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An overview of antimicrobial potential of bamboo

Nikita Kalyan[1*], Aribam Indira[1], Babita Joshi[1], Mamta Rani[1], Mamta Lathwal[1], Anurag Kuhad[2] and Nirmala Chongtham[1]

[1] *Department of Botany, Panjab University, Chandigarh, India- 160014*

[2] *University Institute of Pharmaceutical Sciences, Panjab University, Chandigarh, India- 160014*

Abstract

The antimicrobial activity of bamboo has been known since ancient times as the culm sheaths or bamboo shoot skin has been traditionally used for packing foods. It is used as packaging material for meat and rice balls in Japan and to preserve the taste of tea in China. Different parts of bamboo exhibit multiple biological properties such as antioxidant, anti-cancer, free radical scavenging and antimicrobial. Several bioactive compounds such as glycosides, coumarin lactones, anthraquinones and 2,6-dimethoxy-p-benzuinone have been isolated from bamboo leaves and shoots amongst which anthraquinones and coumarins show strong anti-bacterial and bactericidal properties. Bamboo shows natural immunity against bacteria and renders resistance to a variety of bacteria, fungi, insects and other biotic agents. Three major components of essential oils i.e., tricosane, cedrol, and hexadecanoic acid extracted from leaves of bamboo have shown antimicrobial activity mainly against common food related microorganisms such as *Bacillus subtilis*, *Saccharomyces cerevisiae*, *Fusarium oxysporum*, *Geotrichum candidum* and *Escherichia coli*. Ethanolic extract of *D. asper* leaves has shown antimicrobial and anti-diarrheagenic properties against *E. coli*. The leaves of certain bamboo species have inhibited mycelial growth of rice blast fungus *Pyricularia grisea*. Antimicrobial derivatives originating from bamboo including lignin are considered to be safer alternatives than metal-based and polymer-based agents as it has negligible impact on environment, wide availability and cost-effectiveness. The fresh leaves of bamboo are more effective in inhibiting *Staphylococcus aureus* compared to penicillin. The growing microbial resistance to existing drugs has also increased the concerns of finding new alternatives to be used as preservatives, antibiotics and disinfectants.

