter provided information on the world scale. For that, we reviewed a total of 155 case studies reporting information on bamboo FLR ecosystems worldwide. Journal articles, book chapters, and scientific reports were identified in a comprehensive literature search carried out using Web of Science, Scopus, Google, Google Scholar, and individual journal databases, using permutations of keywords that include bamboo, Forest landscapes, restoration, ecosystem services, bamboo characteristics, nature-based solution, bamboo ecosystem services, bamboo and soil conservation, erosion, roots, rhizomes, canopy, climate adaptation and mitigation, carbon, biomass, tropics. The remaining keywords consisted of individual country and region names if bamboo is commonly found within the locations [114] Africa, China, India, Indonesia, Japan, Laos, Malaysia, Myanmar, Philippines, South America, Southeast Asia, Taiwan, Thailand, and Vietnam, Nepal, Ghana, Ethiopia, Ecuador, and Madagascar. In addition, bibliographies of reviewed articles were used to find obscure and older articles. Furthermore, grey literature sources were examined. Relevant non-English articles (e.g., Indian, Chinese, and French) were translated into English by the second and first authors.

3 Global Status for Bamboo-Based Forest Restoration

It is estimated that around 420 million ha of forest has been lost globally since 1990 through deforestation [38]. Deforestation and other anthropogenic disturbances adversely affect forests' health and vitality and reduce their full range of ecosystem services. Forest degradation exacerbates soil degradation [80] while reducing ecosystem services. The conversion of the native old-growth forest by monoculture tree plantations has been documented in Chile [151]. Thailand [60] and India [106]. When soil degradation is irreversible or very hard to reverse, severe topsoil losses are caused by wind or water erosion [76, 93, 110]. Hence, large-scale forest restoration is essential to ensure the continued flow of vital, forest-related ecosystem services, biodiversity conservation, and livelihood opportunities [62]. In that regard, the landscape approach has emerged as a concept that integrates social and environmental objectives across land-use sectors and scales of governance [104]. Although forest health may be restored, social, ecological, and economic considerations may limit the restorative measures.

Bamboo is an essential part of tropical and subtropical forests and provides a range of goods and services [98]. Globally, many countries, for example, Cameroon, China, Ethiopia, Kenya, Ghana, India, Madagascar, the Philippines, and Vietnam, now specifically include bamboo in their sustainable land management programmes [48]. Bamboo forests are socioculturally connected with forests and people and provide ecological benefits to communities [98]. However, bamboo needed adequate attention in the forestry programme in many countries. While with adequate attention, and investment, bamboo could play a prominent role in forest and landscape restoration and become a significant renewable and sustainable crop [15]. Bamboo is integral to forest landscape restoration efforts [126] and can uphold forest diversity and composition during the succession process [134]. Bamboo can grow well in degraded and marginal soils with low fertility compared to many other perennial species [10]. This implies that, even with less resource input, bamboo can thrive in severely degraded areas where other native species cannot grow [8]. Bamboo has dominated many secondary forests in Southern Brazil and other parts of the world, effectively arresting their successional development [58, 78]. In India, 'Nadi Bachao Samriddhi Lao' (Save Rivers and Bring Prosperity) is an FLR initiative launched to restore the riverbanks. *Bambusa Nathdinacea* was planted along the riverbanks of various tributaries of the Narmada River under the initiative covering 2000 hectares, which is expected to provide a range of environmental and economic benefits to the local inhabitants [110]. Case studies of bamboo restoration still need to be completed. A few successful programmes include the African Bamboo organisation prepares nurseries for large-scale restoration of degraded lands with bamboo. In Latin America, EcoPlanet Bamboo has been active in Nicaragua, restoring 5,000 hectares of degraded pastureland. Likewise, INBAR completed a bamboo restoration project in India, which turned a degraded mining area into green, productive land [15].

4 Critical Characteristics of Bamboo Supporting the Restoration of the Degraded Forest Landscape

The following points advocate why bamboo should be chosen for the forest landscape restoration programme.

4.1 Distribution and Area

Bamboos grow on all continents except for Antarctica and Europe. They grow in association with various mesics to wet forest types in temperate and tropical regions. With an estimated area of 35 million hectares, bamboos account for 1% of the total global forest area [38, 55]. The latest estimate puts the total global bamboo forest area at 30.5 million hectares [28].

4.2 Erosion Control

The extensive fibrous root systems of bamboo can slow down soil erosion, reduce the risk of landslides, and stabilise river banks [119, 124], thereby reducing the loss of nutrients and soil degradation. *Oldeania alpina* has been used in Kenya for erosion control, catchment rehabilitation, and regulation of water flow [97]. In Nepal, the bamboo plantation was highly preferred by the local community to reduce the impacts of landslides [95]. In India and Bangladesh, species such as *Bambusa bambos, B. balcooa, B. vulgaris, B. tulda, Dendrocalamus hamiltonii, D. longispathus* and *Melocanna baccifera* are usually planted in closer spaces on the lands susceptible to floods and along riverbanks [7, 68]). Natural stands of *O. alpina* have been reported to contribute to protecting the water towers of countries in East Africa [119].

4.3 Growth

The rapid elongation of culms characterizes woody bamboo by intercalary expansion during a single "grand period of growth" [83, 84]). Studies on the culm growth extension showed the short periodicity of the culm growth nature of bamboo. For example, the periodicity of culm extension growth in the *Bambusa bambos* was 135 days [113]. Studies from India and Bangladesh revealed the total culm extension growth in different woody bamboos ranges from 60 to 135 days [7, 79]. Such a rapid growth phase in bamboo makes it an essential renewable rural resource for subsistence and commercial utility.

4.4 Soil Health Management

Bamboo plantation development on degraded soils improves soil quality and sequesters carbon in the soil [82]. Bamboo, due to its fast growth and extensive root system, enhances soil's physical, chemical, and biological properties; and is considered suitable for rehabilitating degraded lands [161, 3, 84]. Studies from montane Ecuador revealed bamboo species (*Guadua angustifolia*) establishment reduced soil compactness and enhanced soil organic carbon [132]. A similar trend was also reported for Japan's Moso bamboo (*Phyllostachys pubescens*) [46].

4.5 Other Ecosystem Services

Woody bamboo provides a wide range of uses in the daily life of the rural poor. The rapid phase of culm extension growth, its ability for permanent carbon sink management through phytolith occluded carbon sequestration, and its usefulness in restoring degraded lands makes it a better choice for provisioning ecosystem services [9, 26, 83]. However, at the world scale, multiple services provided by bamboo in nature conservation, environmental protection, support poverty reduction, economic value, and human livelihoods across the tropics are not to be proven again. Therefore, while classifying primary direct and indirect ecosystem services (ES) from bamboo forests, the classification proposed by the Economics of Ecosystems and Biodiversity; and those of the Millennium Ecosystem Assessment (MEA) [13] were adapted in the context of this study. MEA considered services like provisioning services (food provision, forage production, timber, raw material bioenergy medicinal resource, freshwater provision); regulating services (landscape restoration, sediment retention, carbon sequestration and carbon stocks, air quality and local climate regulation, flood/landscape control, groundwater recharge, water purification, healing, moderation of extreme events); habitat services (habitat provision, maintenance of biological diversity and net primary production); and cultural services (landscape beauty and recreation, recreation and ecotourism and cultural/religious values).

4.5.1 Food Provision

Bamboo is an essential source of food for human and animal well-being [88]. However, the role of bamboo in local diets needs to be addressed. Local tribal communities in Asia have been consuming tender shoots of bamboo since time immemorial [7]. Over 500 species of bamboos have been reported to produce edible shoots, including many species like *Phyllostachys* spp*., Bambusa polymorpha, Dendrocalamus asper, D. latiflorus, D. longispathus, D. amiltonii,* etc. *Gigantochloa apus* and *G. atter* [6, 78] Bamboo shoots can be consumed in various forms, including raw, canned, fermented, boiled, marinated, frozen, liquid, and medicinal forms [21]. Bamboo contains proteins, carbohydrates, vitamins, and minerals such as potassium, phosphorous, magnesium, sodium, iron, calcium, and selenium [130, 131, 136]. The young shoots of *Phyllostachys pubescens* and *Bambusa balcooa* are either canned or traded fresh, supplying the bamboo shoots industry in China and India, respectively [10–12]. Similarly, [80] reported that the young shoots of *Oldeania alpina* and *Oxythenantera abyssinica* are eaten in western Ethiopia, Kenya, Uganda, and Tanzania [16, 17, 45]. In Tanzania, bamboo wine called *ulanzi* is produced with the shoot of *O. abyssinica* [17]. Bamboo leaves have antioxidant, antimicrobial, anti-inflammatory, antihelminthic, antidiabetic and antiulcer properties [136]. Bamboo leaves are used for tea/tisane [20, 136] and natural juice production in Cameroon [20].

4.5.2 Forage Production

Bamboo forests also provide critical provisioning services for livestock development [92, 99]. Cows and goats are known to consume leaves in Ethiopia [79]. Leaves are an excellent alternative feed for livestock in the dry season (when green forage are rare) because they can conserve water and maintain their green characteristic and vigour in the dry season. In India and Nepal, for example, bamboo leaves are already used as fodder for ruminants, mainly when pasture is scarce during the winter. Studies have shown that all species of bamboo used as fodder have positive effects on cattle, particularly young calves, and have reportedly increased milk production [66, 67, 95, 98].

4.5.3 Timber and Raw Material

The image of bamboo forests is quickly changing from "poor man's timber," denoting its popularity among poor people as a good substitute for expensive wood from trees by providing high-tech industrial raw materials [61, 65]. Bamboos provide material suitable for small-scale construction, residential fencing, furniture making, handicrafts, and cottage industry products such as basketry, mats, toothpicks, and decorative. Bamboo has excellent mechanical properties, especially tensile strength [74, 77]. Bamboo culms can be used in construction as structural components (pillars, columns, posts, roof trusses, or stringers) or split versions as cover, shingles, wall cladding, load-bearing elements for building bridges and towers, etc. [57, 60]. Artisans use bamboo as a raw material to provide finished and semi-finished products, including chairs, beds, tables, handles of shovels, rakes and crop planters, etc. [49, 50, 85]. Taking the case of the Western highland agro-ecological zone of Cameroon, [20] have shown that in the artisanal sector, bamboo is used to provide some products like flower jars/pots, walking sticks, ballpoint pens and pencils, bamboo muck, bamboo hand bangle, bamboo photo stand, bamboo whistles, bamboo necklace, fork, bamboo lamp holder, bamboo curtains, ash cup, bamboo door curtain, cigarette curtain decoration. Bamboo is also used to manufacture musical instruments like flutes, musical whistles, and bamboo xylophones. For kitchen use, bamboo produces kitchen utensils and bamboo products like drinking cups or mock, kitchen rammer, cupboards, bamboo jars and bamboo egg trays, etc. Concerning the agricultural sector, farmers cultivating crops like tomatoes and vegetables in the dry season benefit from traditional irrigation methods using bamboo as pipes on farmlands. This explains why bamboo is highly valued for crop irrigation and supports crops like plantains /bananas, yams, and beans against extreme winds [20, 23]. Bamboo boring to recharge underground water is practised in Bihar, India [4].

4.5.4 Bioenergy

Bamboos possess a high potential for biomass production [70, 78]. Bamboo biomass can be used as bioenergy to replace fossil fuels and decrease carbon footprints. Biomass is a promising renewable energy option that provides a more environmentally sustainable alternative to fossil resources [148]. Bamboo biomass has been used as a domestic energy source and a substitute for mineral coal and wood charcoal [81, 113]. Bamboo has good fuel characteristics for modern bioenergy production because it is easily accessible, grows fast, has high productivity, and has a short rotation cycle. Moreover, bamboo can be used in charcoal production, biogas, and oil production [9, 78, 97]. Then, it is a potential feedstock for generating electricity through power plants and biofuels to substitute fossil fuels.

4.5.5 Medicinal Resource

Various medicinal products and traditional and indigenous medicine are derived from bamboo [64, 103]. Bamboo is used for antifungal and antibacterial properties because a naturally occurring bio agent gives bamboo resistance to destructive microbes, such as bacteria and fungi. Traditionally, Chinese medicine, primarily known in China, used many bamboos for several treatments, such as reducing inflammation, treating hypertension, arteriosclerosis and cardiovascular disease, fever and convulsions, and fighting nasal congestion [51–53, 118]. According to [19] in Cameroon, bamboo leaves are used in traditional medicine in typhoid treatment. Wang et al. [136] showed that bamboo has several medicinal properties, including antioxidant, antimicrobial, anti-inflammatory, anti-helminthic, antidiabetic and antiulcer. Another aspect of the health benefits of bamboo includes the prevention of cancer and degenerative diseases [118]. Nath et al. [78] reported that bamboo tea is recommended for various pharmaceutical applications, including stomach pain and can be enjoyed warm or cold [18, 65].

4.5.6 Freshwater Provision

Bamboo forests contribute significantly to water source protection, helping to protect water sources, conserve water and supply fresh water to local communities [99]. It has a higher capacity in terms of freshwater provision than natural forests, degraded forests and agricultural land [98]. Bamboo acts as a reservoir by collecting and storing large amounts of water in its rhizomes and stems during the rainy season and returning water to the soil, rivers and streams during droughts. One hectare of Guadua bamboo can store approximately *30,000 l of water* [107, 110].

4.5.7 Landscape Restoration

Soil erosion is one of the leading causes of loss of nutrients and soil degradation [87]. Bamboo is essential for rehabilitating degraded landscapes due to rapid growth, adaptive capability, soil binding and erosion control properties, the provision of a continuous and permanent canopy, and also nutrient and water conservation of land [15, 17, 33, 71, 81, 99, 149]. Furthermore, bamboo can grow on degraded and marginal soils where many woody species cannot grow [25, 71, 98]. Therefore, it demonstrates significant potential as a strategic resource for reducing degradation, protecting against erosion, improving soil fertility, and restoring and repairing damaged ecosystems [39, 69, 98]. Therefore, it is a viable strategy used for landscape restoration in several countries [114]. Furthermore, bamboo's ability to grow on degraded lands and its fast growth, long root system and easy maintenance prove it is a powerful resource for restoring degraded land. Therefore, the bamboo forest has a higher capacity for landscape restoration than other land uses [97].

4.5.8 Carbon Sequestration and Carbon Stocks

Carbon sequestration is a vital ecosystem service from bamboo forests. These bamboo forests contribute significantly to climate change mitigation through the photosynthesis process. For example, the annual carbon fixation of Moso bamboo (*Phyllostachus pubescens*) forests estimated by [44, 46, 152] is 1.3 times the value of that of a tropical mountain rainforest. Also, the carbon sequestration capacity of the bamboo forest is considered higher than that of other land-use types [77, 85, 150]. For example, the total carbon sequestration of five-year-old common bamboo (*Bambusa vulgaris*) was found to be higher (15.53 tC.ha^{-1} year^{-1}) than that of other fast-growing hardwood species, such as Acacia (*Acacia auriculiformis*) (10.21 tC.ha^{-1} yr^{-1}) for an 11-year-old crop [121, 127]. According to [151] the annual carbon accumulation rate of 16 t C.ha^{-1} has been recorded in *Bambusa oldhamii* plantations. Above-ground carbon (AGC) of bamboo forest ranges from 16 to 128 tC.ha^{-1}, below-ground carbon (BGC) biomass from 8 to 64 tC ha^{-1}, soil organic carbon (SOC) from 70 to 200 tC ha^{-1}, and total ecosystem carbon range from 94 to 392 tC ha^{-1} [63, 150].

4.5.9 Air Quality and Local Climate Regulation

Bamboo stands are called 'natural oxygen bars' because it filters the air and removes odours, pollutant gases and dust particles from the air through the action of leaves and bark [124]. Bamboo improves air quality and regulates the microclimate (local climate) better. Maintaining air and soil quality, providing flood and disease control and pollinating crops are some of ecosystems' regulating services. According to [78], in cities, the bamboo crown generates a microclimate by generating oxygen, provides low light intensity, protects against ultraviolet rays, and is an atmosphere and soil purifier.

4.5.10 Flood/landscape Control and Sediment Retention

Bamboo forests are a good ecosystem that helps stabilise the slope and prevents soil erosion, improves the condition of the land, controls floods and landslides, and reduces the deposition load downstream. It is an effective measure that helps in erosion control and soil mass loss due to its extensive rhizome system, thick litter layer, highly elastic culms and dense canopy [129]. For this reason, it controls floods and landslides by holding soil particles together through a complex network of roots and rhizomes [73, 99]. This strategy was used for landscape control of a cliff around the road of Foreke-Dschang in Cameroon. FAO and INBAR [33] have shown that bamboo plantation helps to reduce the average soil erosion by 80%. These characteristics give bamboo forests a high capacity for erosion control, slope stabilisation and protection against erosion, landslide prevention, soil and water conservation, protection of riverbanks, etc. [123]. For Chuchon et al. [22] in Peru, erosion control and sediment retention have been identified as the most critical ES from the mixed plantation with bamboo species. In Brazil, for example, bamboo species such as *Bambusa blumeana* and *Phyllostachys pubescens* are used to prevent nutrient loss, control soil erosion and improve soil structure [93, 94].

4.5.11 Groundwater Recharge

Bamboo forests enhance water infiltration and percolation and reduce runoff, positively influencing the ecosystem's hydrological cycle, which is vital for soil and water conservation. In addition, bamboo forests have a strong capacity for rainfall interception and moisture retention. By maintaining the ground cover, it protects the soil. As a result, bamboo forests conserve water sources and keep a groundwater table. While bamboo can absorb up to 90% of rainwater, trees absorb an average of 35–40% [122]. In Allahabad, India, an INBAR-supported bamboo project has helped raise the water table by over 15 m in 10 years and turned a blasted brick-mining area prone to frequent dust storms into productive agricultural land [98]. Schroder [112] also found that the groundwater level in bamboo forest areas has risen by 10 m within 20 years, which made water available in the nearby region.

4.5.12 Water Purification

Bamboo forests can assimilate and detoxify compounds through soil and subsoil processes by replacing healthy minerals (such as potassium, sodium, and iron), absorbing chlorine, foul odour and toxic substances from water, and acting as an antibacterial and antifungal agents [24, 97, 98]. According to that, the bamboo forest serves the function of water purification.

4.5.13 Healing

Lyu et al. [65] assert that bamboo forest enhances spiritual development, clears negative energy and brightens the mood. That appears like another aspect of the bamboo forest's medicinal value related to psychological and spiritual healing. Bamboo grooves are also considered a favourite place for meditation and an effective practice for relaxation and high-level cognitive functioning [138, 145, 150].

4.5.14 Moderation of Extreme Events

Bamboo forests act as a natural buffer, helping protect against wild animals entering the villages, storms, strong winds, landslides and several other disasters and reducing damaging impacts [98]. For example, on the high cliff of Foreke-Dschang in the West Region of Cameroon, *Bambusa vulgaris* planted around the road helped to protect from soil erosion and floods. Also, in Northern Cameroon, bamboo has been planted along the banks of the Benue River to protect against the constant landslides, erosion and flood [88].

4.6 Habitat Service

The habitat services from bamboo forests refer to the importance of bamboo ecosystems in providing habitat for species and protecting genetic diversity. Paudyal et al. [98] identified habitat provisioning, maintenance of biological diversity and net primary production like sub-classification of habitat service; these sub-classified services were considered in this current section.