Keywords Bamboo; Antimicrobial; Microorganisms; Antibiotics; Bioactive

**Corresponding Author:* Nikita Kalyan, *Department of Botany, Panjab University, Chandigarh, 160014, India*

1. Introduction

India has a rich heritage of knowledge on plant-based drugs for use in preventive and curative medicine. 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 use of plants and plant products as medicines could be traced as far back as the beginning of human civilization. The plant constituents play a part in the physiological functioning of living flora, and thus they have better compatibility with the human body (Lodhi et al. 2016). Bamboo is an eco-friendly and multifunctional plant as it has been serving the daily needs of over 1.5 billion people for centuries (Liese 2009). It has considerable economic, social and ecological importance. The medicinal applications of bamboo have been a part of long history. Several medicinal properties of bamboo were described in famous Chinese pharmacopeia *'Compendium of Materia Medica'* dated back to 16th century. Different parts of various bamboo species are used for numerable applications and known to have extreme therapeutic importance. Korean bamboo salt first developed around 10,000 years ago, by baking sea salt inside bamboo culm, has been an integral part of Korean and traditional medicinal system of other south-east Asian countries, as it possesses potent anti-inflammatory and anti-cancerous properties (Zhao et al. 2013). Flavonoid-rich bamboo leaf extract has multiple biological effects, such as anti-free radical, antioxidation, anti-ageing, anti-fatigue, antibacterial, antiviral, and prevention of cardiovascular diseases (Indira et al. 2023). Bamboo leaves have been used as a remedy for several diseases, including burns, dog bite injuries, hemoptysis, uremia, fever, hypertension, atherosclerosis, detoxification, respiratory disorders, oedema, diarrhoea, and vomiting. It has been shown that the leaves of some bamboo species have an antioxidative activity (Lu et al. 2005). Antibacterial activity of bamboo charcoal and bamboo vinegar has been found (Yang et al. 2017). Bamboo contains a number of valuable substances, which can support the prevention and treatment of various diseases. Due to differences in the chemical composition of the mixture, biologically active substances exhibit the activity of a different type than acting separately, which is the result of synergism or antagonism of their various components. Bamboo species show several promising therapeutic activities like anti-cancer, anti-diabetic, cardioprotective, anti-inflammatory, antioxidant, neuroprotective and anti-bacterial (Patel and Mehta 2021; Kalyan et al. 2023) due to its rich phytochemical spectrum and hence, being the epitome plant with vast potential for the pharmaceutical, cosmeceutical, nutraceutical and food industry. Despite its susceptibility to natural degradation, one of the reasons that bamboo grows rapidly and unblemished in nature is its antibacterial properties. This natural immunity against bacteria, especially on its outermost surface, renders bamboo resistant to varieties of bacteria and other biotic agents such as insects, fungi and marine borers in its natural environment (Ramful et al. 2022). Antimicrobial derivatives which originate from plants, such as lignin, are considered safer alternatives than metal-based and polymer-based antimicrobial agents given their negligible impact on the environment, wide availability and cost-effectiveness. Several studies to determine the antibacterial property of bamboo have identified lignin as being the primary source of the antibacterial compound. In a research study about the origin of the antibacterial property of bamboo, Afrin et al. (2012) identified lignin as the primary source of the antibacterial compound. From FTIR results, the antibacterial property was assumed to stem from the aromatic and phenolic functional groups in lignin (Afrin et al. 2012; Wang et al. 2012). A higher yield of monolignols during lignin extraction was found to be essential to maximize antimicrobial characteristics of lignin. The phenolic components present in syringyl monolignols, guaiacyl (G) and hydroxyphenyl (H) in lignin are considered to have antimicrobial characteristics (Ndaba et al. 2020). Additionally, given their water insoluble nature, the antibacterial agents are believed to reside in lignin, which is also insoluble in water. Recent studies on the antimicrobial characteristics of lignin found that it was effective on pathogenic microorganisms such as *Escherichia coli* and *Listeria monocytogenes* (Guo et al. 2018).Wang et al. (2018) improved the antibacterial activity of bamboo-derived lignin against both Gram-positive and Gram-negative bacteria by using a simple one-step fractionation process. Antifungal proteins have been isolated from a variety of plants, animals and fungi (Wang et al. 2001). An antifungal protein, dendrocin has been isolated by Wang and Ng (2003) from the shoots of *Dendrocalamus latiflora*. The bamboo leaf extract powder is rich in flavonoids with protective function of inducing antioxidant responses in the host under stress conditions. It is highly underutilized natural bioactive compound in management of postharvest diseases, despite its function as food additive and medicine (Vastano et al. 2000). Increasing awareness of hazards including hypersensitivity, immune-suppression and allergic reactions associated with the use of antibiotic and chemical feed additives has accelerated investigations into plants and their extracts as feed additives. In the modern world, multiple drug resistance has developed against many microbial infections due to the indiscriminate use of commercial antimicrobial drugs commonly used in the treatment of infectious disease (Chongtham and Bisht 2020). New sources, especially plant sources, are also being investigated for potential antimicrobial agents. Also, the public is becoming increasingly aware of problems with the over prescription and misuse of traditional antibiotics. In addition, many people are interested in having more autonomy over their medical care. A multitude of plant compounds (often of unreliable purity) is readily available over-the-counter from herbal suppliers and natural-food stores, and self-medication with these substances is commonplace (Cowan 1999).

2. Antimicrobial Agents

The antimicrobial agents are compounds that, at low concentrations, suppress or inhibit the growth of microorganisms. This class of compounds include the antibiotics naturally occurring substances produced by moulds, yeasts and other microorganisms and chemotherapeutics (chemically synthesized substances). The antimicrobial agents are mainly classified into two categories i.e., organic and inorganic. The organic antimicrobial agents mainly include natural biopolymers, such as, the chitosan, lignin, cellulose, halogenated compounds, phenols and quaternary ammonium salts (Sharma et al. 2020; Al-Tayyar et al. 2020). The inorganic antimicrobial agents mainly include metals, metal oxides or metals bonded with phosphates. The most common metal oxides or metallic nanoparticles used are copper, silver, zinc oxide, magnesium oxide, titanium and calcium oxide (Sharma et al. 2020; Al-Tayyar et al. 2020). Several studies have explored the use of different antimicrobial agents by incorporating or applying as coatings on material surfaces. Plants also have a limitless ability to synthesize aromatic substances, most of which includes bioactive compounds namely phenols, polyphenols, flavonoids, quinones, tannins, coumarins, alkaloids, terpenoids, essential oils etc. Major groups of antimicrobials from plants include secondary metabolites. Lignocellulosic materials derived from plants are mainly composed by biopolymer with antimicrobial activity, cellulose and lignin, which mainly shows antimicrobial potential. Lignocellulosic materials show higher antimicrobial potential and are mainly composed of three biopolymers- cellulose, hemicellulose and lignin- combined with other smaller components.