4.6.1 Habitat Provision

Bamboo forests represent suitable habitats for several species, including flora, fauna and microorganisms. For example, the Asian giant panda (*Ailuropoda melanoleuca*) [31, 100], Mountain gorillas (*Gorilla beringei beringei*), the Himalayan black bear (*Selenarctos thibetanus*) [69], African golden monkeys (*Cercopithecus mitis kandti*) and many other kinds of monkeys and bamboo rats [43, 118] for which bamboo forest are their preferred habitat. The forest Elephants (*Loxodonta cyclotis*) in the Lobeke National Park (in Cameroon) eat bamboo shoots and leaves for forage [50]. Crocodile (*Crocodylus niloticus*) take cover under bamboo along the Banks of the Benue River in Garoua, Cameroon, during scorching days.

4.6.2 Maintenance of Biological Diversity

Bamboo forest plays an essential role in maintaining wildlife biodiversity. It provides habitats, food and microclimate required for several wild animals, including insects, birds, mammals, and microorganisms. For example, Giant pandas are found in the bamboo forest, where it eats almost exclusively the tender culms and shoots of bamboo. Similarly, other animals, such as elephants, brown bears, wild oxen and wild boars, depend significantly on bamboo shoots and leaves [98].

4.6.3 Net Primary Production

Net primary production indicates the forest biomass accumulation, carbon sink capacity and overall landscape productivity. Several studies have shown that bamboo forests have a higher production (in the same case, high carbon sequestration potential) than other forests and agroforests land [19, 89, 125]. It is an alternative to the fight against climate change, and bamboo stands can fix 2.5–25 $tC.ha^{-1}.yr^{-1}$ [144, 152]. In the Bundelkhand region of central India, World Agroforestry Centre [139, 140] found that a *Dendrocalamus strictus* based agroforestry system has produced a higher amount of leaf biomass, bamboo stock and sustained crop production over the years.

4.6.4 Landscape Beauty and Recreation

Naturally, bamboo forests create landscape beauty through their regulating service, including preventing land degradation and enhancing landscape restoration [15, 64]. Bamboo stands also provide a beautiful appearance and colour combinations of the clump, culm, and foliage [6, 20]. In China, most bamboo forest landscapes are characterised by relatively high landscape quality areas [98]. This implies bamboo forest or bamboo-dominated forest landscape has high aesthetic and recreational values [136], including on farmlands, riverbanks, roadsides and urban areas. Bamboo forests are also a unique and vital component in Southeast Asia, especially in Chinese gardens and landscapes. For example, *Bambusa multiplex, Phyllostachys bambusoides, and Phyllostachys aurea* are popular garden ornamental plants [124]. Bamboo is now well known and is the most preferred plant in Chinese landscape design because of its unique, beautiful foliage and fast-growing characteristics [14, 97].

4.6.5 Recreation and Ecotourism

Bamboo forests promote greenery and landscape beautification, park-like place forest and tranquillity with the least amount of air and noise pollution, and provide opportunities for ecotourism and recreational services [33, 85]. Lyu et al. [65] showed that the bamboo forest environment is good for psychological and physical relaxation than other forests because it is more natural, comfortable, open and bright, with pleasing ambient noise. For example, some popular tourist destinations like the Shunan Bamboo Sea in Changning, the Bamboo-Lined Path at Yunqi in Hangzhou, and the bamboo forest along the Lijiang River in Guilin.

4.6.6 Cultural/religious Values

Bamboo forests are socio-culturally connected with people [84]. According to Paudyal et al. [97], people often have strong religious, spiritual and cultural connections associated with bamboo. Furthermore, the bamboo forest remains essential to rural livelihoods and civilization. In China, Yeromiyan [146] found that various cultural and religious values related to bamboo uses, such as carvings and weavings, have made Chinese artisans famous worldwide. For Paudyal et al. [98], the capacity of bamboo forest in terms of cultural and religious values are higher than that of any other land-use class. In the same line, Chimi et al. [20] found in the Santchou Sub-division, located in the highlands agro-ecological zone of the West region of Cameroon, a sacred forest constituted by *Phyllostachys aurea* where local people perform traditional rituals. Nfornkah et al. [85] and Ruth et al. [106] reported a high cultural value in the Bamileke tradition (West Region of Cameroon), where bamboo is used during funeral ceremonies, forest fencing and land owners' delimitation and is highly protected in the sacred forests.

5 Bamboo Carbon Stocks Potential in Africa

5.1 Bamboo Forest Cover

Bamboo constitutes about 5–14% of the total forest cover in Sub-Saharan Africa, making it a significant component of forest vegetation [91]. INBAR [48] reports 7.2 million ha of bamboo forest cover in Africa. Zhao et al. [154] estimate bamboo forest cover at 1,438,705; 131,040, and 54,587 ha for Ethiopia, Kenya and Uganda, respectively. University of Tsinghua/INBAR [133] estimates bamboo cover at 1 123 694 ha for Madagascar. Kwame et al. [56] report 300 000 ha in Ghana. Nfornkah et al. [86] estimate 1 215 482.91 ha for Cameroon. This shows interesting data as far as bamboo forest vegetation in sub-Sahara Africa. However, more data is needed to understand the full potential of bamboo in Africa.

5.2 Bamboo Carbon Sequestration in Sub-Sahara Africa

Bamboo produces huge biomass storage, providing opportunities for climate mitigation. For instance, Obiri and Oteng-Amoako [91] report a total dry matter production of between 80 and 120 $tC.ha^{-1}$ for a four-year-old bamboo growing under optimum conditions in Ghana. In Ethiopia, Nigatu et al. [90] recorded that the biomass storage capacity of highland bamboo varied from 92.2 to 118.6 $tC.ha^{-1}$. Amoah et al. [2] reported 4.2 $tC.ha^{-1}$ AGB for *O. abyssinica* and 71 $tC.ha^{-1}$ for *B. vulgaris* var. *vitata* in Ghana. Shiferaw et al. (in press) estimated 64.01 $tC.ha^{-1}$ AGB in *Odeania alpina* in Ghana. Nfornkah et al. [87–89] estimated 13.13 $tC.ha^{-1}$ for *O. abyssinica* and 29.62 $tC.ha^{-1}$ for *Bambusa vulgaris* Var *green* in Cameroon. Adu-Bredu et al. [1] estimated in a typical plantation of 400 bamboo stands per hectare, the values range from 9.2 to 14.4 $tC.ha^{-1}$ for 4-year-old *B. vulgaris*. The following authors also reported values of 100 $tC.ha^{-1}$ AGB [143]; 110 $tC.ha^{-1}$ [32]; 99 $tC.ha^{-1}$ [75], and 108 $tC.ha^{-1}$ [90] in Ethiopia for the same bamboo species. Kaam et al. (submitted) estimated carbon stocks for *B. vulgaris* (61.65 Mg ha^{-1}), *P. aurea* (67.78 $tC.ha^{-1}$), and *O. abyssinica* (27.45 $tC.ha^{-1}$) in Cameroon. Chimi et al. (in press) reported an AGB stock of 92.96 tC.ha-1 and 53.83 $tC.ha^{-1}$ for *B. vulgaris* and *P. aurea,* respectively, in Cameroon. Therefore, bamboo AGC in Sub-Sahara Africa ranged from 4.2 - 120 $tC.ha^{-1}$ according to bamboo species and ecological conditions.

6 Bamboo for Land Reclamation: Lessons Learned to Upscale for Africa

Trials have shown that bamboo benefits beyond restoration ecology [29]. International Bamboo and Rattan Organization (INBAR) completed a prize-winning bamboo restoration project, which turned a degraded mining area into green, productive land in India. However, the bamboo industry has generally centred on a patchwork of small farms which cannot provide the security of supply or quality that global product companies require, particularly those in the timber industry considering a fibre switch. Some organizations are coming in to bridge this gap, such as Ecoplanet; that attempt to industrialize the bamboo industry by developing plantations in Central America, Southern Africa, West Africa and Southeast Asia using non-invasive clumping bamboo species [30]. At the 15th session of the Conference of the Parties of the United Nations Convention to Combat Desertification, bamboo was spotlighted for its essential role in healing degraded soils and safeguarding tropical ecosystems [5]. To bridge the gap globally, the introduction of bamboo-based FLR shall be appropriate. This shall implicate wide-scale, mosaic and remote restoration with bamboo and other important Non-Timber Forest Products (NTFPs).

According to FAO and INBAR [33], a 20-year-old bamboo stand restored FL raised groundwater table by 10 m in India; (2) in Colombia and Nepal, a decrease in soil compaction was recorded by half, that quickly restored several crucial ecological functions, including water regulation and nutrient recycling; (3) in China, a decrease in soil erosion up to 80% (27 t soil/ha/year) and flood damages was reported. By restoring the landscape, they contribute too in generating income, especially for low-income earners and improving people's livelihoods. For example, in Anji, China, bamboo establishments attracted several lucrative markets to develop. The value of Anji bamboo shoots alone reached above USD 2 billion. In addition, Anji's abundant bamboo forests became a lucrative tourist destination. This was witnessed in Tanzania, where bamboo-related enterprises generated an estimated USD 200 per household annually [33].

6.1 Case Study: Bamboo Land Reclamation and Renewable Energy Project, Ghana

Ghana Manganese Company (GMC) owns and operates the Nsuta manganese mine in the Western region of Ghana, a mining concession over an area of 175 km2. The company has been mining manganese since 1916 and has explored innovative sustainable ways of reclaiming mined-out land. In 2013, GMC signed a partnership agreement with Darlow Enterprise, a company specializing in the establishment of commercial bamboo plantations on marginal and degraded land for environmental services, for a renewable energy crop to supplement the high energy demand of the company for its mining operations. Four years later, after importing 20,000 bamboo saplings for the plantation of three bamboo species (*Bambusa vulgaris*, *Beema bamboo* and *Bambusa pervariabilis*) and planting on 10 ha of mined-out land as a trial before upscaling; the project created jobs for the community members who worked at the nursery, preparing land for planting and initial maintenance of the bamboo plantation. The bamboo has formed a thick canopy covering, developed many culms and thoroughly colonized the land, turning the land cover at the site into a forest. The fallen leaves have covered the soil surface and enriched the soil, improving the soil properties, and the extensive root system of the bamboo has bound the gravel and soil, helping to reduce soil erosion on the land. The bamboo plantation has improved biodiversity and served as a habitat for many species, including several bird species. Even though it is evident the bamboo had successfully restored the mined-out land, the project establishment did not collect data on the growth and impact of the intervention on the environment to measure, for instance, the amount of humus added to the soil, the average number of culms, carbon capture, carbon emissions or wildlife numbers. The culms were ready for sustainable harvesting. The bamboo yield was more than 100 tons of bamboo wood chips per ha with a 50-year lifespan [23, 24]. Bamboo has a high calorific value of 4200, and low ash and sulphur content; as such, it is a good source for generating renewable energy [24]. GMC and Darlow Enterprise collaborated to move forward with sustainable harvesting for bioenergy production and other alternative uses. This pilot project has demonstrated the potential of bamboo to restore degraded mined-out land. The project could potentially be upscaled to cover another mined-out land, especially in restoration areas where illegal mining of gold has destroyed the land in Ghana [147].

6.2 Case Study 2: Madi Municipality, Chitwan, Nepal, Asia

The Adoption of Bamboo and Rattan Initiatives (ABARI) and the World Wide Found (WWF) agreed on establishing the Hariyo Ban project in October 2014. Major activities included setting up a nursery, community mobilization, bamboo species plantation and capacity building for the community. ABARI worked closely with UNDP and community-based organizations such as Buffer Zone, Community Based Disaster and Risk Management Group, Someshwor Buffer Zone Community Forest, and Terai Arc Landscape for the project implementation. During the implementation period, local communities were consulted about the availability of their land. The communities were given 10,000 seedlings of commercially viable bamboo, including *Bambusa balcooa*, *Bambusa nutans* and *Bambusa tulda*, which were native to the bioregion. In exchange, the community committed labour, water, land, manure and bamboo fencing against grazing. *Bambusa balcooa, Bambusa nutans* and *Bambusa tulda* were among the 24 species planted in the community of Gaurinagar in Madi, Chitwan. ABARI also provided technical and capacity building on soil testing, land identification, the plantation and harvesting regime, nursery set up and intercropping. With their support, the local communities could plant bamboo on a greater scale. The following are the key results from the site: 10,000 bamboo clumps planted for biodiversity conservation and land restoration; 24 different species of bamboo for ecosystem management; and two bamboo-based enterprises established to improve livelihood and income generation: one was a nursery and the other a product-making enterprise. The nursery was closed due to a lack of funds from the donor, but the skilled workers continue to manage bamboo clumps on their own, and the other enterprise is still running and depends on orders received from the market.

6.3 Case Study 3: Bhakunde Besi, Kavre Nepal, Asia

Historically, the land had large forest areas with various species of Chir pine and other broadleaved species. By 1950, the forest landscape had become open, degraded forest land. Open grazing and the indiscriminate collection of firewood for cooking and timber for house construction placed increasing pressure on the land. Ongoing pressure caused the degraded land to erode, beginning with rill erosion, then sheet erosion and finally gully erosion. Owing to the erosion, massive landslides occurred in the upland affecting households and paddy fields downstream. The paddy land was covered by red soil, thus reducing the production of crops. As nearby households were in danger, some families shifted from the degraded areas to safer sites. Locals, however, should have taken action to address the problems. In 1985, Mr Shashidhar Timilsina, a local leader, took the initiative to reclaim Bhakunde Besi's degraded land. With the support of the Nepal Australia Forestry Project, bamboo and other measures were used in Bhakunde Besi to address the landslides. Bamboo was used to check dams and combat landslides and soil erosion. Local people formed community forest user groups to protect the degraded land from combating the risks posed by landslides. They used bamboo materials and committed to stopping open grazing and participating in conservation works. In addition, local communities took responsibility for managing the land as Panchayat Forest according to government rules. Although most of the reclaimed area is now under the Nepalese Army Complex's control, the upstream conservation effort positively impacted the downstream households and paddy fields. The benefits of replicating the bamboo plantation can be observed in the area. With the support of the DSCO, Kavre Palanchowk, a micro-watershed programme, was launched in the adjoining area.

7 Global Restoration Initiatives that Can Benefit Bamboo for a Bamboo-Based Forest Landscape Restoration in Africa

The International Community has put in place several global initiatives for FLR worldwide. Bamboo can contribute to several global initiatives to attain global restoration initiatives. These global initiatives include:

7.1 African Forest Landscape Restoration Initiative (AFR100)

It is a country-led effort to restore 100 million hectares of these deforested and degraded African landscapes by 2030. The initiative connects political partners in participating African nations with technical and financial support to scale up restoration on the ground and capture associated benefits for food security, climate change resilience, and poverty alleviation [141].

7.2 WRI's Global Restoration Initiative

World Resource Institute (WRI) is partnering with governments, businesses, and communities worldwide to restore millions of hectares of deforested and degraded land. They target 50 countries in 3 regions (Africa, Latin America and Asia) of the world [142].

7.3 Bonn Challenge

The Bonn Challenge is a global goal to bring 150 million hectares of degraded and deforested landscapes into restoration by 2020 and 350 million hectares by 2030. Launched by the Government of Germany and IUCN in 2011, the Challenge surpassed the 150-million-hectares milestone for pledges in 2017. Countries and organizations energized by the Bonn Challenge have fostered regional political and technical cooperation spaces to share expertise and lessons learnt. These initiatives include the African Forest Landscape Restoration Initiative (AFR100), Initiative 20 × 20 in Latin America and the Caribbean, ECCA30 in Europe, Caucasus and Central Asia, and the Agadir Commitment in the Mediterranean region [110]. Pledges in Africa include Bonn Challenge, Central Africa Countries to restore 34,56 million hectares of forest in the species-rich Congo Basin;

Since July 2016, 14 African countries have endorsed the visionary Kigali Declaration—a Pan-African commitment to accelerate forest landscape restoration interventions in support of the Bonn Challenge. Recognizing the close connection between restoring forests and ensuring food and water security for vulnerable communities, signing ministers declared, "Forest landscape restoration offers multiple benefits that align directly with African nation's economic growth and poverty reduction plans [106]".

7.4 The New York Declaration on Forest

In New York, on the 23rd of September 2014, World leaders announced new pledges to restore over 30 million hectares of degraded forest lands. The commitments come from Ethiopia, the Democratic Republic of the Congo, Guatemala, and Uganda, among others, and more than doubled the number of hectares contributing to achieving the Bonn Challenge, a global goal to restore 150 million hectares of deforested and degraded lands by 2020. These goals can potentially reduce annual carbon emissions by 4.5 to 8.8 billion tons of CO_2 equivalent per year, roughly equivalent to the annual emissions of the United States [141].

7.5 REDD + Initiative

REDD + " first emerged in 2007 during the negotiations under the UNFCCC. Then, in 2013, in Warsaw, the Conference of the Parties (COP) to UNFCCC agreed on a set of decisions known as the Warsaw Framework for REDD +, which encourages developing countries to pursue mitigation actions in the forest sector, and all countries to support such efforts, including through finance. The Warsaw Framework includes guidance for countries on developing a Forest Reference Emission Level (FREL) as a benchmark of REDD + performance. It also demonstrates how entities financing REDD +, including the Green Climate Fund (GCF), can apply methodological guidance consistent with COP decisions [140].

7.6 The Great Green Wall (GGW) Initiative

Launched in 2007 by the African Union, the game-changing African-led Great Green Wall initiative aims to restore the continent's degraded landscapes and transform millions of lives in the Sahel. This ambitious project is being implemented across 22 African countries and will revitalize thousands of communities across the continent. It brings together African countries and international partners under the leadership of the African Union Commission and the Pan-African Agency of the Great Green. More than USD 8 billion has been raised and pledged to support this game-changing initiative. The objective of the GGW initiative's ambition is to restore 100 million hectares of currently degraded land, sequester 250 million tons of carbon and create 10 million green jobs by 2030 [132].

8 Conclusions and Recommandations

This study concluded that bamboo possesses outstanding biological characteristics that permit it to rapidly adapts, recolonize and reclaim degraded, abandoned and marginal lands. Bamboo provides all the ecosystem services suitable to support human well-being on earth. Furthermore, bamboo contributed to carbon sequestration, thus a species to be used in FLR interventions. With the proper know-how, case studies have demonstrated the proper use of bamboo in restoration initiatives. Policymakers and development planners should consider bamboo in the different global restoration initiatives in general and Africa in particular.

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Socioecological Problematic and Proposals for the Conservation of Two Endangered Species of Woody Endemic Bamboo of Mexico

Rosa Marina Rodríguez Marín, Eliane Ceccon, Patricia Hernández Rodríguez, and James Rodríguez

Abstract Mexico is a biologically megadiverse country and is the fourth nation in terms of species richness. This country is home to 25,000–30,000 species of plants, one of which is woody bamboo. There are 58 Mexican woody bamboo species, and 41 of these species are endemic to Mexico, Chiapas is the richest State in woody bamboo species. Regrettably, most endemic woody bamboo species are found only in a few sites with anthropic disturbances like *Rhipidocladum martinezii* and *Otatea glauca* that inhabit the regions of Soconusco and Sierra in the south of the state of Chiapas. Both regions have a great biological richness but, at the same time, agribusiness (the most important economic activity) is the main driver of deforestation. Both species have a restricted distribution and face severe threats to the survival of their populations, mainly due to the loss of their habitats by human activities. In this chapter, we developed for both bamboo species a methodology to estimate the extinction risk based on national and international red lists (Mexican Official Norm NOM-059-SEMARNAT-2001 and IUCN Red List, respectively). The result of both lists' evaluation was that these endemic species are endangered of extinction. We discussed the methodology and concluded that the preservation of biodiversity is a multidisciplinary labor that requires the participation mainly of local actors and institutions.