3. Inhibiting Mechanisms of Antimicrobial Agents

The main components responsible for the antimicrobial properties of bamboo are polyphenolic compounds. They exhibit anti-inflammatory and antimicrobial activities *in vitro* and *in vivo* and their mechanism of action is the inhibition of enzymes (phospholipase oxygenase) i.e., by binding with hydrosulphide groups and inactivation of bacterial proteins (Kim et al. 1995; Cowan 1999). Antimicrobial activity is attributed to flavanols, quinones and flavonoids. The main mechanism of action of antimicrobial agents is by affecting protein synthesis inhibition, cell wall disruption, and nucleic acid inhibition. These substances exhibit lipophilic properties and cause the destruction of the cell wall and cytoplasmic membrane of microorganisms. Furthermore, they cause inhibition of synthesis of nucleic acids, structural and enzymatic proteins as well as saccharides (figure 1). It has been shown that the antimicrobial activity of flavonoids may be dependent on their structure. It is believed that unsubstituted flavones are characterized by the highest antifungal activity and flavanones by lower. The introduction to these compounds of hydroxyl or methyl groups reduces their antifungal properties (Małolepsza and Urbanek 2000). Anthocyanins form complexes with metals, participating in this way in shaping the colour of flowers (Quina et al. 2009). The bio-availability and biological activity of these compounds is closely related to their chemical structure, which affects a large variety of them. The plant extracts rich in these substances have anti-bacterial and antitumor activity (Olejnik et al. 2009).Secondary metabolites of plants responsible for their antimicrobial properties also include alkaloids which damage the DNA of microbial cells, leading to their death (Omulokoliet al. 1997). Antimicrobial activity of the protein rather consists of the formation of ion channels in the cell membrane of the microorganism and increasing its permeability. The mechanism of action may also involve blocking the metabolism of the essential compounds for the bacteria and the inhibition of adhesion to the surface of the plant cell (Cowan 1999).

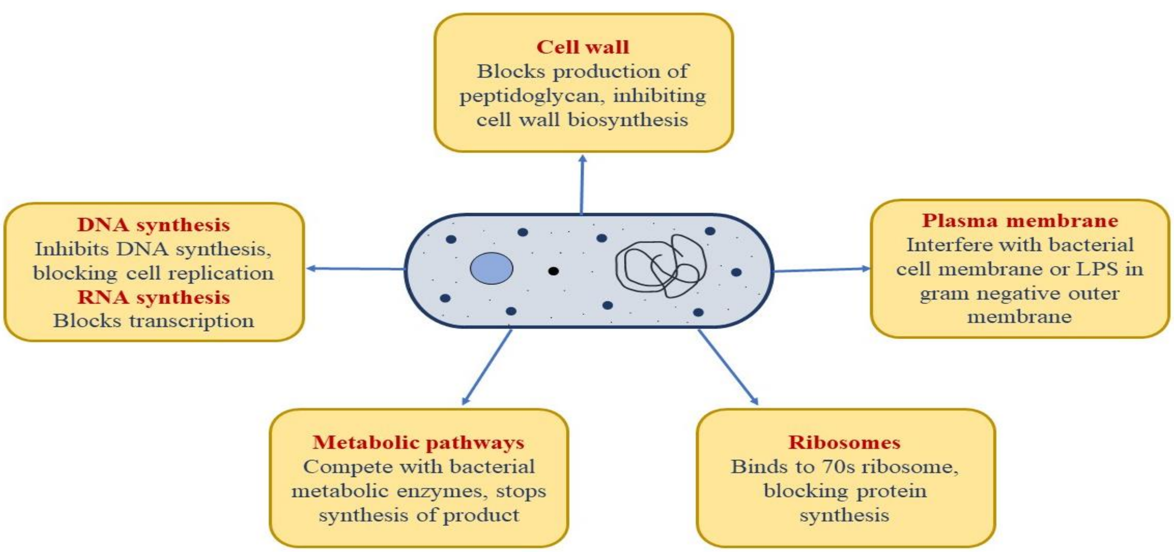

Figure 1. Inhibition mechanisms of antimicrobial agents

Tannins protect the plants against the effects of microorganisms by the formation of the complexes with proteins, while terpenes interfere with the incorporation of the lipophilic compounds in the bacterial cell membrane (Mendoza et al. 1997). The leaf essential oils act by disrupting the membrane integrity of the microbes thus inhibiting their growth (Tao et al. 2019).

4. Antimicrobial Properties of Bamboo

Many studies have indicated that several bamboo parts have multiple biological effects such as anti-free radical, antioxidation, anti-aging, and prevention of cardiovascular diseases (Lv et al. 2012). Bamboos are used as bioactive agents for a variety of applications, including bamboo charcoal, bamboo vinegar and juice, bamboo salt and tender shoots that are used in variety of cuisines. Several bioactive compounds like phenols, phytosterols, flavonoids and dietary fibres are present in young bamboo shoots and leaves which have putative health benefits (Table 1). Because of these characteristics, bamboos are valuable in pharmaceutical and food processing industries where they are processed into medicine, additives or health food. Park and Jhon (2010) reported the presence of eight phenolic acids such as protocatechuic acid, p-hydroxybenzoic acid, catechin, caffeic acid, chlorogenic acid, synergic acid, p-coumaric acid and ferulic acid in shoots of *Phyllostachys pubescens* and *P. nigra.* Bamboo leaves are also rich in flavonoids such as orientin, isoorientin, vitexin, isovitexin and tricin. Several traditional drugs have been associated with bamboos for treating fever and detoxification which have been used in ancient times. Bamboo, acting as therapeutic agents in ethnomedicine, are used to inhibit inflammation, and enhance natural immunity for a long time. The presence of bioactive compounds like polyphenols, carotenoids, anthocyanin, phytosterols, dietary fibre, alkaloids, glycosides, saponins, anthraquinones, flavonoids, phenolics, tannins, phytosterols, and triterpenoids indicate towards the potential antimicrobial potential of bamboo.

4.1. Antibacterial Properties

The anti-bacterial activity of bamboo has been known since ancient times as the culm sheaths or bamboo shoot skin has been traditionally used for packing food. Several parts of bamboo such as shoot, culm, leaves, sheath, oils, charcoal and vinegar have shown antibacterial activities. 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 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* and *Escherichia coli* (Tao et al. 2018; Chongtham and Bisht 2020). GC-MS analysis of volatile compounds found the hexadecenoic acid, pentacosane and phytol as the major components in essential oils. Wang et al. (2021) reported that the addition of bamboo leaf volatile oil improvised the anti-bacterial potential of cornstarch- based films and hence, can extend the shelf life of food. Essential oils of *P. edulis* extracted by steam distillation contain cis-3-hexenol and have antioxidant and antimicrobial activities (Jin et al. 2011). 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 (Fujimura et al. 2005). Antibacterial screening of *Bambusa vulgaris* shoot extracts (n-hexane, chloroform and ethyl acetate) against Gram-positive (*B. cereus*, *Staphylococcus aureus)* and Gram-negative (*E. coli*, *Klebsiella pneumoniae)* bacteria showed that all concentrations tested significantly inhibited the growth of microorganisms. Therefore, the extract of *B. vulgaris* has antimicrobial activity which supports the traditional use of aqueous extract of *B. vulgaris* to treat sexually transmitted diseases and for wounds (Fitri et al. 2020).

Ambika and Rajagopal (2017) reported the antimicrobial activity of acetone fraction of *B. vulgaris* shoot against *K. pneumoniae*, *S. epidermidis*, *B. subtilis*, *Enterococcus faecalis* and *E. aerogenes.* The antibacterial activity of hexane, ethanol, water and ethyl acetate extracts of *B. vulgaris* and *Guadua ligulate* shoots have been determined against some gram-positive (*B. cereus*, *S. aureus)* and gram-negative bacteria (*E. coli, K. pneumoniae* and *P. aeruginosa)* which showed a similar extent of bacteriostatic activity (Kong et al. 2020). Dichloromethane extract of *P. pubescens* shoot skin has also been shown to have anti-bacterial activity against *S. aureus,* which may be due to the presence of 2, 6-dimethoxy-p-benzoquinone (Tanaka et al. 2013).