Keywords Chiapas · Red list · *Rhipidocladum martinezii* · *Otatea glauca* · Communities · Risk of extinction · Deforestation · Soconusco

R. M. Rodríguez Marín (✉)
The Latin American Faculty of Social Sciences (FLACSO), Mexico City, Mexico
e-mail: rosamarina11@yahoo.com.mx

E. Ceccon
Regional Center for Multidisciplinary Research (CRIM), National Autonomous University of Mexico (UNAM), Mexico City, Mexico

P. H. Rodríguez
Eizia- Civil Association, Tuxtla Gutiérrez, Chiapas, Mexico

J. Rodríguez
Independent Consultant, Cintalapa, Chiapas, Mexico

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1 Introduction

Mexico has a territorial extension (continental and insular part) of almost 2 million km^2 [1] that represents less than 2% of the Earth's surface but is one of the richest countries in biological diversity worldwide [2]. This country occupies fourth place in the group of megadiverse countries [3], mainly due to its geographical position, the extension of its coastline, and its geological history, which results in a complex relief, which generates a great variety of ecosystems [1].

Regarding vascular plant species richness, Mexico occupies the fourth in the world, approximately 25,000 have been described nowadays, but it is estimated around 30,000 [3]. The most abundant families are Compositae, Leguminosae, and Graminae or Poaceae [4–6]. Particularly Mexican humid tropics zone, in the states of Oaxaca, Chiapas, and Veracruz, have the biggest floristic lists in the country [7]. Moreover, they are recognized as centers of origin of agrobiodiversity [8]. Associated with this biological richness, there is in Mexico an important cultural diversity, mainly related to languages [9]. Mexico belongs to the 10 countries with the highest linguistic diversity [3]. Around 68 indigenous peoples speak their own native languages, which are organized into 11 linguistic families [10].

In terms of endemisms, around 50% of Mexican native flora is exclusive to its territory [11]. If one of these species extinguishes in Mexico, it will disappear from the planet. Therefore, endemic species are particularly important in relation to biological diversity and consequently have priority for conservation public policies [3].

Due to the above-mentioned reasons, it can be stated that Mexico has a heterogeneous territory, with a remarkable biocultural diversity [8], and a high ecological fragility [12]. Thus, this extraordinary biodiversity is at risk, mainly in the last forty years, ecosystem degradation and deforestation have seriously been affected by diverse economic and social drivers [13, 14]. Unfortunately, the health of ecosystems and their provision of ecosystem services strongly depends on the diversity of species and their interactions [15].

Mexico is also considered as one of the most important centers of diversity and endemism of the grass family (Poaceae) [16]. In this family, the subfamily Bambusoideae (bamboos) can be highlighted, as the third most diverse subfamily with 1,698 species [17]. This subfamily is subdivided into three tribes: Olyreae or herbaceous, the woody Arundinarieae (mild weather), and the Bambuseae (woody tropical bamboos) [18].

The Mexican territory is part of the third region with the greatest diversity of bamboo species on the American continent [19]. Nowadays, 62 species have been described in Mexico: four herbaceous and 58 woody bamboos, of which 41 species are endemic [20]. The eight genera of native woody bamboos found in Mexico are: *Arthrostylidium, Aulonemia, Chusquea, Guadua, Merostachys, Rhipidocladum, Otatea,* and *Olmeca.* Their geographical distribution is wide, they can be found in different vegetation types (both humid and arid) (Fig. 1), from sea level to more than 3000 m.a.s.l. The states with more species are Chiapas, Oaxaca, and Veracruz [21].

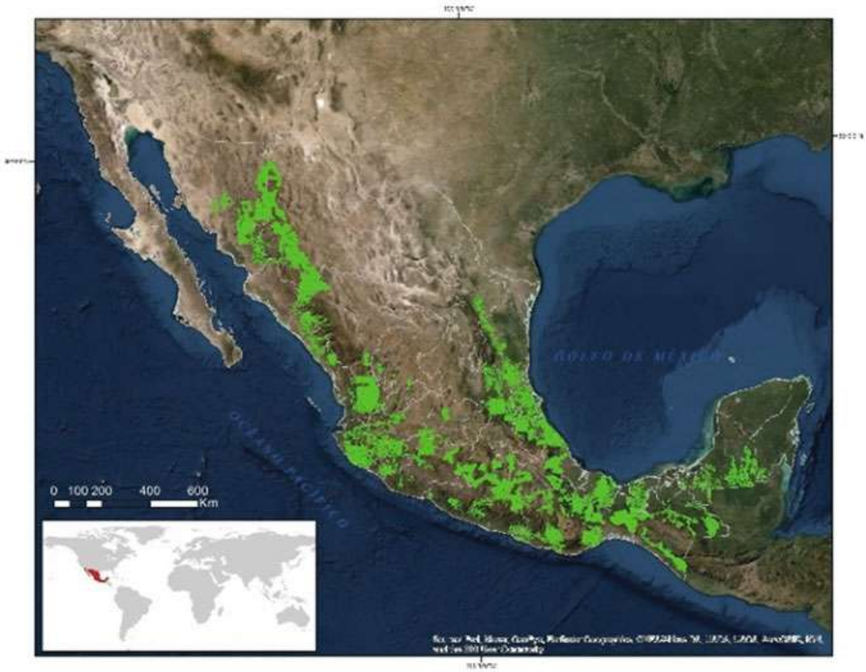

Fig. 1 Woody bamboo species distribution area in Mexico (green areas). Adapted from [18], License CC BY"

In a multicultural country like Mexico, the same biological resource may present different uses and meanings according to the different ethnicities and territories. Woody bamboo native species have been used since pre-Hispanic times as construction material, arms, or furniture. Currently, almost 80% of the species found in Mexico have some use, among the most frequent are basketry, housing construction, and fodder [22].

Approximately 75% of bamboo species in Mexico are known by one or more local names and 50% of the species have one or until two names in each one of the 68 indigenous languages spoken in Mexico. This reveals the high degree of interaction between human beings and bamboo species [21].

Bamboo species in Mexico constitute an important source of natural resources, providing different environmental services and offering multiple options for different social groups. However, due to the anthropic disturbances in their habitats, some species, particularly the endemics, are threatened with extinction. Such is the case of *Rhipidocladum martinezii* and *Otatea glauca*, endemic species located in socioeconomic regions Soconusco and Sierra in the south of the state of Chiapas. Both regions have a great biological richness but agribusiness (the most important economic activity) is a very important driver of deforestation [23].

The vulnerability of bamboo species is magnified by the simultaneous flowering and the subsequent complete death of the population. In addition, flowering cycles are irregular (ranging from two to 120 years). In this way, if a flowering coincides with a disturbance (deforestation, fire, or hurricanes), the seeds or seedlings in a short time will die because they will not be able to tolerate the harsh conditions of a degraded environment. Therefore, an entire population may be lost instead of reproducing since, in rare cases, the rhizome survives to regenerate and produce new ones. Seed production is also uncommon and when stored, they retain their viability for a short time [24, 25]. Another factor is when bamboos die after flowering, people remove them to carry out agriculture, livestock, or construction [26].

Therefore, one way to contribute to protecting *R. martinezii* and *O. glauca* species is to develop proposals for their conservation. The first very important step is to determine their risk of extinction, to later put them on the red list of species protection, if it is necessary. Each list has its own methodology, which was designed for all species however bamboo, due to its own ecophysiological characteristics, requires an *ad hoc* methodological adaptation, which was still not developed. It is also important to evaluate which of these methodologies is more adequate to be applied in Mexico socioeconomic conditions.

In this sense, this chapter has the following objectives: (i) Develop a methodological adaptation based on a national and an international red list (Mexican Official Norm NOM-059-SEMARNAT-2001 and IUCN Red List), to estimate the extinction risk of *R. martinezii* and *O. glauca* populations, (ii) Evaluate and compare the conservation status of both species, (iii) Discuss which of the used methodologies is more adequate to be applied in México, (iv) Evaluate the scope of this research, (v) Design complementary proposals for their conservation considering the effective local people participation in the process.

For the development of this research, an interdisciplinary perspective was required that allowed us to approach in an integral way the complexity of these socioecological problems and propose effective actions.

2 Methods

2.1 Study Area

The socioeconomic regions Soconusco and Sierra are located in the south of the state of Chiapas, bordered to the north by the southern mountains chain "Sierra Madre" and the Central Depression of Chiapas, to the east by the Republic of Guatemala, to the south by the Pacific Ocean and to the west by the socioeconomic regions Istmo-Costa and Frailesca (between 15° 56′ 58.1166″ and 14° 31′ 55.5522″ N of latitude and −91° 54′ 52.5024″ −92° 55′ 51.459″ W of longitude) [27] (Fig. 2). In these regions, there are four physiographical provinces: Central Depression, Southern Sierras, Volcanoes of the North Gulf Coast and Coastal Plain of Chiapas and Guatemala [28]. Elevation ranges from 0 to 4,100 m.a.s.l [29]. In the Sierra and Volcanoes, the main rock types are andesite, granites, and granodiorites of the late Mesozoic and tuffs of different

Fig. 2 Location of study areas and species (by Rodríguez-Marín in ArcMap 10.4.1, Vivid Imagery Basemap Layer 2020–2021, [27]

stages of the Cenozoic. The soils are andosols and acrisols; at Coastal Plain, there are Pliocene and Quaternary sediments of alluvial origin [30, 31].

The climate in these regions is tropical and temperate in areas of higher altitudes. Temperatures range between 5 and 27 °C, and precipitation from 600 to 7,000 mm, with influence from cyclones in summer [32]. The main rivers are Grijalva or Grande, Huehuetán, Huixtla, and Suchiate, the natural boundary with Guatemala [33].

Due to the topographic, soil, and climatic variability, the diversity of plant species is extremely high in these regions, there are five types of forest (oak, oyamel, pine, pine-oak, and cloud forest), six types of rainforests (high and medium evergreen, high and medium semi-deciduous, low deciduous and sub-deciduous), and also others, like high mountain meadows, mangroves, coastal dune and riparian vegetation [34].

The Soconusco and Sierra regions have a great biological richness and are in specific sites considered a high biodiversity value and classified as Priority Terrestrial Regions (RTPs, in Spanish acronym). These RTPs were delimited based on criteria of biological type, a threat to the maintenance of biodiversity and opportunity for its conservation. In the Soconusco and Sierra there are four: (i) RTP-133 "El Triunfo- La Encrucijada-Palo Blanco", with two Federal Protected Natural Areas (ANPs, in Spanish): "El Triunfo" and "La Encrucijada" categorized as Biosphere Reserves, in addition, there is a State ANP "Cordón Pico El Loro-Paxtal", (ii) RTP-134 "El Mozotal"; (iii) RTP-135 "Tacaná-Boquerón" including the Tacaná Volcano Biosphere Reserve, and (iv) RTP-136 "Selva Espinosa Alto Grijalva-Motozintla" [35, 36]. There are also two State ANPs "El Cabildo Amatal" and "El Gancho Murillo"

[37] in the coastal zone. Recently, in the plain area, two ADVCs were decreed (Areas Voluntarily Destined for Conservation, in Spanish). These voluntary ANPs are "El Rosario" and "El Silencio" [38].

2.1.1 Socioecological Context

The region Soconusco has 16 municipalities, and the region La Sierra has 12 municipalities [39]. The total population is 1,146,401, and 1% is indigene, most belong to the Mam Group. The most populated municipalities are Tapachula, Frontera Comalapa, Motozintla, and Huixtla, where 50% of the population is concentrated [40]. These regions have a high degree of marginalization [41], between 60 and 80% of the population lives in poverty conditions [42].

Agriculture is the most important economic activity in Soconusco and Sierra regions, more than 60% of the population is dedicated to cultivating coffee, oil palm, banana, mango, corn, and cocoa. Almost 80% of regional agriculture is destined for the national and international markets [23, 43]. At the same time, according to Escobar Flores and Castillo Santiago [44], these regions currently have strong deforestation processes. In fact, Soconusco has been one of the most dynamic regions in agricultural production since pre-Hispanic times and continued during the colonial era, in which it was one of the most productive areas of cocoa worldwide [23].

During the eighteenth century, new lands were opened for the cultivation of coffee, mainly by immigrants, who took advantage of the facilities offered by the Mexican government to acquire lands in this region. At this time, coffee was considered a luxury item in Europe [45], however, this process of immigration to open new coffee farms continued during the nineteenth century [46].

In fact, the coffee plantations were a profitable activity to which a significant percentage of the population of Soconusco was dedicated. However, in the late 1980s, the international price of coffee began to decline dramatically, which adversely affected small coffee producers, so, some of them looked for other employment alternatives in urban centers, while most remained. This led to indiscriminate logging to increase the cropping area to compensate for the lower income caused by the fall in prices [47]. This huge exploitation of the land caused environmental degradation, which increased due to the management system used (clearing, lumbering, and burning), which also frequently caused forest fires. This deforestation increased the vulnerability of natural vegetation populations, which was reflected in the increased destructive force of extreme hydrometeorological events such as hurricanes. Hurricanes Roxane in 1995, Mitch in 1998, and the Hurricane Stan in October 2005. These events caused the greatest destruction and economic losses that these regions have suffered [23, 48].

Hurricane Mitch in 1998 caused severe flooding in Soconusco, Sierra, and other regions. Communities were completely flooded, and thousands of agricultural hectares were destroyed, approximately 50% of the coffee production was lost by sliding the slopes where it was cultivated [48]. Also, seven years later, Hurricane Stan caused in these regions, the greatest damage provoked by a hydrometeorological event. The devastation was of great magnitude resulting in an unprecedented loss of human lives and ecosystem destruction, 75% of the localities were flooded, so it was decreed as a Disaster Zone. The economic loss was equivalent to 370 million dollars [49, 50].

2.2 Description of Species

2.2.1 *Rhipidocladum martinezii* Davidse & R.W. Pohl (1992:90) [51–53], Fig. 3

Classification: family: Poaceae, subfamily: Bambusoideae, tribe: Bambuseae, subtribe: Arthrostylidiinae, genus: *Rhipidocladum* McClure, section: *Racemiflorum.*

Botanical description: Caespitose, scandent, ligneous bamboo. Rhizome short; pachymorph, culm length 5–12 (m), culm diameter 8–16 (mm), relatively thin-walled, hollow, cylindrical, glabrous. Internode length 24 (cm), 100–200 branchlets per node, culm leaves narrowly lanceolate, 15 or more times longer than wide (blades at least 4 cm long), 2–5 foliage leaves per branchlet, branchlet length 10–30 (cm), Synflorescence length 2.5–4.5 (cm), 2–4 spikelets per synflorescence, Spikelet spacing 8–15 (mm). Caryopsis 5.5- 6.1 mm long, 1.0–1.2 mm wide, flattened and

Fig. 3 *Rhipidocladum martinezii* (by Rodríguez-Marín in situ 2016)

slightly grooved on the hilar side, rounded on the embryo side, dark brown; embryo ca. 1 mm long; hilum as long as the caryopsis.

Phenology: Perenne, gregarious-monocarpic flowering, the only records of florescence are from 1987 and 2003.

Common name: “carrizo chico” (Spanish).

Uses: cattle fodder [54].

Distribution and Habitat: It is an endemic and restricted species, only growing on the montane cloud forest of the Mexican slopes of the Tacaná Volcano, at 1770 m.a.s.l in the Soconusco region of the State of Chiapas [51]. The type of soil is Andosol (volcanic origin), the temperature is 18 °C average, and the total annual precipitation is 4,000 mm [55].

2.2.2 *Otatea glauca* L.G. Clark & G.Cortés [53, 54, 56, 57], Fig. 4

Classification: family: Poaceae, subfamily: Bambusoideae, tribe: Bambuseae, subtribe: Guaduinae, genus: Otatea (McClure & E. W. Sm.) Calderón & Soderstr.

Botanical description: Rhizomes sympodial, pachymorph, the necks at least slightly elongated. Culms to 3 cm in basal diameter, to 8 m tall, erect; internodes 27–30 cm long, terete, glabrous, glaucous especially when young, hollow with the walls 1.5–2 mm thick, the lacuna occupying >50% of the total diameter. Culm leaves 18–30 cm long; sheaths 14–22 cm long, 8–17 cm wide at the base, 2.4–5.2 times as long as the blades. Foliage leaves 4–5 per complement; sheaths glabrous, weakly keeled at the summit, sheath summit extension absent. Synflorescences 4–9 cm long,

Fig. 4 *Otatea glauca* (by Rodríguez-Marín in situ 2007)

racemose or paniculate, 2–7 spikelets per synflorescence. Spikelets 3–4 cm long, laterally compressed, 3–5 florets per spikelet with an additional apical rudimentary floret. Fruit not seen [56].

Phenology: Little is known about the phenology of this species, as only one flowering collection (the type) from a wild population is known. This flowering (2002–2003) was apparently gregarious and monocarpic because all the plants in the area were flowering and dying.

Common names: "*mute*" (Mochó-Motozintleco), "*mayan silver bamboo*" (English) [56].

Uses: material to build houses and fences and to make musical instruments (flutes). In the United States was introduced and cultivated for ornament [56].

Distribution and Habitat: This species is a narrow endemic in the Sierra region of the State of Chiapas, growing in dry secondary vegetation derived from the original dry forests at 600 to 1,500 m.a.s.l. The plants are usually found in small canyons along rivers or streams. The type of soil is acrisol and regosol, the temperature is 22 °C average, and the total annual precipitation is 3,000 mm [58].

2.3 Estimating the Extinction Risk

We used two evaluation systems, a national and an international, to estimate the extinction risk of *R. martinezii* and *O. glauca.*

The national system is the NOM-059-SEMARNAT (Mexican Official Norm by the Secretariat of Environment and Natural Resources (SEMARNAT in Spanish). This Norm is a set of official regulations developed by the Mexican federal government to determine the risk category of species. This NOM provides the Method to Assess the Risk of Extinction (MER) (Table 1). This method uses four criteria about distribution, habitat, vulnerability, and human impact. Conventional numeric values are assigned, in ascending order of risk, which are subsequently added up. Depending on the numeric value assigned, the species or populations at risk are classified as: Endangered of extinction (12–14 points) or Threatened (10–11 points). Other categories are Special protection, and Probably extinct in the wild [59].

The international system is the Red List of Threatened Species, developed by the International Union for the Conservation of Nature (IUCN), the world's largest environmental network (Table 2). The Red List was established in 1964 and has evolved to become the world's most comprehensive information source on the global extinction risk status of animals, fungi, and plant species. This system is characterized by nine categories: (i) Not Evaluated, (ii) Data Deficient, (iii) Least Concern, (iv) Near Threatened, (v) Vulnerable, (vi) Endangered, (vii) Critically Endangered, (viii) Extinct in the Wild and (ix) Extinct. To determine these categories' uses, it is necessary specific data about population, geographic range, and external risk factors as criteria. The criteria are independent and can be evaluated individually. In case of presenting different categories of threat in each evaluated criterion, the one of the highest value threat will be taken (Table 2) [60].