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 (Muniappan and Sundaraj 2003). *Sasa veitchii* (Kuma bamboo grass) extracts that contained a variety of fatty acids, exhibited antibacterial activity against nine *Aeromonas* strains including 5 atypical *A. salmonicida* (Asakura et al. 2019). The antimicrobial activity of 70% ethanol extract and fractions of crude extract containing the essential oil from P. *bambusoides* culms and leaves was studied against scalp infection causing fungus *Malassezia* (Lee et al. 2010). The leaves of *S. borealis* have been investigated against food poisoning bacteria including *Micrococcus luteus, S. typhimurium, P. aeruginosa, B. subtilis* and *E. coli* (Park and Lim 2010). The bamboo grasses are generally recognized to contain a variety of natural antimicrobials that inhibit survival and/or growth of representative foodborne bacteria or enteric bacteria（Fu-Chu et al. 2009; Shirotake et al. 2009). Majority of the specimens from bamboo plant species and natural bamboo fibres showed a quantifiable percentage reduction of bacteria against *K. pneumoniae* (8–95%) but had more modest results against *S. aureus* (3–50%). It also showed that the natural bamboo fibres extracted from four bamboo species i.e., *P. bissetii, P. edulis, P. nigra* and *P. rubromarginata* showed higher reduction in bacteria than raw bamboo specimens (Rocky and Thompson 2020).

Anti-bacterial activity of leaf extracts using different solvents have been determined. The ethanolic and methanolic leaves extract of *B. bambos* showed excellent inhibitory action against all tested ten multiple drug resistant bacteria which all were clinical isolates from wound infection (Wasnik and Tumane 2014). Here also ethanol solvent comparatively showed better results like previous studies. Effectiveness of plant extract against microbial strains was determined by measuring zone of inhibition (ZOI) in all the studies. Ethanolic extracts of *B. arundinacea* and *Mangifera indica* had higher inhibition on both gram positive as well as gram negative bacteria indicating both are potential source of natural antioxidants, phytochemicals and antibacterials (Singh et al. 2010). Ethanolic extract of *D. asper* leaves has shown antimicrobial and anti-diarrheagenic properties mainly due to the presence of fatty acids and esters. It also contained a phenol with similar antimicrobial activity to guaiacol (Mulyono 2012). Antibacterial activity of *B. arundinacea* was tested against the strains of *S. aureus, P. aeruginosa, E. coli and Bacillus*. Ethanolic extract was moderately effective against all four organisms, while aqueous extract showed moderate effect against *E. coli* and *S. aureus*. Bamboo is considered as a good source of phytosterols that are the precursors of various pharmaceutically active steroids found in plants and these also act as nutraceuticals (Voravuthikunchai and Kitpipit 2005). 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 bamboo leaf extract and probiotics (Kimura et al. 2022). The antimicrobial effect of *B. vulgaris* leaf extract has been determined with respect to their inhibitory effect on the growth of *E. coli, B. cerise* and *Lactobacillus spp*. (Owolabi and Lajide 2015). The leaves of bamboo are used as an astringent, ophthalmic solution, vulnerary, emmenagogue and febrifuge to heal wounds. According to Singh et al. (2003a) 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*, *P. aeruginosa*, and *Bacillus* spp. An ethanolic extract from the leaves of *P. edulis* contains high levels of polyphenols and flavonoids (Lin et al. 2008).

Anti-bacterial properties of bamboo charcoal were reported by Choi and Suk (2014). Growth of *S. mutans* reduced by 58% on bamboo charcoal medium. Bamboo pyroligneous acid or wood vinegar is produced as a byproduct during the pyrolysis of bamboo charcoal and contains more than 200 different organic compounds, such as alkane, aldehyde, alcohol, phenols and acetic acid (Mun and Ku 2010). The antimicrobial action of the methanolic fraction of *D. asper* pyroligneous liquor has been studied against *E. coli* and *S. aureus*. The results of disc diffusion assay demonstrated the inhibition of cellular growth of both the bacteria at different concentrations of the extract (Jankowsky et al. 2018). GC/MS analysis of the methanolic fraction revealed the presence of aldehydes, ketones, lactones and phenolic compounds.

Yang et al. (2009) reported the high antibacterial efficiency of bamboo silver composites. With 18 hours of inoculation, bacterial colonies of gram-positive *S. aureus* were found to be completely killed. In addition to this, above mixture showed strong antibacterial properties against Ciprofloxacin-resistant *P. aeruginosa* (CRPA), *E. coli* and *E. coli* JM109, and *B. subtilis* bacteria. Nanoparticles prepared from leaves of *B. arundinacea*, *B. bambos*, *D. hamiltonii* and *P. aurea* have promising antimicrobial activity against *E. coli* and *S. aureus*, *S. epidermidis* (Singla et al. 2017).Anti-bacterial silver nanoparticles had been synthesized by Yasin et al. (2013) using *P. aurea* leaves and were tested against *E. coli* and *S. aureus* using the disc diffusion method. The antibacterial activity of AgNPs was evaluated by Jayarambabu et al. (2022) against five bacteria i.e., *S. epidermidis, B. subtilis, P. aeruginosa, E. coli, S. Shigella boydii.* The mechanism of action involves the release of Ag^0 ions from metal nanoparticles which are absorbed by the bacterial cell membrane resulting in the subsequent alteration in permeability of the membrane, inhibition of respiration, altered enzyme function, solidification of protein structure and finally leading to cell membrane damage. AgNPs have elevated tendency to react with sulfur and phosphorus of the biomolecules in the bacterial cell, interact and inhibit DNA replication and also destabilize and degrade the outer membrane of the plasma membrane, thus reducing the intracellular ATP. In addition, the presence of single peptidoglycan layer, Gram-positive bacteria are more susceptible to the treatment of AgNPs compared to Gram-negative bacteria (Jayarambabu et al. 2022). The most-reported mechanism is based on the reactive oxygen species generation (ROS). The antibacterial activity of different concentrations of Cu NPs against four pathogenic bacteria i.e., *P. vulgaris, E. coli, S. aureus,* and *B. subtilis* have been studied by Naradala et al (2022). The antibacterial activity of Cu NPs includes dramatic enhance in cellular ROS level that influences lipid peroxidation, protein oxidation, and DNA destruction and finally kills the microorganism cells. The ROS contain radical compounds such as hydroxyl (-OH), superoxide radical (O_2 -), singlet oxygen ($^1O_2$), and hydrogen peroxide (H_2O_2), which destroy the bacteria. Hence, green synthesized Cu NPs demonstrated significant antibacterial activity against various organisms (Naradala et al. 2022).

4.2. Antifungal Properties

Antifungal potential of leaf extracts from *B. vulgaris* and *D. strictus* against the strains of *Aspergillus fumigatus, A. niger, Candida albicans, C. glabrata and C. tropicalis* and *Trichoderma viride* have been studied by Owolabi and Lajide (2015), and Ambika and Rajagopal (2017). Bamboo leaf has been reported as a potent natural source to manage rice blast disease as the leaves of *P. pubescens* inhibit mycelial growth of rice blast fungus *Pyricularia grisea* (Toan et al. 2018). Kong et al. (2020) reported stronger fungistatic and fungicidal effects of hexane, ethyl acetate, ethanol and water extracts of *B. vulgaris* and *G. ligulata* shoots against three species of filamentous fungi (*A. fumigatus, Trichophyton interdigitale* and *T. rubrum*) and yeasts (*C. albicans, C. parapsilosis* and *Cryptococcus neoformans*). The chitin-binding peptides like Pp-AMP1 and Pp-AMP2 obtained from bamboo shoots of *P. pubescens* have shown anti-fungal activity against *Fusarium oxysporum* and *Geotrichum candidum* (Fujimura et al. 2005). Antimicrobial screening of n-hexane, chloroform and ethyl acetate extracts from *B. vulgaris* shoots showed that the crude extract significantly inhibited the growth of the *A. niger* and *Verticillium alboatrum* (Fitri et al. 2020).

Zhang et al. (2010) demonstrated the antifungal activity of water-phase extract of bamboo shavings (WEBS) against a range of food spoilage and foodborne fungi such as *Saccharomyces cerevisiae, A. niger* and *Penicillium citrinum* using agar disc diffusion assay in nutrient agar. The anti-fungal activity of leaf extracts of *B. vulgaris*, *D.* strictus, *Gigantochloa manggong* and *P. pubescens* against strains of fungi such as *A. fumigatus*, *A.niger*, *Botrytis cinerea Pers*, *Botryosphaeria dothidea*, *Trichoderma viride*, *Candida albicans*, *C. glabrata*, *C. tropicalis*, *F. graminearum*, *Phytophthora capsici* and *Venturia nashicola* have been shown (Ambika and Rajagopal 2017). Liao et al. (2021) identified a compound, 4-hydroxycinnamic acid as the main active component of leaf extract of *P. pubescens* with anti-fungal activity. Wang and Ng (2003) extracted an antifungal protein dendrocin which is a thaumatin-like protein from the shoots of *Dendrocalamus latiflora*. Dendrocin exerts antifungal activity against a variety of fungi including *B. cinerea*, *F. oxysporum*, and *Mycosphaerella arachidicola*. The antifungal potency of dendrocin towards *B. cinerea* is lower than that of its kiwi fruit counterpart. However, dendrocin is more active towards *F. oxysporum*. Antimicrobial screening of the n-hexane, chloroform and ethyl acetate extracts of *B. vulgaris* showed that the crude extracts inhibited the growth of fungi *A. niger*. This supports the ethno medicinal use of aqueous extracts of this species to treat sexually transmitted diseases and for wounds (Ogunjinmi et al. 2009).