Table 1 Description of the Method to Assess the Risk of Extinction (MER) of the Mexican Official Norm (NOM-059-SEMARNAT)

NOM-059-SEMARNAT criteria	Information requested	Scale	Description	Score
A) DISTRIBUTION	A1. Distribution A2. Map A3. Explanation of how the map was made A4. Evaluation of the relative size of the distribution	(i) Very restricted	Less than 5% of the national territory	4
		(ii) Restricted	Between 5 and 15% of the national territory	3
		(iii) Moderately restricted	More than 15% but less than 40% of the national territory	2
		(iv) Widely distributed	Equal to or greater than 40% of the national territory	1
B) HABITAT	B1. Description B2. Diagnostic of the current state B3. Assessment of the current status of the habitat	(i) Hostile or very limiting	Habitat effects with respect to known requirements for the natural development of the species	3
		(ii) Hostile or very limiting		2
		(iii) Conducive or non-limiting		1
C) VULNERABILITY	C1. Life history of the species C2. Diagnosis of the current status of the population or species C3. Assessing what factors makes the specie vulnerable	(i) High vulnerability	Particular factors related to the life history of the species that make it vulnerable	3
		(ii) Medium vulnerability		2
		(iii) Low vulnerability		1
D) HUMAN IMPACT	D1. Actual and potential risk factors D2. Prognostic analysis of the trend of the referred species or population D3. Impact assessment	(i) High impact	The magnitude of impact and trend of human influence on the species	4
		(ii) Medium impact		3
		(iii) Low impact		2

Source Authors, based on information Sánchez [59]

Table 2 Description of the IUCN Red List Categories and Criteria (in bold the analysis realized)

IUCN criteria	Options of analysis or data requested	Description	Parameters	Critically endangered	Endangered	Vulnerable
A) POPULATION SIZE REDUCTION	a) Direct observation	Measured over the longer of 10 years or three generations (use at least one of the options of analysis)	A1. Population reduction observed, estimated, inferred, or suspected in the past where the causes of the reduction are clearly reversible AND understood AND have ceased	≥90%	≥70%	≥50%
	b) Index of abundance appropriate to the taxon		A2. Population reduction observed, estimated, inferred, or suspected in the past where the causes of reduction may not have ceased OR may not be understood OR may not be reversible	≥80%	≥50%	≥30%
	c) Decline in area of occupancy, the extent of occurrence and/or habitat quality		A3. Population reduction projected, inferred or suspected to be met in the future (up to a maximum of 100 years) [(a) cannot be used for A3]			

(continued)

Table 2 (continued)

IUCN criteria	Options of analysis or data requested	Description	Parameters	Critically endangered	Endangered	Vulnerable
	d) Actual or potential levels of exploitation		A4. An observed, estimated, inferred, projected or suspected population reduction, where the time period must include both the past and the future (up to a max. of 100 years in the future), and where the causes of reduction may not have ceased OR may not be understood OR may not be reversible			
	e) Effects of introduced taxa, hybridization, pathogens, pollutants, competitors or parasites					
B) GEOGRAPHIC RANGE	**a) Location**	Geographic range in the form of extent of occurrence and/or area of occupancy (use at least two of the options of analysis)	Number of locations	1	≤5	≤10
	b) Continuing decline observed, estimated, inferred or projected in any of: (i) **extent of occurrence**; (ii) **area of occupancy**; (iii) area, extent and/or quality of habitat; (iv) number of locations or subpopulations; (v) number of mature individuals		B1. Extent of occurrence	<100 km^2	<5,000 km^2	<20,000 km^2

(continued)

Table 2 (continued)

IUCN criteria	Options of analysis or data requested	Description	Parameters	Critically endangered	Endangered	Vulnerable
	c) Extreme fluctuations in any of: (i) extent of occurrence; (ii) area of occupancy; (iii) number of locations or subpopulations; (iv) number of mature individuals		B2. Area of occupancy	<10 km^2	<500 km^2	<2,000 km^2
C) SMALL POPULATION SIZE AND DECLINE	**Mature individuals**	Small population size and decline (use at least one of the options of analysis)	Number of mature individuals	<250	<2,500	<10,000
	C1. Population projected		An observed, estimated or projected continuing decline of at least (up to a max. of 100 years in the future)	25% in three years or one generation (whichever is longer)	20% in five years or two generations (whichever is longer)	10% in 10 years or three generations (whichever is longer)
	C2. Mature individuals (Observed, estimated, projected or inferred continuing decline)		**(ai) Number of mature individuals in each subpopulation**	≤50	≤250	≤1,000
			(aii) % of mature individuals in one subpopulation	90–100%	95–100%	100%

(continued)

Table 2 (continued)

IUCN criteria	Options of analysis or data requested	Description	Parameters	Critically endangered	Endangered	Vulnerable
			b) Extreme fluctuations in the number of mature individuals			
D) RESTRICTED POPULATION	–	Very small or restricted population	**D1. Number of mature individuals**	<50	<250	<1,000
			D2. Restricted area of occupancy or number of locations with a plausible future threat that could drive the taxon to CR or EX in a very short time	–	–	Area of occupancy <20 km^2 or number of locations ≤ 5
E) QUANTITATIVE ANALYSIS	–	Indicating the probability of extinction in the wild	–	$\geq 50\%$ in 10 years or three generations, whichever is longer (100 years max.)	$\geq 20\%$ in 20 years or five generations, whichever is longer (100 years max.)	$\geq 10\%$ in 100 years

Source Authors, based on information IUCN [60]

2.3.1 Application of the Method to Assess the Risk of Extinction (MER) of the Mexican Official Norm (NOM-059-SEMARNAT)

A) DISTRIBUTION

A1, A2, A3. Different herbaria were consulted, including the National Autonomous University of Mexico (MEXU in Spanish), the Institute of Ecology of Xalapa (XAL in Spanish), electronic collections of Missouri Botanical Garden (MBG), the Royal Botanic Gardens (KEW), the World Biodiversity Information Network (Remib in Spanish) National Commission for the Knowledge and Use of Biodiversity (Conabio in Spanish). With the information obtained, the found locations were ubicated in topographic maps. During the fieldwork, we contacted local people that was able to identify the places and the bamboo species that we were looking for. We visited all reported places (April and July 2007), and where we found a population of the bamboo species searched, we registered with a GPS (Garmin). The distribution maps were made using the GIS *Arc View 3.2*, topographic maps (1:50,000) and digital orthophotos (1:75,000) (INEGI), and the georeferenced information obtained in the field was under the concept of "Area of occupancy" is defined as the area which is occupied by a species, excluding cases of vagrancy [60]. (For this publication, the distribution maps were reissued using ArcMap 10.4.1, and Vivid Imagery Basemap Layer 2020-2021).

A4. For each species, the area of the distribution was calculated in km^2, and the proportion of this area was related to the surface of Mexico, as requested by the MER.

B) HABITAT

B1, B2. The characterization and diagnostic of the habitat where the populations of the bamboo species were found, was carried out through the consultation of various bibliographic sources, cartographic, herbarized specimens, databases of meteorological stations near the area, talks with the collectors and local inhabitants as well as from observations and samplings carried out in the field.

B3. To evaluate the current state of the habitat, we applied the measurement of chronic disturbance [61]. At each site with the presence of the bamboo species studied, three transects 50m long by 2m wide were traced and the following factors were measured:

- Livestock raising: Goat droppings frequency (GOAT), Cattle droppings frequency (CATT), Browsing (BROW), Livestock trail density (LTRA), Soil compaction (COMP)
- Human activities: Fuelwood extraction (FUEL), Evidence of wildfires (FIRE), Human trails density (TRAN), Land use (LUSE), Contiguity to activity cores (CORE), Land use (LUSE)

- Land degradation: Erosion (EROS), Presence of soil islands (ISLA), Totally modified surfaces (TOMS)

  The calculated values were integrated into the following formula. The scale of values was between 0 and 100, values close to 0 were for the conserved sites and close to 100 were for the disturbed sites:

$$\begin{aligned} D = {} & 0:1334\,\text{GOAT} - 0:1631\,\text{CATT} + 0:1334\,\text{BROW} + 0:0799\,\text{LTRA} \\ & - 0:1257\,\text{COMP} + 0:1931\,\text{FUEL} - 0:0231\,\text{LTRA} + 0:0758\,\text{TRAS} \\ & + 0:1389\,\text{PROX} + 0:1371\,\text{CORE} + 0:0929\,\text{LUSE} + 0:1133\,\text{EROS} \\ & + 0:1837\,\text{ISLA} + 0:1009\,\text{TOMS} \end{aligned}$$

C) VULNERABILITY

C1. The information was obtained from different sources: bibliography, herbaria above-mentioned, as well as talking with experts and local inhabitants.

C2. The diagnosis of the current state of the population was obtained through a population census, and calculation of productivity:

- Population census: Three plots of 10 × 1 m were established. The total of the individuals observed was counted, and the heights and diameters of the main culms were measured, as well as the ages according to De la Cruz, Cruz, and Castaño [62–64].
- The productivity was obtained through the count of the number of culms and shoots in a unit of surface (ha) in a year, according to Loetsch, Montes, and Botero [65–67].

C3. The evaluation of the factors that make the population of vulnerable species was carried out based on the results of the analyses

D) HUMAN IMPACT

D1. It was determined based on a literature review, as well as observations made in the field.

D2, D3. It was done a regional analysis of habitat loss between 1976 and 2005 in the Soconusco and Sierra regions was carried out by the GIS ArcView 3.2. From these spatial analyses, forecasts were made about the possible trend. It was considered for both species. The following cartographic materials were used:

- Land use. Series I and III of INEGI. Scale 1:250,000
- National Forest Inventory. 2000. UNAM. Scale 1:250,000
- Satellite imagery from 1970, 1974, 1980, and 1990 Landsat MSS spatial resolution (60*60 km), 2000 Landsat ETM spatial resolution (30*30 km)

The difference between periods, the rate of annual change and the average (ha/year), the average rate of change between the years evaluated, as well as the projection for the next decade, were calculated for the land use class with the formula used by Peña [68].

A landscape analysis was also performed with the Patch Analyst 3.0 tool of the GIS ArcGIS 3.2. Were considered metrics about landscape, edge, shape, diversity, and core area, according to Cayuela, Peña, Altamirano and Fontúrbel [68–71].

2.3.2 Application of the Method of the Red List of Threatened Species of IUCN

Because in this method, each criterion offers analysis options to choose from, to develop the present research, the following analyses were selected based on the available information according to the characteristics of the species (in bold, Table 2).

A) POPULATION SIZE REDUCTION

  c) Based on the observations made in the field, testimonies of local people and collectors, as well as ecological and biological characteristics of the species and a cartographic analysis with digital orthophotos (1996) scale of 1:75,000 and digital topographic charts (2003) scale of 1:50,000 of the study area; was delimited in the ArcGIS ArcView 3.2, the "extent of occurrence" (all sites where the specie was present at the moment of visit and in the past) [60]. We compared and calculated the percentage loss per year.

B) GEOGRAPHIC RANGE

  a) The parameter of this analysis was the number of locations. A location is an area (geographic or ecologic) where a threatening event could devastate all the individuals of the specie [60]. For *R. martinezii*, fires were considered the biggest threat because they frequently occur in the area. In the GIS ArcGIS *3.2* with data from [72], the possible areas where fires could occur and seriously affect the population were calculated.

     For *Otatea glauca*, flooding caused mainly by hurricanes was considered the greatest threat to the geographical area. The possible affected areas were calculated with GIS ArcGIS *3.2* and data from COCyTECH, CONANP and ECOSUR [73].

  b) This parameter demands complement data about (i) the extent of occurrence and (ii) the area of occupancy, which was previously described.

C) SMALL POPULATION SIZE AND DECLINE

a), ai), aii) The number of mature individuals was obtained from the population census previously described (Criteria Vulnerability, Subsection C2, Method to Assess the Risk of Extinction of the Mexican Official Norm).

D) RESTRICTED POPULATION

D1) This criterion is similar to the previous one (population size), so information was obtained from the population census, explained previously.

E) QUANTITATIVE ANALYSIS

This analysis was not performed because the necessary data were not available.

3 Results

3.1 Method to Assess the Risk of Extinction (MER) of the Mexican Official Norm (NOM-059-SEMARNAT)

3.1.1 *Rhipidocladum martinezii*

Table 3 presents the results obtained from *Rhipidocladum martinezii* applying the "Method to Assess the Risk of Extinction (MER) of the Mexican Official Norm (NOM-059-SEMARNAT)". We found a score of 12 points, which means that this species is endangered of extinction [59].

3.1.2 *Otatea glauca*

Table 4 shows the results obtained from *Otatea glauca* after the application of the "Method to Assess the Risk of Extinction (MER) of the Mexican Official Norm (NOM-059-SEMARNAT)". The found score of 12 points means this species is endangered of extinction [59].

Table 3 Results of *Rhipidocladum martinezii* Method to Assess the Risk of Extinction (MER) of the Mexican Official Norm (NOM-059-SEMARNAT)

NOM-059-SEMARNAT criteria	Information requested	Results	Scale	Parameters/Reference	Score
A) DISTRIBUTION	A1. Distribution	Populations were found inside of Tacaná Volcano Biosphere Reserve, near the border. In July 2007, some sites reported in 2005, were disappeared	i) Very restricted	Less than 5% of the national territory	4
	A2. Map	Figure 5			
	A3. Explanation of how the map was made	See methods			
	A4. Evaluation of the relative size of the distribution	This species presented a distribution of 1.06 km^2			
B) HABITAT	B1. Description	Rugged relief on steep slopes, mainly in the wettest ravines, protected from wind and insolation. Altitudes between 1,600 and 1,770 m.a.s.l. The climate is semi-warm humid with temperatures from 12 to 28 °C, with a rainfall regime in summer (mainly from June to September) with a range of total precipitation that reaches 3000–3500 mm per year [32, 74–76]. The predominant vegetation is montane cloud forest in transition with high evergreen forest [77]. The type of soil is humic andosol of medium texture [78]	i) Hostile or very limiting	Besides living on a Biosphere Reserve, there was logging, mines, and garbage. The area is susceptible to fires and hurricanes. The chronic disturbance was highly	3

(continued)

Table 3 (continued)

NOM-059-SEMARNAT criteria	Information requested	Results	Scale	Parameters/Reference	Score
	B2. Diagnostic of the current state	Human disturbances that directly impact the species: clearing of vegetation to introduce crops (mainly coffee), sand mines to extract construction material, and dumping for waste (Fig. 6). Other threats are fires and hurricanes			
	B3. Assessment of the current status of the habitat	According to the methodology applied "measurement of chronic disturbance" [61], the site obtained an off-scale value (114.87), indicating that it is currently a very disturbing site			
C) VULNERABILITY	C1. Life history of the species	The type of flowering is gregarious-monocarpic, with records of fluorescence (1987, 2003, herbaria data)	ii) Medium vulnerability	Endemic species need trees to climb, population with a low number of individuals and low productivity, and are susceptible to an atypical flowering	2
	C2. Diagnosis of the current status of the population	Population density: A total of 54 tillers (individuals), each with six culms on average; 10 seedlings and 21 shoots on an area of 30 m^2, 74% of the culms were juveniles of approximately 1.5 years; the rest were dry. On average, there were 1.8 tillers/m^2 and each had a diameter of 4 cm			
		Productivity: A total of 339 culms in 30m^2			

(continued)

Table 3 (continued)

NOM-059-SEMARNAT criteria	Information requested	Results	Scale	Parameters/Reference	Score
	C3. Assessing what factors makes the specie vulnerable	An endemic species, with restricted distribution. This species is scandent, therefore in the absence of trees, it couldn't find where to climb. Also, the highest amount of light can produce more atypical bloom events, causing mortality [79]			
D) HUMAN IMPACT	D1. Actual and potential risk factors	Main risk: disturbances by human activities, fires and hurricanes. Biosphere Reserve, without a management program	ii) Medium impact	Fragmented region with a very high rate of logging, hence, the species experiments edge effect and vulnerability by extreme tropical storms. However, is located inside of a Biosphere Reserve	3
	D2. Prognostic analysis of the trend of the referred species or population	The regional analysis of habitat loss between 1976 and 2005, concluded that the types of vegetation that have lost the highest number of hectares are high and medium evergreen and sub-evergreen forests (8,298 ha), followed by montane cloud forest with 721 ha The landscape analysis showed that the surface area of the patches of all types of natural vegetation decreased and the number of patches increased. The oak forest disappeared from some areas. In the northeast, there were the smallest patches (<20 ha), and their connectivity was very low			

(continued)

Table 3 (continued)

NOM-059-SEMARNAT criteria	Information requested	Results	Scale	Parameters/Reference	Score
	D3. Impact assessment	The landscape analysis showed that the surface area of the patches of all types of natural vegetation decreased and the number of patches increased. The oak forest disappeared from some areas. In the northeast, there were the smallest patches (<20 ha), and their connectivity was very low			
TOTAL					12 points

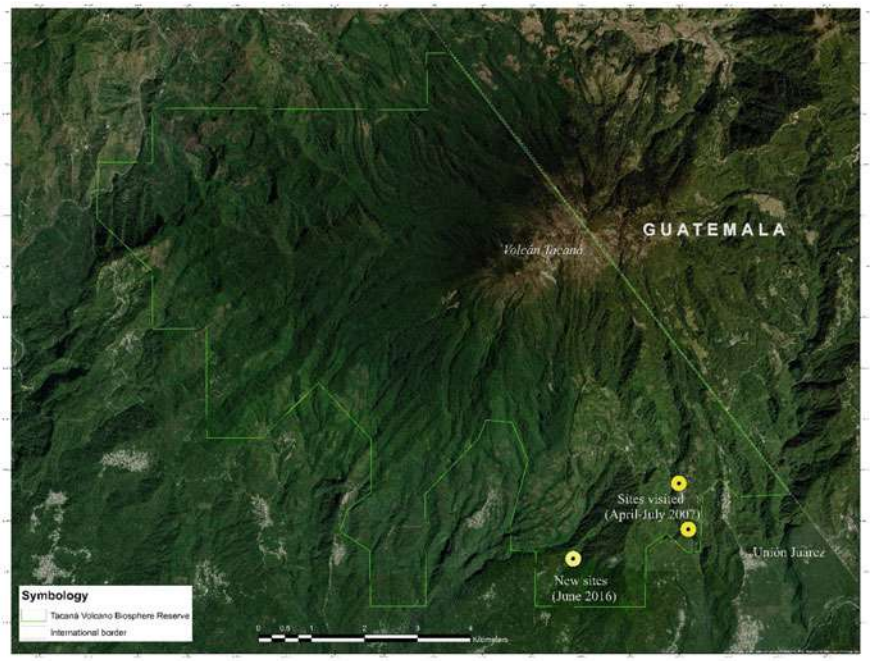

Fig. 5 Distribution of the specie *Rhipidocladum martinezii* inside of Tacaná Volcano Biosphere Reserve in the Soconusco region of the State of Chiapas, Mexico, near Guatemala

(a) (b) (c)

Fig. 6 Human activities observed that directly impacting the population of *Rhipidocladum martinezii* **(a)** crops **(b)** mining activity **(c)** dump for waste (by Rodríguez-Marín in situ 2007)

Table 4 Results of *Otatea glauca* method to assess the risk of extinction (MER) of the Mexican Official Norm (NOM-059-SEMARNAT)

NOM-059-SEMARNAT criteria	Information requested	Results	Scale	Parameters/Reference	Score
A) DISTRIBUTION	A1. Distribution	We discovered a new site, it was the only site where this species remains. The previous report with species presence was described in April 2007, but in July 2007, this species had already disappeared	(i) Very restricted	Less than 5% of the national territory	4
	A2. Map	Figure 7			
	A3. Explanation of how the map was made	See methods			
	A4. Evaluation of the relative size of the distribution	This species presented a distribution of 0.060 km^2			
B) HABITAT	B1. Description	Both sites had an abrupt relief with very steep slopes, this species was established near the rivers. Site 1 is at an altitude of 1,100 m.a.s.l, and Site 2 (the last discovery) is at 1,500 m.a.s.l. The climate at both sites is semi-warm humid with temperatures of 14° to 30 °C with a rainfall regime in summer (mainly from June to September) with a total precipitation range between 2,500 and 3,000 mm per year [32, 74–76]. The vegetation type is high sub-deciduous forest in transition with the coniferous forest [77]. The soil in both sites corresponds to a humic acrisol of medium and fine texture, respectively [78]	(ii) Intermediate or limiting	Logging, the area is susceptible to hurricanes. The chronic disturbance was moderate	2

(continued)

Table 4 (continued)

NOM-059-SEMARNAT criteria	Information requested	Results	Scale	Parameters/Reference	Score
	B2. Diagnostic of the current state	Both sites have been affected by hydrometeorological events. Particularly at Site 1, Hurricane Stan caused extreme rainfall, flooding, and landslides [80]. Since that event, local people have noticed a considerable decrease in the population of *Otatea glauca*. The main factor affecting the species at both sites is deforestation, to establish new crops and roads (Figs. 8 and 9). Presence of the invasive species *Arundo dunax* near the riverbeds			
	B3. Assessment of the current status of the habitat	According to the methodology applied "measurement of chronic disturbance" [61], both sites obtained values indicating a moderate perturbation, Site 1 (55.30) and Site 2 (48.60)			
C) VULNERABILITY	C1. Life history of the species	The type of flowering is gregarious-monocarpic, with records of florescence in 2002– 2003 [56]	(ii) Medium vulnerability	Endemic species, with a very low number of individuals, productivity, and potential problems of low genetic diversity. Susceptible to Hurricanes	2
	C2. Diagnosis of the current status of the population or species	Population density: six tillers (individuals) at Site 2. Each tiller had 28 culms on average and 21 shoots. Around 50% of the culms were dry or too old. On average, there were 0.16 tillers/m^2, and each had 2 cm of diameter			
		Productivity: 122 culms in 30 m^2			

(continued)

Table 4 (continued)

NOM-059-SEMARNAT criteria	Information requested	Results	Scale	Parameters/Reference	Score
	C3. Assessing what factors makes the specie vulnerable	Endemic bamboo with extremely restricted distribution with the possibility of low genetic diversity [81]. High vulnerability to extreme hydrometeorological events (massive decrease of the population)			
D) HUMAN IMPACT	D1. Actual and potential risk factors	Main risk: Destruction and modification of the only site where it still remained a population of this species by different human activities	(ii) Medium impact	The fragmented region with a very high rate of logging, hence, the species experiments edge effect and vulnerability by extreme tropical storms	4
	D2. Prognostic analysis of the trend of the referred species or population	The regional analysis of habitat loss between 1976 and 2005, concluded that the types of vegetation that have lost the highest number of hectares are high and medium evergreen and sub-evergreen forests (8,298 ha), followed by montane cloud forests with 721 ha The landscape analysis showed that the surface area of the patches of all types of natural vegetation decreased, and the number of patches increased. The oak forest disappeared from some areas. In the northeast, there were the smallest patches (<20 ha), and their connectivity was very low			

(continued)

Table 4 (continued)

NOM-059-SEMARNAT criteria	Information requested	Results	Scale	Parameters/Reference	Score
	D3. Impact assessment	The deforestation in Soconusco and Sierra regions began centuries ago, and this process has accelerated in the last 20 years. Commonly even in lands with high slopes, there are crops. This loss of forest cover negatively impacts the ecosystem in various ways, specifically increasing the vulnerability to extreme tropical storms (Hurricanes Mitch 1998 and Stan 2005)			
Total					12 points

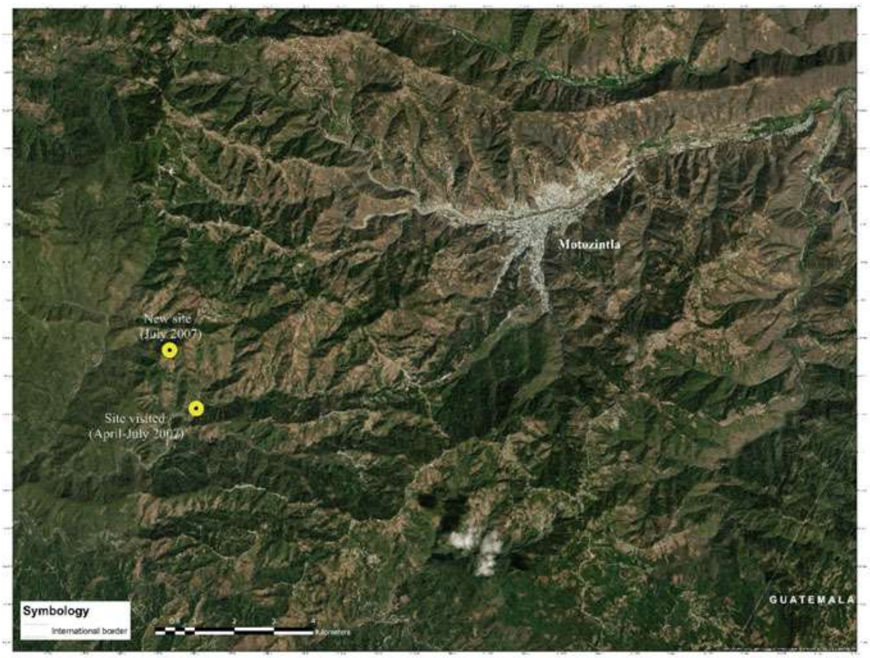

Fig. 7 Distribution of the specie *Otatea glauca* in the Sierra region of the State of Chiapas, Mexico, near Guatemala

Fig. 8 Human activities observed directly impacting the population of *O. glauca* in Site 1. **(a)** Roads **(b)** pruning **(c)** slopes with sliding and crops (by Rodríguez-Marín in situ 2007)

Fig. 9 Human activities were observed directly impacting the population of *O. glauca* in Site 2 **(a)** pruning **(b)** opening new roads (by Rodríguez-Marín in situ 2007)

3.2 Method of the Red List of Threatened Species of IUCN

3.2.1 *Rhipidocladum martinezii*

Table 5 shows the results obtained through the application of the "Method the Red List of Threatened Species of UICN" to *Rhipidocladum martinezii.* According to this methodology, this species is Critically endangered, due to the results of the criteria being independent, and by a precautionary principle, we assigned the criterium with the highest degree of threat [60].

3.2.2 *Otatea glauca*

Table 6 presents the results obtained by applying the "Method the Red List of Threatened Species of IUCN" to *Otatea glauca.* According to this methodology, this species is Critically endangered, due to the results of each criterion are independent, and by a precautionary principle, we assigned the criterium with the highest degree of threat [60].

4 Discussion

4.1 The Bamboo Species

More than 60% of the population of Sierra and Soconusco is dedicated to agriculture for the national and international markets [23, 43]. This kind of land exploitation has caused deforestation and environmental degradation. This degradation increased the vulnerability of bamboo populations and added to the increased destructive force of extreme hydrometeorological events such as hurricanes [23, 48]. The most destructive hurricane in the area was Hurricane Stan, that in 2005 caused a huge rainfall (up to 457 mm in one day), which produced many landslides, so slopes where the species grew disappeared or flooded [50, 80]. Besides that, the vulnerability of bamboo species is magnified by the irregular flowering cycles [26] and the simultaneous flowering and the subsequent complete death of the population.

In the context mentioned above, although the population of *Rhipidocladum martinezii* (an endemic and scandent bamboo species) was found inside the Tacaná Volcano Biosphere Reserve, and supposedly this population should entitle to special protection. Unfortunately, this protected natural area still did not have a management program. This absence of a management program generates several socioecological problems, mainly because local people developed their productivity activities inside the Reserve, without strict surveillance. Therefore, the most important risk factors we could observe for *R. martinezii* were the destruction and modification of its habitat by different human activities: deforestation to introduce crops, sand mines over the

Table 5 Results to *Rhipidocladum martinezii* Method the Red List of Threatened Species of UICN

IUCN criteria	Analysis	Results	Parameters	Metrics	Ranking
A) POPULATION SIZE REDUCTION	Decline the extent of occurrence in 10 years	Reduced its extension by 35% in 10 years	Population reduction observed, estimated, inferred, or suspected	$\geq$50%	Vulnerable
B) GEOGRAPHIC RANGE	Number of locations	1 locality	Number of locations	1	Critically endangered
	Extent of occurrence	1.13 km^2	Extent of occurrence	<100 km^2	Critically endangered
	Area of occupancy	1.06 km^2	Area of occupancy	<10 km^2	Critically endangered
C) SMALL POPULATION SIZE AND DECLINE	Number of mature individuals	There were no mature individuals	Number of mature individuals	<250	Critically endangered
	Number of mature individuals in each subpopulation		Observed, estimated, or projected	<50	
	% of mature individuals in one subpopulation		Observed, estimated, or projected	90–100%	
D) RESTRICTED POPULATION	Population	Total 54 tillers (individuals), anyone mature	Number of mature individuals	<50	Critically endangered
E) QUANTITATIVE ANALYSIS	*Not evaluated*				

Table 6 Results of *Otatea glauca* Method the Red List of Threatened Species of IUCN

IUCN criteria	Analysis	Results	Parameters	Metrics	Ranking
A) POPULATION SIZE REDUCTION	Decline the extent of occurrence in 10 years	Reduced its extension by 99.3% in 10 years	Population reduction observed, estimated, inferred, or suspected	≥90%	Critically endangered
B) GEOGRAPHIC RANGE	Number of locations	1 locality	Number of locations	1	Critically endangered
	Extent of occurrence	9.3 km^2	Extent of occurrence	<100 km^2	Critically endangered
	Area of occupancy	0.060 km^2	Area of occupancy	<10 km^2	Critically endangered
C) SMALL POPULATION SIZE AND DECLINE	Number of mature individuals	1	Number of mature individuals	<250	Critically endangered
	Number of mature individuals in each subpopulation	1	Observed, estimated, or projected	<50	
	% of mature individuals in one subpopulation	100	Observed, estimated, or projected	90–100%	
D) RESTRICTED POPULATION	Population	Total 6 tillers (individuals) 1 mature	Number of mature individuals	<50	Critically endangered
E) QUANTITATIVE ANALYSIS	*Not evaluated*				

slopes and dump for waste, coupled with incidental threats, mainly fires and hurricanes. Deforestation strongly affects this species' population because it is a scandent bamboo, so without trees, it couldn't have where to climb and develop. Also, the increase of the light can cause more atypical bloom events that cause bamboo to die [79]. However, a population census (July 2007) showed that although the population of *Rhipidocladum martinezii* had a very low number of individuals and low productivity, in areas where it still grows, it maintains an acceptable density. In addition, three-quarters are individuals in the juvenile phase (seedlings and regrowths).

In short, despite the only place in the world where *Rhipidocladum martinezii* lives is inside of biosphere reserve, it was considered endanger of extinction species for both methods.

For its part*, Otatea glauca* is also an endemic bamboo species with extremely restricted distribution. Its population showed a very low number of individuals and low productivity. Particularly its population presented a high sensitivity to Hurricane Stan, for the rain was so intense that the slopes where the species inhabited disappearing or flooding [50]. Another factor to consider was the size of the population, being so small, could present low genetic diversity [81]. For these reasons, it must be considered the possibility of restoration of the population of this species, which will require measures not only compatible with the interests of the local inhabitants but mainly must include the exchange of genetic material with plants that are commercialized in the United States. The only place where *Otatea glauca* is still living is not part of an ANP, and the probability of finding more sites where it could be present is very low, due to the high degree of disturbance and fragmentation that persists in the region. In this sense, this species was evaluated as an endangered extinction species for both used methods.

4.2 Lessons Learned About MER and IUCN Methods

Both methods to know the risk of extinction of the species *R. martinezii and O. glauca* used during this research, may be considered consistent, mainly because the results obtained were equivalent, however, we could find several similarities and differences.

The Method to Assess the Risk of Extinction (MER) of the Mexican Official Norm (NOM-059-SEMARNAT) evaluates through mandatory criteria, which present different requirements to be supported. These requirements include different evaluations, analyses and diagnoses, which can be carried out according to the expertise of the researcher, however, not all concepts are clearly defined, so, this flexibility can lead to a low certainty of the results. Nevertheless, the main advantage of MER is the possibility that offers to generate new scientific information about the evaluated species, since in most cases, many aspects of the biology and ecology of evaluated species that are at risk of extinction, are still unknown.

On the other hand, the investigation of required aspects established by MER implies a process that requires considerable time and budget. Due to the state of these species' populations being critical; this method finally represents a disadvantage. However, the most weakness of the MER is the legal long process required for the approval and entry of a species to the list of protected species, since can take up to five years after when the application is submitted, in addition to the research time necessary to obtain the required information. Therefore, the probability that during this process, the situation of the species could be worsened drastically, is high. In the present study, it was observed that in less than a year, the environmental conditions of the sites worsened and negatively impacted the studied species.

Despite the IUCN method also requires several analyses and generating information, it is possible to categorize a species even if there is no precise information on each topic because the criteria are independent (is not necessary to develop each one), it has more options for analysis to choose, as well as a greater number of less strict options to evaluate (it is enough to infer or suspect). In general, this method is easier to apply since the concepts it handles are clearly explained. However, this may, in turn, present low reliability in the results, since the more information obtained from the species, the degree of threat can increase or decrease. Thus, with little scientific information, the measures in favor of its conservation that are adopted may not be adequate.

Another disadvantage of the IUCN method is that it focuses on assessing demographic and geographical distribution aspects; unlike the MER that in addition to these aspects, includes habitat and the impact of human activity, which gives a complete vision and facilitates the design of measures for its conservation.

The process to determine the risk of extinction of a species and make it enter into a red list of protected species should be practical, reliable, and achievable in a short time, for all types of species. In that, there are species such as bamboo that, due to their ecophysiological characteristics, do not fully conform to the established guidelines of existing methods, since they were designed based on other types of organisms with other structures and reproductive cycles. For example, the identification of the number of mature individuals is the most difficult characteristic to determine.

4.3 Recommendations

- The bamboo species studied require that actions be carried out in favor of their conservation, also taking into account the social dimension, mainly effectively involving the local people in the conservation and restoration activities of these species [82] to obtain more sustainable results.
- It is important to create projects to reproduce *O. glauca* and *R. martinezzii* in greenhouses to increase their population and safeguard genetic material in local botanical gardens.
- Promote a bamboo species valuation among local people that highlight not only the ecological importance but also as a productive element that can bring them tangible benefits and thereby help their conservation and reproduction.

- Create landscape restoration programs where bamboo species live as well as programs to minimize edge effects, encourage the expansion of existing habitat patches and increase connectivity between fragments where species are located.
- Promote the development of research through programs in which students from local universities participate, to generate more knowledge about the species, as well as search explorations in more places where other populations could be found.
- Simplify the requirements of the methods and keep open the calls to be able to enter a species in the list.
- It should also be considered that the state of Chiapas where the study was carried out, has shown conflicts between the federal government and the communities, so any government initiative can generate distrust, and any proposal will require transparent positions from both parties.
- Because the places where *O. glauca* and *R. martinezzii* still live are very close to Guatemala, it would be advisable to strengthen binational plans in favor of the conservation of this region.

4.4 The Scope of This Research

In January 2014, an announcement was opened to submit proposals for endangered species inclusion to NOM-059-SEMARNAT [83]. We sent the applications to enter the species *Otatea glauca* and *Rhipidocladum martinezii*[1]. It was until November 2019, that the new list of species at risk was published in the Federal Official Gazette, in which only the species *Otatea glauca* was included and entered the list with the category "Endangered of extinction". This implies since that date, it is necessary to solicit permission from SEMARNAT to carry out any activity with this species (restoration, repopulation, reintroduction) [84], otherwise, it will be considered a crime (imprisonment and fine). It is also considered a crime to damage any specimen of this species, and some other activities, such as its extraction from Mexico [85]. There is an observation record of the species in February 2022, as evidence that it remains present at the site [86].

The Tacaná Volcano Biosphere Reserve was decreed in 2003, however, until 2007 the Advisory Council was established with the participation of people belonging to "ejidos" (collective properties), social organizations, municipal governments, NGOs, academics, Mexican and Guatemalan government institutions.

The results of our research about *Rhipidocladum martinezii* were sent to the Director of The Tacaná Volcano Biosphere Reserve, to be considered in the elaboration of the Reserve Management Program. Between 2010 and 2013, as part of the strategy for the development of the Reserve Management Program, community workshops were carried out in each one of the populations that lived inside of the reserve, and in the localities on the outskirts of the reserve (area of influence) (Fig. 10). In these workshops, the communities participated in the regulation of activities and

(a) (b)

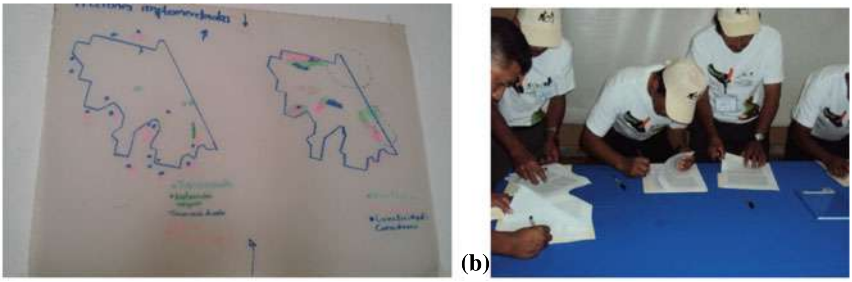

Fig. 10 **(a)** Map results of workshops with communities **(b)** Participants signing agreements (by Hernández-Rodríguez, 2013)

established commitments in accordance with the zonings of the ordinance (exclusive areas of preservation, sustainable use, and public use). Also, inspection and surveillance committees were created in coordination with Guatemala authorities.

Finally, the Reserve Management Program was published in 2013 [87], which has allowed greater control of tourist activities, fire prevention, the establishment of restoration programs, water and soil conservation, productive reconversion, environmental management, scientific research, and environmental monitoring.

Lastly, in June 2016, we carried out a verification of the status of *Rhipidocladum martinezii* population in the Tacaná Volcano Biosphere Reserve. We found it in three new sites for which there were no records. We realized a population census according to De la Cruz, Cruz, and Castaño [62–64], and to evaluate the state of the habitat, we applied the measurement of chronic disturbance [61]. Also, we have informal conversations with local people.

The results of the census indicated an improvement in the population of *Rhipidocladum martinezii* and its habitat conditions. The population increased by 30% (of which about half of the individuals were mature). In contrast to the previous census, where there was none. Regarding the measurement of chronic disturbance, from being a highly disturbed site before, disturbances from fires and mining activities decreased and presented a medium level of disturbance (54.97). This is consistent with the comments of the local people, which observed an increase in the population of this species, approximately since 2013. They told us that the extraction of sand from the slopes was suspended since 2008, but was partially reactivated in 2011, and in 2016 the mines were finally closed. This was the main type of disturbance that affected this species.

From the Management Program of Tacaná Volcano Biosphere Reserve, other activities such as tourism were also regulated. Near one of the new sites of the species, it was created a trail to practice birdwatching from were observed the following species: *Chlorophonia occipitalis, Atthis ellioti, and Myadestes occidentalis* [88]. However, new threats were also detected as the earthquake of magnitude 6.9 on July 7, 2014, [89]. This event caused landslides in the surroundings, due to the area being seismically active, new similar events can occur and turn out to affect the slopes where the species regenerated. Also, the local people told us that the tuzas (*Orthogeomys* *sp.*) and the squirrels (*Sciurus sp.*) eat the shoots of this species; if the populations of these rodents become unbalanced, could be considered a threat to *Rhipidocladum martinezii* and other plant species.