Table 1. Antimicrobial activity of several bamboo species

S. No.	**Species**	**Antimicrobial compound/ Extract**	**Plant part used**	**Micro-organisms**	**Reference**
1	*Bambusa arundinacea*	Cu Nanoparticles	Leaves	*Escherichia coli, Staphylococcus aureus, Bacillus subtilis, Proteus vulgaris*	Naradala et al. 2022
2	*B. arundinacea*	Ag Nanoparticles	Leaves	*S. epidermis, B. subtilis, Pseudomonas aeruginosa, E. coli, S. Shigella boydii*	Jayarambabu et al. 2022
3	*B. bambos*	Ethanolic and methanolic extract	Leaves	*S. aureus, P. aeruginosa, E. coli, Klebsiella spp., Enterococcus spp. Citrobacter spp., Acinetobacter spp.*	Wasnik and Tumane 2014

				Streptococcus spp., Enterobacter spp. and P. mirabilis	
4	*B. blumeana*	Apigenin, luteolin, p-coumaric acid	Leaves, rhizome, roots, culm	*E. coli, S. aureus, B. subtilis, Pasteurella multocida Aspergillus niger, Penicillium chrysogenum*	Saducos 2022
5	*B. vulgaris*	Ascorbic acid	Leaves	*B. cerise, E. coli, Lactobacillus* spp., *A. niger*	Owokotomo and Owoeye 2011
6	*B. vulgaris*	Acetone fraction	Shoot	*K. pneumoniae, S. epidermidis, B. subtilis, Enterococcus faecalis* and *E. aerogenes*	Ambika and Rajagopal 2017
7	*vulgaris*	Hexane, ethanol, water and ethyl acetate extract	Shoot	*B. cereus, S. aureus, E. coli, K. pneumoniae* and *P. aeruginosa*	Kong et al. 2020
8	*B. vulgaris*	Hexane, ethanol, ethyl acetate, choloroform extract	leaves	*B. cereus, S. aureus, E. coli, K. pneumoniae A. niger A. fumigatus, Candida albicans, C. glabrata, C. tropicalis, Verticillium albo-atrum, Trichoderma viride*	Owolabi and Lajide 2015
9	*B. vulgaris*	Phenol (wood vinegar)	Culm	*S. aureus, P. aeruginosa, Salmonella*	Gama et al. 2023

				enteritidis, E. coli, Streptococcus agalactiae *C. albicans*	
10	*B. vulgaris*	n-hexane, ethanol, ethyl acetate	Leaves	*P. aeruginosa, B. subtilis, S. aureus, B. pumilus, E. coli* *C. albicans*	Htwe 2017
11	*B. vulgaris*	Acetone fraction	Leaves	*A. fumigatus, A. niger, Botrytis cinerea Pers, Botryosphaeria dothidea, T. viride, C. albicans, C. glabrata, C. tropicalis, Fusarium graminearum, Phytophthora capsici Venturia nashicola*	Ambika and Rajagopal 2017
12	*B. vulgaris*	n-hexane, chloroform and ethyl acetate extract	Leaves	*A. niger*	Ogunjinmi et al. 2009
13	*Dendrocalamus asper*	Fatty acids and esters	Leaves	*E. coli*	Mulyono et al. 2012
14	*D. latiflora*	Dendrocin	Shoots	*F. oxysporum, Botrytis cincerea, Mycosphaerella arachidicola*	Wang and Ng 2003
15	*D. strictus*	Acetone fraction	Leaves	*A. fumigatus, A. niger, Botrytis cinerea Pers, Botryosphaeria dothidea, T. viride, C. albicans, C. glabrata, C. tropicalis, Fusarium graminearum,*	Ambika and Rajagopal 2017