As this research was the first study the determinate the extinction risk for bamboo species in Mexico, this methodological adaptation was used as a basis to develop new studies and determine the risk of extinction of two endemic species of bamboo to the state of Veracruz, Mexico (*Chusquea enigmatica* and *Chusquea bilimekii*) [90].

5 Conclusions

Determining a species' risk of extinction is an important step in its conservation, but the process can be time-consuming and costly. The biggest obstacle to conducting this research was the scarce and dispersed information available.

The inclusion of the local population in the elaboration of the Tacaná Volcano Biosphere Reserve management program helped to improve the state of conservation of endangered bamboo of *Rhipidocladum martinezii.*

Otatea glauca now is officially a protected species by Mexican law and the ANP where *Rhipidocladum martinezii* was located, already has a Management Program. However, both species are still endangered and need to be protected by law and the monitoring must be maintained, mainly because they are endemic species with restricted distribution, and the Soconusco and the Sierra regions even present high rates of deforestation and fragmentation.

The preservation of biodiversity is a multidisciplinary labor that requires the participation mainly of local actors and institutions.

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Bamboo Biomass: A Strategy for Climate Change Mitigation and Adaptation, and Forest Landscape Restoration (FLR) in Cameroon

Rene Kaam, Barnabas Neba Nfornkah, Cedric Djomo Chimi, Jovis Arnold Nguefack, Martin Tchamba, and Louis Zapfack

Abstract Studies suggest that bamboo is an excellent biological resource with the capacity to sequester and stock carbon while providing direct and indirect services that support human well-being. Cameroon, despite having a huge bamboo potential, has not benefited from these offers with respect to Forest Landscape Restoration (FLR) and climate combat. This chapter aimed at estimating carbon stocks of *Oxytenanthera abyssinica* **(A. Rich.) Munro** in the High Guinea Savannah of Cameroon; compared with carbon stocks of different dominant bamboo species in different forest strata in Cameroon; assessed the place of bamboo for possible use for FLR, and valued bamboo carbon monetarily. Data were destructively collected for carbon assessment. 14 circular plots of 100 m^2 were set up. 5% of bamboo of different age classes were harvested for biomass, separated into components, weighed, and subsampled oven-dried for dry mass. The results showed that *O. abyssinica* means

R. Kaam · B. N. Nfornkah (✉)
International Bamboo and Rattan Organization (INBAR), Central Africa Reginal Office (CARO), Door 63, Road No. 1860, Behind Bastos Factory, Yaounde 1St District, PO BOX 17056, Yaounde, Cameroon
e-mail: barnabasneba@yahoo.com

B. N. Nfornkah
Fokabs INC, 2500 St. Laurent Blvd, Ottawa ON K1H 1B1, Canada

Fokabs INC, Tsinga Yaounde, Cameroon

C. D. Chimi
Institute of Agricultural Research for the Development (IRAD), Yokadouma, East Cameroon, Cameroon

J. A. Nguefack
Department of Geography, Faculty of Letters and Social Sciences, University of Yaounde I, Yaounde, Cameroon

M. Tchamba
Laboratory of Environmental Geomatics, Department of Forestry, Faculty of Agronomy and Agricultural Sciences, University of Dschang, P. O. Box 222, Dschang, Cameroon

L. Zapfack
Plant Systematic and Ecology Laboratory, Department of Plant Biology, Faculty of Sciences, University of Yaounde I, Yaounde, Cameroon

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culm density and above-ground carbons were about 10,343 ± 4910 ha^{-1} and 27.45 ± 17.22 $tC.ha^{-1}$, respectively. Literature showed that total bamboo carbon in Cameroon ranges from 16.41 to 157.93 $tC.ha^{-1}$. High carbon was found with *Bambusa vulgaris* and *Phyllostachys aurea*. The total bamboo carbon stocks were less than those of forest strata, but similar to those of agroforestry and plantations and greater than that for woody savannah, grasslands, shrublands, and pastures. The total carbon of bamboo in Cameroon was estimated at 82.47 $tC.ha^{-1}$ and corresponded to a monetary value of 272 $ USD.ha^{-1}. Policymakers can consider this and integrate bamboo into sustainable strategies to restore degraded lands in Cameroon.

Keywords *Oxytenantera abyssinica* · Forest landscape restoration · Climate change · mitigation and adaptation · Carbon farming · Carbon credit · Carbon stocks · Cameroon

1 Introduction

Global warming is one of the serious problems that the world is facing at present [46]. The rising CO_2 level in the atmosphere is the prime contributor to global warming [18]. Efforts at International levels are being initiated to address the problem of global warming and climate change. The United Nations Framework Convention on Climate Change (UNFCC) passed a landmark resolution in 2015 in Paris [62]. The resolution of Paris agreement is to limit the average temperature on earth from rising above 2 °C from the level of the pre-industrialization period [61]. Many countries since then have been mainstreaming this accord into their Nationally Determined Contributions (NDC) to mitigate and adapt to climate change. Within this context, the research on identifying cost-effective managed ecosystems that can substantially remove atmospheric CO_2 while providing essential societal benefits has gained momentum since the Kyoto Protocol of 1997 [47]. Studies suggest bamboo as a complementary crop to address global warming [7, 18, 79].

Bamboo is one of the fastest-growing plants on earth belonging to the Family of Poaceae. It is widely distributed across tropical and subtropical regions; and within and outside forests in Africa, Asia, and Central and South America [4, 10, 36, 64]. There are more than 1,663 species belonging to 123 genera of bamboo throughout the world [41, 81]; with 115 known species in Africa [21]. Up to 35 million ha of the global land area is covered by bamboo forests, which represent approximately 1% of the total forest area [23], with at least 7.2 million hectares of bamboo across Africa [26].

Many bamboo species are important in local economies; their most important economic uses include food, handcrafting, fencing, and cottage industry [1]. As such bamboos are a major commodity in domestic trade and subsistence use, generating over US$ 4.6 billion per year globally [6]. In 2019, Africa exported USD 19.2 million of bamboo products [26]. In addition, they contribute to soil and water management, and biodiversity conservation [68]. Most importantly, bamboo plays a crucial role as a carbon sink, thus contributing to climate change mitigation [45, 70, 84].

A number of studies have reiterated that among the perennials, bamboo can particularly be a powerful tool in carbon farming [9, 47, 49, 68], rural livelihoods [37] as well as multiple Ecosystem Services and benefits that support human well-being [64]. Because bamboo grows back quickly after being harvested, it can store carbon in a large number of durable products, as well as in the plant itself. Over time, this means that bamboo can sequester more carbon than some tree plantations [25, 80]. Thus, bamboo has a multifaceted potential in supporting the fight against climate change, supporting the livelihoods of the local people, and providing ecosystem services.

The Government of Cameroon, through the Ministry of Environment, Protection of Nature and Sustainable Development (MINEPDED) contributes to the sustainable development goals (13 and 15), which support the fight against climate change and life on land respectively; to achieve the restoration of 12 million ha of degraded landscape as a commitment to a number of international initiatives such as the Bonn Challenge, Afr100 initiative, Great Green Wall by evaluating the restoration opportunities of some sub-landscapes (Waza, Mbalmayo, and Douala-Edea) in Cameroon estimated at about 700 000 ha excluding protected areas [27, 34, 44]. Among these landscapes is the Waza landscape in the Sudano-Sahel region of Cameroon. MINEPDED in its program « the restoration initiative (TRI)» solicited bamboo as a candidate for restoration.

This choice raises the next question « which bamboo species is best for restoration in this landscape». Nfornkah et al. [53] report of Oxythenanthera abyssinica (A. Rich.) Munro species is a native dominating bamboo species in the High Guinea Savannah (HGS) and Sudano-Sahel (SS) regions of Cameroon. Other studies further observe that it is a lowland bamboo, indigenous species, and sequestrates carbon of 16.28 $tC.ha^{-1}$ [51], which is greater than Savannah grassland, which sequesters 10.78 $tC.ha^{-1}$ [61]. The data provided by Nfornkah et al. [54] was not enough to appreciate the potential of O. abyssinica for carbon sequestration and its use as the main restoration bamboo species in the landscape.

This study is, therefore, initiated to (1) evaluate the density and carbon stocks potential of O. abyssinica in the HGS; (2) Compare the carbon stocks of O. abyssinica with those of different bamboo species estimated in different forest strata or agroecological zones of Cameroon; (3) Compare the carbon stocks of O. abyssinica with those of other crop plantations and agroforestry systems, and forest strata ecosystems; (4) monetize bamboo carbon in Cameroon. These results permit this study to propose bamboo species suitable in supporting the restoration initiative in Cameroon, but also carbon farming through the integration of bamboo in agroforestry systems and plantations in different agroecological zones of Cameroon.

2 Bamboo for FLR, Carbon Farming, and Trading: Concepts Definition

2.1 Forest Landscape Restoration

There is an urgent need to accelerate the recovery of degraded ecosystems for the benefit of humans and nature, which requires a comprehensive and inter-sectoral approach. This has to be done through restoration. Restoration is any intentional activity that initiates or accelerates the recovery of an ecosystem from a degraded state [64]. Looking at the FLR interventions of the IUCN-Bonn Challenge, they include natural regeneration, silviculture, agroforestry, planted forest and woodlots, improved fallows, mangrove restoration, watershed protection, and erosion control. A number of studies earmarked bamboo as a great biological resource for restoration [3, 17, 18, 49, 64, 65].

Bamboo forests are an important forest type ecologically, socioeconomically, and culturally in the subtropical and tropical regions of the world [44]. Due to its biological characteristic and growth habits, bamboos are not only an ideal economic investment that can be utilized in many different manners but also has enormous potential for the eco-restoration of degraded lands [13, 45, 49, 64, 65]. Bamboos are one of those communities which rapidly colonized disturbed lands due to their adaptability and nutrient conservation ability [16, 19, 45, 50]. Bamboo protects steep slopes, soils, and waterways, prevents soil erosion, sequesters carbon, and brings many other ecosystem benefits [45, 64, 65, 84].

However, a number of studies have warned of a number of risks involved in planting bamboo, including invasiveness of species, decrease biological diversity, food scarcity, soil pollution due to fertilizers and pesticides, land grabbing nature of bamboo [3, 7, 67, 73, 83]. In order to mitigate the risks involved, the International Bamboo and Rattan Organization (INBAR) and a team of experts/researchers working in this domain have documented and made available on its website a number of Manuals, voluntary standards guidelines, and standards to guide every plan of investment in the whole value chain of bamboo from seedlings production, planting, management, harvesting, transformation, bioenergy, construction, trade overviews, research and development [18, 19, 25, 32].

Without over-emphasizing the importance of bamboo over other plants for restoration, Net Primary Production (NPP) is an important indicator of forest biomass accumulation and carbon sink capacity. Some studies show that NPP from bamboo forests have gained much attention because of their high carbon sequestration potential and supply capacity of other Ecosystem Services [11, 39, 73]. Comparing NPP in a bamboo-dominant forest to a neighbouring secondary evergreen broad-leaved forest in South China using the space-for-time substitution method, Song et al. [73] concludes that the mean NPP of the former was 51.5% greater than that of the latter cycles. Similarly, several studies in semi-arid, dryland ecosystems and agroforestry systems show bamboo forests have high NPP compared to many forests and sole crops [14, 67]. This study results shall propose bamboo species proper for landscape restorations, justifying the choices for landscape restoration.

2.2 Carbon Farming

Carbon farming allows farmers and investors to generate tradable carbon offsets from farmlands and forestry projects through carbon trading. Carbon farming involves implementing practices that are known to improve the rate at which CO_2 is removed from the atmosphere and converted to plant material and/or soil organic matter. Thus, carbon sequestration has the potential to offset fossil-fuel emissions by 0.4–1.2 gigatons of carbon per year, or 5–15% of the global fossil-fuel emissions [20, 33]. It is a method of capturing CO_2 from the atmosphere or from a point source like a fossil-fuel-based power plant and storing it for a very long duration under the earth's surface. CO_2 Sequestration from the atmosphere through plants is a very effective, natural, and inexpensive process [43].

Among the terrestrial ecosystems, agroforestry and forest ecosystems have been given priority for carbon trading based on the efficiency of particular land use in reducing emissions or capturing carbon by storing it. Reforestation, afforestation, and reducing deforestation and forest degradation (REDD) are also eligible for carbon trading [22, 29]. To date, most of the studies have been done on the carbon trading potential of tree species/forest/agroforest, but little on woody bamboo species [37]. Meanwhile, the present review suggests that bamboo offers tremendous opportunities for carbon farming and tradable carbon under CDM and REDD schemes. Ecosystem carbon storage and sequestration rates of 94–392 $tC.ha^{-1}$ and 8–14 $tC.ha^{-1}\ yr^{-1}$ [47, 49, 79, 84], respectively, in woody bamboos are comparable with agroforestry and forest ecosystems. This study's results shall put to evidence tradable carbon in Cameroon with respect to agroforestry and forest ecosystems.

2.3 Carbon Trading

Carbon trading is pertinent to climate negotiations by decelerating the climate change phenomenon. Carbon farming is successful when carbon gains resulting from enhanced land management and/or conservation practices exceed carbon losses [71, 72]. Carbon trading, part of carbon farming, as described in the Kyoto Protocol, is a voluntary and mandatory emission trading market for greenhouse gases [70, 74, 77].

Bamboo ecosystems can provide an income stream to rural communities from dual sources (i) selective harvest and selling of bamboo products (e.g., for scaffolding purposes, to the papermaking industry, bamboo crafts) and, (ii) from carbon credits (Certified Emission Reductions) under various afforestation/reforestation mechanisms under CDM and REDD [18, 47, 49]. Certified emission reductions can be traded in the national and international markets that have committed to reducing their carbon footprint. The 20th Session of the Conference of the Parties of the UNFCCC, held in Lima in December 2014, incorporated under any program of activities, an unlimited number of component project activities across a sector, country, or region can be registered under a single administrative umbrella [49]. Considering its role in climate change adaptation and mitigation, its noteworthy contribution to the social, and economic aspects of rural life, and numerous other environmental services, woody bamboos warrant serious consideration for carbon farming and carbon trading. Integrating woody bamboo with carbon trading will promote the cultivation and management of woody bamboo in agroforestry and forest ecosystems and, therefore, generate another income stream for rural communities [49]. Additional research is needed to determine bamboo biomass, vegetation, and soil carbon capture and storage by incorporating improved methodological protocols to enable precise estimation of bamboo ecosystem carbon storage and sequestration rate [49].

The result of this study shall bring out the possibilities of considering carbon farming in forest landscape restoration to produce tradable carbon in Cameroon using an indigenous bamboo species *Oxytenanthera abyssinica,* especially in the High Guinea Savannah and Sudano-Sahel regions of Cameroon.

3 Materials and Methods

3.1 Study Area

This study was carried out in Ndoumdjom and Ndem-ndem, located in Bankim Sub-Division Mayo–Banyo Division, Adamaoua Region of Cameroon. It is geographically located on latitude 5°9’–8°35’ North and longitude 11°15’–11°48 East (Fig. 1). This area is characterized by a tropical humid climate, with two seasons, that is a rainy season from mid-March to mid-November (over 8 months) and a dry season from mid-November to mid-March. The average annual rainfall is 1700 mm with a standard deviation of 210.82 mm during August–September-October, and with average temperatures of about 23 °C [62]. The soils are essentially ferralitic and hydromorphic. The relief is essentially made up of plains (Tikar Plain), with altitudes varying from 500 to 800 m. In the hinterland, there are a few isolated hills that are scattered throughout the area, with granite outcrops. In the western part of Nigeria, we note the presence of a mountainous chain (the Mambila Mountains) which culminates at 1662 m. The piedmont zone presents volcanic rocks, which certainly testify with the other hills and depressions of the relief of an eventful geological past. The hydrographic network is mainly made up of two rivers, the Mbam, which runs along the entire eastern boundary of the Municipality and forms the boundary with the Ngambé Tikar, and the Mapé, which forms the boundary with the Magba area. They are also several lakes, including Mbegou, Tantou, Houmtchie, Wouemi, Wui, Kongui Nduoh [35, 62]. Bankim constitutes a transition zone between the forest and the savannah

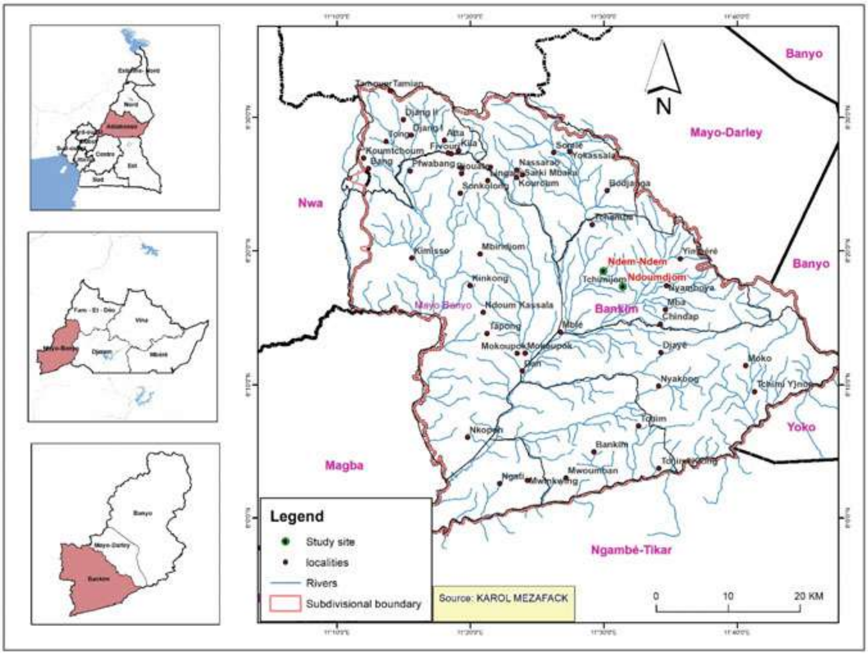

Fig. 1 Map of the study area

and therefore has a fragile ecology, it has only the remnants of highly degraded forests and other ecological units, including the tree and shrub savannahs; forest galleries along the rivers, dense humid forests; and the flooded grassy savannahs. The forest galleries are mainly along the watercourses, and tree and shrub savannahs are in their major part. The forest species, although in clear decline, remains varied, and include *Kaya grandifoliola*, *doussie pachiloba*, *Termminalia superba*, *Lovoa trichiloides*, *Milicia exelsa*, *Afzelia grandis,* and *A. bipendensis*. The vegetation cover of the Bankim is under great threat due to the Mapé dam, which has swallowed up thousands of hectares of forest; the destructive effect of bushfires; the poor cultivation methods that are intensifying with the increase in population; and the illicit exploitation of the remains of the forests [35]. In terms of wildlife, it witnesses a rarefaction of species due to the combined action of poachers and bushfires, and especially to the invasion of gallery forests, the animals' retreat to the zone by the dam's water.

3.2 Methodology

A literature review was carried out through search engines such as Google, Google Scholar, and Scopus database, grey data from project documents (working papers, technical reports, national strategy, and project/program documents) were used to collect data on bamboo carbon stocks tree carbon stocks in different tree ecosystems (forests, savannah agroforestry, and plantations).

Primary data on carbon stocks of *O. abyssinica* bamboo in the natural bamboo forests were collected in the Ndoumdjom and Ndem-Ndem villages in Bankim. For biomass inventory of *O. abyssinica,* it was carried out destructively. For that inventory, 14 circular plots of 100 m^2 were sampled as recommended by Nfornkah et al. [54]. In each circular plot of 100 m^2, 5% of bamboo with respect to age group was felled for sampling. It is important to note that for each plot sampled, bamboo culms collected were grouped into 3 age classes (≤1 year, ≤ 2–3 years, and > 3 year-old) culms as recommended by Devi et al. [14, 15]. Morphologically, *O. abyssinica* culm colour changes, and the abundance of primary, secondary, and tertiary branches aided in identifying these different age groups under 3 years old [3]; but above 3 years, it appears difficult to distinguish the bamboo age, thus grouped under this class. For each culm sampled, in addition to specimen collection, dendrometrics parameters like total height and the diameter at 1.50 cm were recorded as recommended by Huy and Trinh [25]. Additional data like girth (m) and the number of culms (N_{culm}) were also collected using a clump-based sampling design (Fig. 2). Then, the harvested bamboo was sorted out into components (such as culms, branches and leaves), and weighed with an electronic suspension scale (capacity 300 kg) separately for the Total Fresh Biomass (TFW) of the bamboo. Subsamples of the different bamboo components: culm (at 3 positions on the culm: root collar, middle and top); branches and leaves with approximately 100–300 g (using an electronic scale of precision 0.1 g) were collected as Sample Fresh Weight (SFW) for each bamboo sampled. These subsamples were oven-dried at 105 °C in an oven until constant weight (SDW) was obtained in the laboratory of Rural Engineering of the University of Dschang, Cameroon; for biomass ratios.

In addition to the data collection of *O. abyssinica*, we used primary data of other bamboo species considered such as *Bambusa vulgaris, O. abyssinica* and *Phyllostachys aurea* with respect to their different agroecological zones of Cameroon made available by their authors (Kaam et al., Submitted; Chimi et al., Submitted) for use in this study.

3.3 Data Analysis

Data analysis was done using R software version 4.1.1. Descriptive analysis was done for measurement variables and bamboo biomass of components.

3.3.1 Bamboo Density Calculation

The calculation of the number of clumps and culms per hectare of *O. abyssinica* was done using the following formulae respectively:

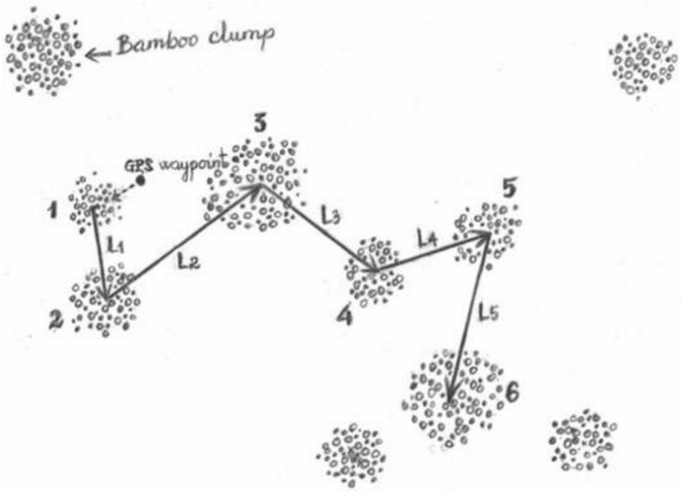

Fig. 2 Clump-based sampling for clumping bamboo with very dense culms [25]

$$N_{clump}ha^{-1} = N_{clump} \times \frac{10^4}{\text{plot area}\left(m^2\right)} \quad (1)$$

$$N_{i\ culm}ha^{-1} = N_{i\ culm} \times N_{clump}ha^{-1} \quad (2)$$

3.3.2 Bamboo and Biomass and Carbon Stocks Calculation

The total dry weight of each component (for each culm bamboo sample) was determined using the following formulae by FAO [23]

$$\text{TDW} = \frac{SDW}{SFW} \times \text{TFW} \quad (3)$$

where; TDW = total component dry weight; SDW = subsample dry weight; SFW = subsample fresh weight; and TFW = total component fresh weight.

Culm bamboo above-ground biomass (AGB_{bamboo}) corresponds to the sum of the total dry bamboo biomass of the culm (AGB_{cl}, kg), branches (AGB_{br}, kg) and leaves (AGB_{le}, kg) [25]:

$$AGB_{bamboo} = AGB_{cl} + AGB_{br} + AGB_{le} \quad (4)$$

The above-ground clump biomass (AGB_{clump}) was calculated by the formula:

$$AGB_{clump} = AGB_{bamboo} \times N_{i\ culm} \quad (5)$$

The extrapolation factor was used to extrapolate the clump above-ground biomass calculation of each plot at the hectare.

$$\text{AGB}\left(\text{t.ha}^{-1}\right) = \text{AGB x}\frac{10^4}{\text{plot area}\left(\text{m}^2\right)} \quad (6)$$

AGB corresponds to the bamboo above-ground biomass in 100 m^2.

Hence, bamboo BGB was estimated using the following formula:

The ratio of belowground to above-ground biomass of *O. abyssinica* is 1:4 (25%) [24] for *B. vulgaris* = 0.32 and for *P. aurea* = 1.33 [82]. With the value of AGB and BGB, total bamboo biomass corresponds to the sum of these 2 biomass components (AGB + BGB). According to Huy & Trinh [25] the carbon fraction in bamboo represents the default value proposed by IPCC [32] for trees = 0.47. Furthermore, bamboo carbon stocks per hectare were estimated with the following formulae:

$$\text{Carbon stock}\left(\text{t C.ha}^{-1}\right) = \text{biomasses}\left(\text{t ha}^{-1}\right)\text{ x 0.47} \quad (7)$$

With respect to the fact that 1tC = 3.67 tCO_{2eq}, the following formulae was used for bamboo CO_2 stocks.

$$\text{Stock CO}_2\left(\text{tCO}_2\text{eq .}^{-}\right) = \text{Carbon stock}\left(\text{t C ha}^{-1}\right)\text{ x 3.67} \quad (8)$$

3.3.3 The Monetary Value of Ecosystem Services Linked to the Carbon Stocks Potential of Bamboo

According to Busch & Engelmann [5] and Cannon [8], carbon prices could take the form of some combination of taxes on emissions or payments for emission reductions in tropical forest countries, with the potential to receive external funding from international carbon markets or public funds. We adopted the following conversion: 1 t CO_{2eq} = 3.3 USD [18]; which is found in the REDD + framework.

4 Results

4.1 *Density and Above-Ground Carbon of* O. Abyssinica

The mean density of *O. abyssinica* culms and clumps per ha was 10,343 ± 4910 and 264 ± 93, respectively. The average AGB of culm was 4.61 ± 1.73 kg per culm. AGC and BGC of *O. abyssinica* found in the study area were 27.45 ± 17.22 t $C.ha^{-1}$ and 6.86 ± 1.31 $tC.ha^{-1}$, respectively. The total CO_{2eq} per ha of *O. abyssinica* was 125.93 ± 79.00 (Table 1).

Table 1 Descriptive statistics of the density of culm and clump, AGB culm and the clump of *O. abyssinica* in the High Guinea Savannah

Descriptive statistic	Mean	Min	Max	Sd
N_{culm} ($N.ha^{-1}$)	10,343	3700	18,500	4910
N_{clump} ($N.ha^{-1}$)	264	100	400	93
Average AGB_{culm} (kg)	4.61	2.20	13.63	1.73
AGC_{bamboo} ($t\ C.ha^{-1}$)	27.45	7.66	61.43	17.22
BGC_{bamboo} ($t\ C.ha^{-1}$)	6.86	1.915	15.36	4.31
TC_{bamboo} ($t\ C.ha^{-1}$)	34.31	9.58	76.79	21.53
AGC_{bamboo} ($t\ CO_2.ha^{-1}$)	125.93	35.14	281.81	79.00

N/B: N_{culm} ($N.ha^{-1}$) = number of culms in one hectare; N_{clump} ($N.ha^{-1}$) = number of clumps in one hectare, Average $AGB.plant^{-1}$ (kg) = average total above-ground biomass of a bamboo plant; AGC_{bamboo} ($t.C\ ha^{-1}$) = total above-ground carbon of bamboo in one hectare; and AGC_{bamboo} ($t\ CO_2.ha^{-1}$) = total above-ground carbon dioxide (CO_2) in one hectare, BGC_{bamboo} ($t\ C.ha^{-1}$) = mean belowground carbon of bamboo on one hectare, TC_{bamboo} ($t\ C.ha^{-1}$) = total bamboo carbon stocks in tons on one hectare

4.2 Comparative Analysis of Carbon Stocks of O. Abyssinica *Relative to Carbon Stocks from Other Bamboo Species in Different Forest Strata in Cameroon*

The density and carbon stocks of *O. abyssinica* with respect to other bamboo species estimated by similar studies are summarized in Tables 2 and 3. *O. abyssinica* density (10,343 ± 4910) in the High Guinea Savanah agroecological zone of Cameroon is 4.5 times higher than the density of *B. vulgaris* (2296 ± 2631) of the Tropical evergreen rain forest of Cameroon (Monomodal rainfall forest). However, it was not too far from those of *B vulgaris* (13,330 ± 7718) in the WH, which is approximately 4 and 2 times less than the density of *P. aurea* (38,010 ± 3361) in the Western Highlands (Guinea Savannah) of Cameroon; and *B. vulgaris* (20,679 ± 14,835) in the Tropical Semi Deciduous Humid Forest (Bimodal rainfall forest) of Cameroon respectively.

The average culm biomass of *O. abyssinica* found was 4.61 ± 1.73 kg. Compared to those of other species, it appears to be similar to those of *P. aurea* which is a running bamboo and not different from those found by Nfornkah et al. [53] of the same bamboo species. However, *O. abyssinica* biomass found in this study was 3–6 times less than those of *B. vulgaris* found in diverse AEZs in Cameroon (Chimi et al. submitted; Kaam et al. submitted; Nfornkah et al. [52, 53].

Regarding the total carbon of bamboo per ha; the mean TC of *O. abyssinica* (34.31 ± 21.53) was greater than 16.41 ± 8.60 of *O. abyssinica* in Beyala; but less than *B. vulgaris* (39.10 ± 2.55) in the Tropical evergreen rain forest; 81.38 ± 30.45 in Tropical semi-deciduous humid Forest; and *P. aurea* (125.42 ± 45.20; 157.93 ± 23.63) in the Western Highlands.

Table 2 Descriptive summary of bamboo density and carbon stocks in Cameroon

Forest stratum	Bamboo species	Descriptive statistics	Mean	Minimum	Maximum	Stand.dev	References
HGS	*O. abyssinica*	N_{culm} ($N.ha^{-1}$)	10,343	3700	18,500	4910	This study
		N_{clump} ($N.ha^{-1}$)	264	100	400	93	
		Average AGB_{culm} (kg)	4.61	2.2	13.63	1.73	
		AGC_{bamboo} (t $C.ha^{-1}$)	27.45	7.66	61.43	17.22	
		BGC $_{bamboo}$ (t $C.ha^{-1}$)	6.86	1.915	15.36	4.31	
		TC $_{bamboo}$ (t $C.ha^{-1}$)	34.31	9.58	76.79	21.53	
		AGC_{bamboo} (t $CO_2.ha^{-1}$)	125.93	35.14	281.81	79.00	
	O. abyssinica	N_{culm} ($N.ha^{-1}$)	4374	1600	9300	2604	This study; Nfornkah et al. [53, 54]
		N_{clump} ($N.ha^{-1}$)	184	100	300	83	
		Average AGB_{culm} (kg)	6.39	3.55	14.09	3.44	
		AGC_{bamboo} (t $C.ha^{-1}$)	13.13	3.68	23.66	6.88	
		BGC $_{bamboo}$ (t $C.ha^{-1}$)	3.28	0.92	5.92	1.72	
		TC $_{bamboo}$ (t $C.ha^{-1}$)	16.41	4.60	29.58	8.60	
		AGC_{bamboo} (t $CO_2.ha^{-1}$)	60.23	16.88	108.54	31.56	
WH	*B. vulgaris*	N_{culm} ($N.ha^{-1}$)	13,330	5600	30,000	7718	
		N_{clump} ($N.ha^{-1}$)	133	56	300	77	
		Average AGB_{culm} (kg)	15.73	6.69	27.74	5.29	
		AGC_{bamboo} (t $C.ha^{-1}$)	92.96	42.05	170.69	43.73	This study; Chimi et al., submitted
		BGC $_{bamboo}$ (t $C.ha^{-1}$)	29.75	13.46	54.62	13.99	
		TC $_{bamboo}$ (t $C.ha^{-1}$)	122.71	55.51	225.31	57.72	
		AGC_{bamboo} (t $CO_2.ha^{-1}$)	450.34	203.71	826.89	211.85	
	P. aurea	N_{culm} ($N.ha^{-1}$)	38,010	31,200	43,200	3361	
		Average AGB_{culm} (kg)	4.18	0.72	4.18	0.73	

(continued)

Table 2 (continued)

Forest stratum	Bamboo species	Descriptive statistics	Mean	Minimum	Maximum	Stand.dev	References
		AGC_{bamboo} (t $C.ha^{-1}$)	53.83	27.18	80.16	19.4	
		BGC_{bamboo} (t $C.ha^{-1}$)	71.59	36.15	106.61	25.80	
		TC_{bamboo} (t $C.ha^{-1}$)	125.42	63.33	186.77	45.20	
		AGC_{bamboo} (t $CO_2.ha^{-1}$)	460.31	232.42	685.46	165.89	
	P. aurea	N_{culm} ($N.ha^{-1}$)	38,017	31,200	42,500	4510	This study; Kaam et al., submitted
		Average AGB_{culm} (kg)	3.79	3.16	4.44	0.54	
		AGC_{bamboo} (t $C.ha^{-1}$)	67.78	49.85	80.16	10.14	
		BGC_{bamboo} (t $C.ha^{-1}$)	90.15	66.30	106.61	13.49	
		TC_{bamboo} (t $C.ha^{-1}$)	157.93	116.15	186.77	23.63	
		AGC_{bamboo} (t $CO_2.ha^{-1}$)	579.59	426.27	685.46	86.71	
TEF	*B. vulgaris*	N_{culm} ($N.ha^{-1}$)	2296	1675	5293	2631	This study; Nfornkah et al. [51]
		N_{clump} ($N.ha^{-1}$)	20	19	25	3	
		Average AGB_{culm} (kg)	29	23.21	37.08	649	
		AGC_{bamboo} (t $C.ha^{-1}$)	29.62	2.2	31.99	1.93	
		BGC_{bamboo} (t $C.ha^{-1}$)	9.48	0.70	10.24	0.62	
		TC_{bamboo} (t $C.ha^{-1}$)	39.10	2.90	42.23	2.55	
		AGC_{bamboo} (t $CO_2.ha^{-1}$)	143.49	10.66	154.97	9.35	
TDF	*B. vulgaris*	N_{culm} ($N.ha^{-1}$)	20,679	8871	57,229	14,835	This study; Kaam et al., submitted
		N_{clump} ($N.ha^{-1}$)	257	75	402	112	
		Average AGB_{culm} (kg)	10.3	3.54	13.5	11.37	
		AGC_{bamboo} (t $C.ha^{-1}$)	61.65	14.77	92.47	23.07	
		BGC_{bamboo} (t $C.ha^{-1}$)	19.73	4.73	29.59	7.38	
		TC_{bamboo} (t $C.ha^{-1}$)	81.38	19.50	122.06	30.45	

(continued)

Table 2 (continued)

Forest stratum	Bamboo species	Descriptive statistics	Mean	Minimum	Maximum	Stand.dev	References
		AGC_{bamboo} (t $CO_2.ha^{-1}$)	298.66	71.55	447.96	111.76	

N/B: N_{culm} ($N.ha^{-1}$) = number of culms in one hectare; N_{clump} ($N.ha^{-1}$) = number of clumps in one hectare, Average AGB.plant^{-1} (kg) = average total above-ground biomass of a bamboo plant; AGC_{bamboo} (t.C ha^{-1}) = total above-ground carbon of bamboo in one hectare; and AGC_{bamboo} (t $CO_2.ha^{-1}$) = total above-ground carbon dioxide (CO_2) in one hectare, BGC_{bamboo} (t $C.ha^{-1}$) = mean belowground carbon of bamboo on one hectare, TC $_{bamboo}$ (t $C.ha^{-1}$) = total bamboo carbon stocks in tons on one hectare. HGS: high guinea savannah; WH: western highlands; TEF: tropical evergreen rain forest; TDF: tropical semi-deciduous humid forest

Table 3 Bamboo mean densities and carbon stocks in Cameroon

Descriptive statistics	HGS		WH			TEF	TDF
	O. abyssinica	***O. abyssinica***	***B. vulgaris***	***P. aurea*** **(*****Chimi*** **et al.)**	***P. aurea*** **(*****Kaam*** **et al.)**	***B. vulgaris***	***B. vulgaris***
N_{culm} ($N.ha^{-1}$)	10,343	4374	13,330	38,010	38,017	2296	20,679
N_{clump} ($N.ha^{-1}$)	264	184	133	na	na	20	257
Average AGB_{culm} (kg)	4.61	6.39	15.73	4.18	3.79	29	10.3
AGC_{bamboo} (t $C.ha^{-1}$)	27.45	13.13	92.96	53.83	67.78	29.62	61.65
BGC $_{bamboo}$ (t $C.ha^{-1}$)	6.86	3.28	29.75	71.59	90.15	9.48	19.73
TC $_{bamboo}$ (t $C.ha^{-1}$)	34.31	16.41	122.71	125.42	157.93	39.10	81.38
AGC_{bamboo} (t $CO_2.ha^{-1}$)	125.93	60.23	450.34	460.31	579.59	143.49	298.66

N/B: N_{culm} ($N.ha^{-1}$) = number of culms in one hectare; N_{clump} ($N.ha^{-1}$) = number of clumps in one hectare, Average AGB.plant^{-1} (kg) = average total above-ground biomass of a bamboo plant; AGC_{bamboo} (t.C ha^{-1}) = total above-ground carbon of bamboo in one hectare; and AGC_{bamboo} (t $CO_2.ha^{-1}$) = total above-ground carbon dioxide (CO_2) in one hectare, BGC_{bamboo} (t $C.ha^{-1}$) = mean belowground carbon of bamboo on one hectare, TC $_{bamboo}$ (t $C.ha^{-1}$) = total bamboo carbon stocks in tons on one hectare. HGS: high guinea savannah; WH: western highlands; TDF: tropical semi-deciduous humid forest; tropical evergreen rain forests

4.3 *Comparative Analysis of Bamboo Carbon Stocks Relative to the Carbon Stocks of Other Plant Ecosystems in Different Forest Strata Cameroon*

In the HGS, bamboo AGCs were about one to three times greater than those of the savannah grassland, same with the Neem agroforest but less than those in the shrubby savannah; Cashew agroforest and *Eucalyptus* agroforestry. In the WH, bamboo AGC varies from 53.83–93 t C.ha^{-1}. This carbon is greater than those of the coffee agroforestry but less than those of a sacred forest. In TEF, bamboo carbon was less than those of coffee agroforest; mangrove and secondary evergreen forest. In TDF, bamboo carbon was three times greater than those of Coffee agroforestry, but less than those of the t Cocoa agroforest and semi-deciduous forests (Table 4).

4.4 *Monetizing Bamboo Carbon Stocks in Cameroon*

Considering the carbon-free market, bamboo carbon stocks were monetized in US Dollars. In HGS recorded US Dollars ranging from 54 to 113; in WF 405–521; in TEF 129 and in TDF 269. Cameroon records a mean total of 82 t C.ha^{-1} with an equivalent US Dollars 272 (Table 5).