				Phytophthora capsici Venturia nashicola	
16	*Guadua ligulate*	Hexane, ethanol, water and ethyl acetate extract	Shoot	*B. cereus*, *S. aureus*, *E. coli*, *K. pneumoniae* and *P. aeruginosa*	Kong et al. 2020
17	*Gigantochloa manggong*	Acetone fraction	Leaves	*A. fumigatus*, *A. niger*, *Botrytis cinerea Pers*, *Botryosphaeria dothidea*, *T. viride*, *C. albicans*, *C. glabrata*, *C. tropicalis*, *Fusarium graminearum*, *Phytophthora capsici Venturia nashicola*	Ambika and Rajagopal 2017
18	*Phyllosrachys bambusoides*	Essential oil	Leaves	*Trichophyton mentagrophytes*, *Epidermophyton floccusum*, *Trichophyton rubrun*	Lee 2003
19	*Phyllostachys bambusoides*	Essential oil	Culms and leaves	*Malassezia* fungi	Lee et al. 2010
20	*P. bissetii*	Bamboo fibres	Culms	*K. pneumoniae*, *S. aureus*	Rocky and Thompson 2020
21	*P. edulis*	Bamboo fibres	Culms	*K. pneumoniae*, *S. aureus*	Rocky and Thompson 2020
22	*P. heterocycla*	Essential oils (cedrol, tricosane, hexadecanoic acid)	Leaves	*B. subtilis*, *E. coli*	Tao et al. 2018
23	*heterocycla*	2,6-dimethoxy-p-bezoquinone	Shoot skin	*Erwinia carotovora*, *Agrobacterium radiobacter*, *A.*	Fujimura et al. 2005

				rhizogenes, Clavibacter michiganensis, Curtobacterium flaccumfaciens	
24	*P. heterocycla*	Chitin binding peptides (Pp-AMP1 and Pp-AMP2)	Shoot	*E. carotovora, A. radiobacter, A. rhizogenes, C. michiganensis, C. flaccumfaciens F. oxysporum, Geotrichum candidum*	Fujimura et al. 2005
25	*P. nigra*	Bamboo fibres	Culms	*K. pneumoniae, S. aureus*	Rocky and Thompson 2020
26	*P. pubescens*	2,6-dimethoxy-p-benzoquinone	Shoot skin	*S. aureus*	Tanaka et al. 2013
27	*P. pubescens*	Hexane, ethyl acetate, butanol and water extract	Leaves	*S. aureus, B. subtilis, P. aeruginosa, E. coli, F. oxysporum*	Toan et al. 2018
28	*P. pubescens*	Acetone fraction	Leaves	*A. fumigatus, A. niger, Botrytis cinerea Pers, Botryosphaeria dothidea, T. viride, C. albicans, C. glabrata, C. tropicalis, Fusarium graminearum, Phytophthora capsici Venturia nashicola*	Ambika and Rajagopal 2017
29	*P. rubromarginata*	Bamboo fibres	Culms	*K. pneumoniae, S. aureus*	Rocky and Thompson 2020
30	*Sasa borealis*	Ethanolic extract	Leaves	*M. luteus, S. typhimurium, P. aeruginosa, B.*	Park and Lim 2010

				subtilis, E. coli, Listeria monocytogens	
31	*S. veitchii*	Fatty acids	Leaves	*Aeromonas salmonicida*	Asakura et al. 2019
32	*B. vulgaris*	n-hexane, chloroform and ethyl acetate	Shoots	*B. cereus, S. aureus, E. coli, K. pneumonia, A. niger, Verticillium alboatrum*	Fitri et al. 2020

Conclusion

Mainstream medicine is increasingly receptive to the use of antimicrobial and other drugs derived from plants, as traditional antibiotics have become ineffective. Also, in recent years, people have been paying more attention to herbal-based medicines due to their properties. The plants including bamboo hold great promise as a source of novel antimicrobial agents. They are readily available, cheap and almost have no side effects. Plant derived compounds including phytochemicals have been employed to treat various infectious disease and have also shown antimicrobial activity against several human pathogens. Some of these compounds show both intrinsic antibacterial activity and antibiotic resistance modifying activities. Co-administration of these compounds with commercial antibiotics leads to reduce the MIC of antibiotics and synergistic effects were observed. Antimicrobials are extensively used in pharmaceutical, food and cosmetic industries. In cosmetics, the preservatives mainly protect at the production stage as well as during use of product by consumers. Food is easily affected by several microorganisms such as bacteria, moulds and fungi, which can lead to severe complications to human health and can cause several diseases. In food industry, these additives can increase the organoleptic characteristics of the food as well as can protect the food during production, storage and consumption. Also, the growing microbial resistance to existing drugs has increased the concerns of people and has generated a need for the pharmaceutical industry to search for new compounds that can be used as antibiotics, preservatives and disinfectants. Bamboo contains a range of compounds such as carotenoids, terpenoids, alkaloids, tannins, polyphenols and minerals that shows antimicrobial activity. Hence, bamboo can be used as an alternative to synthetic substances and additives to improve the quality of additives as well as reducing the harmful effects of the synthetic compounds.

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Conflict of Interest

The authors declare there is no conflict of interest.

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