5 Discussion

5.1 *Density and Above-Ground Carbon of* **Oxytenanthera Abyssinica**

Density and Carbon stocks of bamboo are crucial in carbon farming, and culm yields have enormous socioeconomic importance. This study was interested in the culm yields of *O. abyssinica* in the HGS of Cameroon, given that this species has been identified as dominating bamboo in the Northern part of Cameroon. This bamboo species is a drought-resistant species, and from observation, cattle eat the leaves as fodder. This is a species that can be integrated into the farming system (landscape restoration and agroforestry system) to supply feedstock for fodder, and culm for construction and also sustain its carbon sequestration potential because of its rapid growth rates and its durability when carefully processed into secondary products.

We found in the context of this study that this specie has a high mean culm density (10,343 stems.ha^{-1}) and AGC stock (27.45 tC.ha^{-1}). Nfornkah et al. [53, 54] reports 13.13 tC.ha^{-1} AGC carbon for *O. abyssinica* in the same agroecological zone (HGS) of Cameroon. The AGC of our study is two times greater than that of Nfornkah et al. [53]. This difference may be a result of the difference in the microclimate, of the same HGS. Ndoumdjom and Ndem-ndem are found in the transition zone between WH and HGS while Beyala is found deep in the HGS region. Therefore, precipitation (1700 mm), altitude (500 to 800 m), temperature (23 °C), and location of Ndoumdjom

Table 4 Carbon stocks of bamboo forests and other ecosystems in the different forest strata in Cameroon

Forest strata	Ecosystem types	Carbon stocks t C.ha^{-1}	References
HGS	Bamboo forest (*O. abyssinica*)	27.45	This study
	Bamboo forest (*O. abyssinica*)	13.13	This study; Nfornkah et al. [56]
	Savannah grassland	10.78	Noumi et al. [58]
	Shrubby savannah	40.89–45.03	Tchobsala et al. [75]
	Cashew agroforest	40.02	Noumi et al. [57]
	Neem agroforest	28.24	Noumi et al. [57]
	Eucalyptus agroforest	64.46–108.51	Noumi et al. [59, 60]
WH	Bamboo forest (*B. vulgaris*)	92.96	This study; Chimi et al. submitted
	Bamboo forest (*P. aurea*)	53.83	This study; Chimi et al. submitted
	Bamboo forest (*P. aurea*)	67.78	This study; Kaam et al. submitted
	Coffee agroforestry	24.28–41.20	Temgoua et al. [76]; Ngomeni et al. [55]
	Sacred forest	129.78	Louanang et al. [38]
TEF	Bamboo forest (*B. vulgaris*)	29.62	This study; Nfornkah et al. [49, 51]
	Coastal/mangrove	189.31	Ngueguim et al. [56]
	Evergreen secondary forest	327.35	Kabelong et al. [30]
	Coffee agroforestry	34–45	Ngomeni et al. [55]
TDF	Bamboo forest (*B. vulgaris*)	61.65	This study; Kaam et al., submitted
	Semi deciduous Forests	235.88	Temgoua et al. [73]
	Semi deciduous Forests	369.77	Kabelong et al. [31]
	Coffee agroforest	20.67	Ngomeni et al. [56]
	Cocoa agroforest	78.43	Noumi et al. [58, 60]
	Traditional cocoa agroforest	113.5	Madountsap et al. [39]

HGS: high guinea savannah; WH: western highlands; TDF: tropical semi-deciduous humid forest; tropical evergreen rain forests

Table 5 Monetary value of bamboo carbon stocks t $C.ha^{-1}$

Forest strata	Bamboo species	Average total carbon of bamboo (t C.ha-1)	Amount (Dollars US)
HGS	*O. abyssinica*	34.31	113
	O. abyssinica	16.41	54
WH	*B. vulgaris*	122.71	405
	P. aurea	125.42	414
	P. aurea	157.93	521
TEF	*B. vulgaris*	39.10	129
TDF	*B. vulgaris*	81.38	269
Mean total	//	82.47	272

HGS: high guinea savannah; WH: western highlands; TDF: tropical semi-deciduous humid forest; tropical evergreen rain forests

and Ndem-ndem vary from Beyala with precipitation (1200 mm), altitude (1000 to 1200 m), temperature (24 °C), and located on latitude North and between 13,10 and 14,12° from longitude East [63].

Other reasons may include differences in relief and periods during which data was collected. Similar studies in Cameroon have estimated bamboo densities and carbon stock potential confirming the results meaning that it is one of the bamboo species that have a high potential in terms of carbon stocks in Cameroon (Table 3). However, *O. abyssinica* has a less density and carbon stock potential compared to *Oldeania alpina* bamboo species in Ethiopia which, Shiferaw et al. (in press) reports for its density of 19,343 $stems.ha^{-1}$ and the carbon stocks estimated at 64.10 t $C.ha^{-1}$. Moreso, Devi and Singh [14] also estimate the density of *Bambusa tulda* and *Dendrocalamus longispathus* as >10 000 and >12 000 $stems.ha^{-1}$ respectively. According to this, we can confirm that bamboo density and carbon stocks varied greatly in terms of bamboo species, even if they are all belonging to the clumping bamboo.

5.2 *Comparative Analysis of Carbon Stocks of* **Oxytenanthera Abyssinica** *Relative to Carbon Stocks from Other Bamboo Species in Different Forest Strata in Cameroon*

The natural bamboo stands in Cameroon covers a surface area of about 1.2 M ha [51]. A number of studies estimate the carbon stocks of the dominating bamboo species across the agroecological zones of Cameroon [52–54]. A comparative analysis is necessary to make out the differences and similarities in terms of carbon stocks of different bamboo species. This gives a better understanding of how much carbon a bamboo species can sequestrate and stock in relation to the different agroecological zones where these studies were carried out.

This analysis shows that *O. abyssinica* recorded the least carbon stocks in the HGS and the highest was that of *B. vulgaris* in the WH. Despite having the least carbon stocks among the bamboo species in Cameroon, *O. abyssinica* is a lowland bamboo and equally an indigenous species in the three northern regions of Cameroon, the dominating bamboo species [51], as well as maintain particular biodiversity in its habitat, should be recommended for initiatives towards landscape restoration to fight desertification. It can also be integrated into bamboo-based agroforestry systems in the HGS, the Sudano-Sahel and the mining sites in the East region of Cameroon.

Some studies show that NPP from bamboo forests have gained much attention because of their high carbon sequestration potential and supply capacity of other ecosystem services [11, 40, 73]. Comparing NPP in a bamboo-dominant forest to a neighbouring secondary evergreen broad-leaved forest in South China using the space-for-time substitution method, Song et al. [73] concluded that the mean NPP of the former was 30.0 $tC.ha^{-1}.yr^{-1}$, which was 51.5% greater than that of the latter (19.8 $tC.ha^{-1}$ yr^{-1}) cycles. Also, a study in Japan shows bamboo forests have a higher productivity of production than Cedar forests [59, 68].

Many studies compiled bamboo carbon stocks to show their importance in terms of carbon potential thus: Amoah et al. [2] compare the stand distribution of *B. vulgaris*, *O. abyssinica*, and *B. vulgaris* var. *vitata* by estimating the AGC storage in different components of the bamboo species. They find the AGC in the bamboo to be 61% higher in *B. vulgaris* (115 $tC.ha^{-1}$) than in *B. vulgaris* var. vitata (71 $tC.ha^{-1}$) and is 27-fold that of *O. abyssinica.* Arun et al. [48] estimate AGC density in Bamboo Based Family Forests (BBFF) to be 16.38 $tC.ha^{-1}$for *B. cacharensis*, 38.42 $tC.ha^{-1}$ for *B. vulgaris* and 19.64 $tC.ha^{-1}$ for *B. balcooa.* In addition to the various ecosystem services provided by village-grown bamboo, total biomass (52.8 $tC.ha^{-1}$) and carbon (25.8 $tC.ha^{-1}$) storage in BBFFs can offer an opportunity for carbon farming. Yuen et al. [84] report of estimate plausible ranges for AGC biomass (16–128 $t.C.ha^{-1}$), BGC biomass (8–64 $tC.ha^{-1}$), soil organic carbon (SOC; 70–200 $tC.ha^{-1}$), and total ecosystem carbon (TEC; 94–392 $tC.ha^{-1}$). In addition, Yuen et al. [84] estimate the annual carbon accumulation rates ranging in the order of 8–14 $tC.ha^{-1}$, to about 4 $t.C.ha^{-1}$ after selective harvesting of stands commences following maturation. Nath et al. [47] report that the mean carbon storage and sequestration rate in woody bamboo range from 30 to 121 $tC.ha^{-1}$ and its productivity is estimated at 6–13 $tC.ha^{-1}$ yr^{-1}, respectively; and with such vigorous growth, it will complete its growth cycle between 120 and 150 days. According to Devi and Singh [15] they find in North-East India the carbon storage of *B. tulda* range from 36.34 to 64.00 $tC.ha^{-1}$ and those of *Dendrocalamus longispathus* range from 50.11 to 65.16 $tC.ha^{-1}$.

5.3 *Comparative Analysis of Bamboo Carbon Stocks Relative to Agroforestry and Forest Ecosystems Carbon Stocks in Different Forest Strata Cameroon*

Natural forests are disappearing in many tropical countries, resulting in loss of biodiversity and erosion of forest-dependent livelihoods. The maintenance and restoration of forests as well as a search for alternative natural resources that can concurrently improve the environment and enhance the incomes of local communities has become crucial. Bamboo is suggested as a resource which could substitute trees for socioeconomic and ecological purposes in developing countries in the (sub)tropics [60]. In fact, in addition to the goods and services that they provide for people, with its high capacity in terms of carbon stocks, it can represent a good opportunity in terms of carbon stocks in the market and payment of ecosystem services.

Our results suggest that bamboo carbon stocks range from 13.13 $tC.ha^{-1}$ for *O. abyssinica*, 122.71 $tC.ha^{-1}$ for *B. vulgaris* in Cameroon while carbon stocks from other land use ecosystems: agroforestry systems range from 20.67 $tC.ha^{-1}$ for Coffee agroforestry to 108.51 $tC.ha^{-1}$ for *Eucalyptus* agroforestry in Cameroon. Comparing bamboo to typical natural ecosystems, their carbon stocks range from 10.78 $tC.ha^{-1}$ for Savannah grassland to 369.77 $tC.ha^{-1}$ for semi-deciduous forests of Cameroon. These results suggest that bamboo can totally be integrated into the agroforestry systems in Cameroon because it has the capacity to sequestrate and stock carbon equivalent to the other agroforestry ecosystems used in this study with the specific example of the carbons 122.71 $tC.ha^{-1}$ and 108.51 $tC.ha^{-1}$ for *B. vulgaris* versus *Eucalyptus* respectively.

For the natural ecosystems, bamboo carbon stock sequestration was better than those of savannah grassland and shrubby savannah. This implies that bamboo can be carefully integrated into the restoration initiative of the Western Highlands and the High Guinea savannah agroecological zones to restore degraded forest landscapes and marginal lands in Cameroon, prone to desertification.

According to King et al. [31], studies on total ecosystem carbon (TEC) of certain woody bamboo species show that bamboo forest ecosystems can store between 94 and 392 $tC.ha^{-1}$ of carbon per hectare (t $C.ha^{-1}$): that is, significantly less carbon than in natural forest ecosystems (126–699 t $C.ha^{-1}$) but similar to tree plantation ecosystems (85–429 t $C.ha^{-1}$) and more than grassland or pasture (70–237 t $C.ha^{-1}$). This agrees with the results of Yuen et al. [84] that the total ecosystem carbon range is below that for most types of forests, on par with that of rubber plantations and tree orchards, but greater than agroforests, oil palm, various types of swidden fallows, grasslands, shrub lands, and pastures, which is similar to this results.

5.4 Monetizing Bamboo Carbon Stocks in Cameroon

Carbon trading, part of carbon farming, as described in the Kyoto Protocol, is a voluntary and mandatory emission trading market for greenhouse gases (GHGs) [69]. Among the terrestrial ecosystems, agroforestry and forest ecosystems have been given priority for carbon trading based on the efficiency of particular land use in reducing emissions or capturing carbon by storing it. Reforestation, afforestation, and REDD are also eligible for carbon trading [29]. Carbon trading is pertinent to climate negotiations by decelerating the climate change phenomenon. Carbon farming allows farmers and investors to generate tradable carbon offsets from farmlands and forestry projects through carbon trading [49]. Bamboo has the potential to generate carbon credits due to high carbon sequestration rates, which can be traded internationally [18]. Farmers can use Bamboo farming in sub-optimal land to generate additional income and improve the fertility of the land.

The result of this study suggests that, for a mean total bamboo carbon stock per ha in Cameroon estimated at 82.47 $tC.ha^{-1}$, the prize in the carbon market is US $ 272. Cameroon's subnational Forest landscape restoration opportunities stand at 720,991.50 ha (Table 5) [44]. Considering that bamboo was used to restore the 720,991.50 ha of restoration opportunities in Cameroon, and with the current carbon price used for this study, 44,269,062.3 $tC.ha^{-1}$ and US $ 12,041,184,945.6.

Bamboo farming to exploit these restoration opportunities in Cameroon shall be welcomed. Dwivedi et al. [18] suggest that bamboo farmers can improve financial conditions by utilization of cultivable wasteland and helping in climate change mitigation by avoiding deforestation, improving afforestation, and carbon sequestration. They report that farmers can earn up to US $800 per hectare annually by selling raw bamboo from their degraded land. Bamboo cultivation can generate around US $ 0.0002087 per hectare annually, which can be traded as carbon credits. Additionally, under-employed farmers can work as skilled workers in the bamboo handicraft industry and can earn up to US $2700 annually at current exchange rates, which is significantly higher than the present average income of US Dollars $1750 of farmers [18]. King et al. [33] report that carbon market methodologies do more than quantify the amount of carbon stored in a bamboo plantation, as they also guide project developers in determining project boundaries, setting baselines, assessing the addition of carbon stored or removed and quantifying the overall GHGs emissions reduced or removed under the project.

5.5 Managing Bamboo for Landscape Restoration

Land degradation is the temporary or permanent decline in the productive capacity of the land that will result in negative consequences for agriculture, biodiversity, and the environment [60]. Further, as it affects people who depend on land-based economic activities, land degradation could lead to increasing poverty in developing countries like Cameroon. Landscape restoration has received increased attention as a measure to tackle the land degradation crisis, as reflected in the UN Sustainable Development Goals (SDGs) and in conventions such as the United National Framework of the Convention on Climate Change (UNFCCC), the United Nations Convention to Combat Desertification (UNCCD), and the Convention on Biological Diversity (CBD). Initiatives such as the Bonn Challenge; Afr100, New York Declaration, REDD + strategy, and the Great Green Wall have committed to restoring 350 M ha of degraded landscape [65]**.** The results of this study permit us to suggest bamboo species for use in this initiative based on the availability and adaptations in the different forest strata. Table 6 summarizes the planning.

6 Conclusions

This study put to evidence the fact that *O. abyssinica* a native species, has substantial carbon stocks making it a complementary species for landscape restoration that can be capitalized on climate change mitigation strategies and also generating carbon credits from the carbon-free market; although its carbon stocks potential appears to be the least compared to those of the other bamboo species within the different forest strata or agroecological zones of Cameroon. Also, bamboo carbon stocks were proven to have similar or higher potential with respect to those of other agroforestry systems and plantations in the different forest strata or agroecological zones, or in certain cases higher than those of some natural ecosystems like the savannah grasslands and swidden fallows (HGS). These results serve as a baseline for further studies as well as data that can be exploited by policymakers and development planners in integrating bamboo in degraded landscape restoration initiatives for which Cameroon is counted among countries that have ratified conventions such as the Bonn Challenge, Afri100, REDD+ , which will contribute to climate combat and life on land (SDGs 13 &15) respectively.

Table 6 Restoration initiative proposal in Cameroon

Forest Strata	Bamboo species	Growth form	Origin	Comments	References
HGS, Sudano- Sahel and the abandoned mine sites in the East of Cameroon	*O. abyssinica*	Sympodial	Indigenous to Africa	Lowland bamboo and very adapted to the Sudano-Sahel regions. This is a great candidate to be integrated to combat Desertification in the Adamaoua, North and Far North of Cameroon. This can be done through initiatives like Afr100, Bonn Challenge, and Great Green wall	This study, Nfornkah et al. [51]
	B. vulgaris	Sympodial	Exotic	This is a Pan tropical species. It has naturalized in Africa. It adapts to all tropical climates. In Cameroon, it is found in all Regions of Cameroon. It can be used for landscape restoration	This study, Nfornkah et al. [51]

(continued)

Table 6 (continued)

Forest Strata	Bamboo species	Growth form	Origin	Comments	References
	Dendrocalamus asper, and D. strictus	Sympodial	Exotic	Introduced by INBAR (International Bamboo and Rattan Organization) in Cameroon. It's drought-resistant (fight desertification), has high carbon sequestration capacity, and large and medium-sized culm production bamboo species respectively. It can be used to support restoration initiatives in these forest strata	Chimi et al. [12], Ruth et al. [66]
WH	*B. vulgaris*	Sympodial	Exotic	It is highly recommended for bamboo-based agroforestry systems in the western Highlands of Cameroon	

(continued)

Table 6 (continued)

Forest Strata	Bamboo species	Growth form	Origin	Comments	References
	D. asper, and D. strictus	Sympodial	Indigenous to Africa	It's drought-resistant (fight desertification), has high carbon sequestration capacity, and large and medium-sized culm production bamboo species respectively. It can be used to support restoration initiatives in this forest stratum	Nfornkah et al. [51]; Ingram et al. [28]; Chimi et al. [12]
	Yushiana alpina	Amphipodia (Mixed)	Indigenous to Africa	Solicit this species for bamboo plantation, Agroforestry and home gardens. The demand for bamboo culm for constructions is very high in the towns and cities (Kribi, Edea, Douala, Nkongsamba etc	

(continued)

Table 6 (continued)

Forest Strata	Bamboo species	Growth form	Origin	Comments	References
TEF	*B. vulgaris*	Sympodial	Exotic	Solicit this species for bamboo plantation, Agroforestry and home gardens. The demand for bamboo culm for construction is very high in the towns and cities (Kribi, Edea, Douala, Nkongsamba etc	Ingram et al. [28], Dwivedi et al. [18]
	D. asper, and D. strictus	Sympodial	Exotic	They have high carbon sequestration capacity, and large and medium-sized culm production bamboo species respectively. It can be promoted in agroforestry systems and bamboo plantations, for socioeconomic reasons	

(continued)

Table 6 (continued)

Forest Strata	Bamboo species	Growth form	Origin	Comments	References
	Bambusa sp longinternode	Sympodial	Exotic	Introduced by INBAR in Cameroon. It's a good species for home garden, agroforestry systems and bamboo plantations. Has the capacity of substitution of wood demand in construction and bioenergy	Chimi et al. 2021, Ruth et al. [66]
TDF	*B. vulgaris*	Sympodial	Exotic	Solicit this species for bamboo plantation, Agroforestry and home gardens. The demand for bamboo culm for construction is very high in the towns and cities (Yaounde, Bertoua, Ngoundal etc.)	Ingram et al. [28]; Dwivedi et al. [18]

(continued)

Table 6 (continued)

Forest Strata	Bamboo species	Growth form	Origin	Comments	References
	D. asper, and D. strictus	Sympodial	Exotic	It has high carbon sequestration capacity, and large and medium-sized culm production bamboo species respectively. It can be promoted in agroforestry systems and bamboo plantations, for socioeconomic reasons	
	Bambusa sp longinternode	Sympodial	Exotic	It is a good species for home garden, agroforestry systems and bamboo plantations. Has the capacity of of substitution wood demand in construction and bioenergy	

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