Bamboo as a Source for Value Added Products: Paving Way to Global Circular Economy

Perminder Jit Kaur,[a] Preity Yadav,[b] Manyata Gupta,[b] Vinita Khandegar,[b] and Arinjay Jain [b]

Bamboo biomass is known for its low cost, abundance, fast growth rate, low weight-to-height ratio, and load-bearing abilities, making it an attractive alternative to materials such as wood, metal, steel, and plastic for multiple applications. Bamboo is traditionally used in handicrafts, food, building, construction, pulp, and paper. The production of energy and green adsorbents with unique properties are a few emerging applications of bamboo. Porous structured, bamboo-based charcoal allows the separation of solute from solvent and can be used to detoxify the air, water, and soil. The surface functional groups can be enhanced during thermal processing, yielding activated carbon products and serving greenhouse gas capturing applications. Nanoparticle particles ($Ni_{0.5}Zn_{0.5}Fe_2O_4$ and silver) coated bamboo charcoal has shown microwave and Infrared energy shielding effects. Bamboo-based charcoal also has exceptional medicinal values, is an efficient drug-delivery agent, and has tremendous potential for small and medium enterprises. Bamboo charcoal is also investigated as a toxin adsorber and hence a blood purifier. This review also considers the potential and challenges in using bamboo and its products for many applications that can contribute to a renewable society.

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Contact information: a: Department of Science and Technology, Centre for Policy Research-Indian Institute of Science (IISC), Bangalore, India; b: University School of Chemical Technology, Guru Gobind Singh Indraprastha University, New Delhi; Email: perminder.dua@gmail.com

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INTRODUCTION

Depleting forest areas, reducing metal resources, and increasing plastic waste call for a paradigm shift towards a renewable and sustainable society. A direct consequence of decreasing forest reserves is a degrading state of environmental conditions and human health. Non-biodegradability of plastic has become a global gremlin that causes problems related to waste disposal and management (Bahl *et al.* 2020). Metal reserves are limited and are thus expensive. Their processing is also highly energy-intensive and onerous. Therefore, there is a need to replace wood, metal, and plastic with a versatile renewable materials having diverse applications.

United Nations Framework Convention on Climate Change held in 2003 led to a consensus on developing pathways toward the reduction of deforestation and to achieve global carbon neutrality by 2060 (Xu *et al.* 2022). Due to increasing global warming and severe climate change conditions globally, the circular economy concept to replace the generally prevalent linear economy model emerged, where the optimal usage of natural raw materials generating minimum waste is practiced. Thus, all countries are framing their policies keeping sustainable development goals (SDG) as the primary target to achieve before 2030 (Chauhan *et al.* 2020).

Bamboo is a grass belonging to the Gramineae family that is found in the tropical, subtropical, and mild temperate zones, occurring in about 90 genera of 1200 species (Elejoste *et al.* 2021). Most bamboo forests are found in Asia, Africa, south, central and north America covering 33 million ha of land. Asia alone contains about 1000 bamboo species in the land of over 18 million ha (Solomon *et al.* 2020). Using bamboo as a raw material for multiple high-end applications could contribute toward attaining many SDGs, including poverty reduction, employment generation, less deforestation, and reducing climate change (van Dam *et al.* 2018).

The lightness, biodegradability, high growth rate, ease, and low cost of processing, have made bamboo one of the most desirable materials for utility in innumerable ways. Bamboo, with superior properties, is a low-cost, readily available, sustainable, and renewable alternative to be used by small and medium enterprises. The flexibility of bamboo makes it a suitable alternative to plastic. The tensile strength of bamboo is ideal for replacing even steel in load-bearing applications (van Dam *et al.* 2018; van der Lugt *et al.* 2006).

Bamboo's major constituents are lignin, cellulose, and starch, with minor constituents including resin, gums, and tannins (Kaur *et al.* 2016a). Traditionally, bamboo is a part of many societies and cultures, where it is used as a building material, producing handicrafts, furniture, pulp, and paper (Kaur 2018). Bamboo, a rich carbon source, has been explored to produce charcoal and activated carbon. Biochar is a low-cost carbon-rich material formed through biomass heating in specially designed reactors under controlled conditions. Charcoal is further modified using physical or chemical agents to enhance its properties for specific applications. Many publications have described the soil amendment properties of biochar. Porous structured, bamboo-based charcoal allows for the separation of solute from solvent and can be used to detoxify the air, water, and soil (Chien *et al.* 2011). The enhanced surface functional groups can be used in carbon and greenhouse gas capturing applications. Bamboo charcoal has shown potential for electromagnetic, radioactive iodine, and infrared radiation shielding (Chien *et al.* 2011).

Bamboo is a rich carbon source with high-strength long fibers. It has the potential to generate numerous value-added products. Most studies on bamboo utilization are focused on individual applications of the bamboo culm either in the construction, fiber, or food industry. However, best of our knowledge, no study encompasses the vibrant nature of bamboo, considering its role in the bio-circular economy and utilizing each component of the plant. There is a lack of available literature on the valorization of bamboo in a closed-loop system. Also, there is an immediate need to explore research trends on alternative and eco-friendly bamboo conversion to industrial products.

With this objective, the current paper broadly reviews the research trends in traditional and emerging potential applications of bamboo. This review systematically examines the potential of bamboo to contribute toward sustainable development goals and achieve the target of a circular economy. The strengths and technical limitations of the sector are discussed here. The observations made in this study can assist in addressing the gaps in the large-scale utilization of bamboo as an engineering material.

RESEARCH TRENDS ON BAMBOO SPECIES

Scopus, a bibliographic database, was used to investigate the global trend in research on bamboo species. It is inferred that by the 1960s, researchers started paying attention to this field. The number of publications over time was plotted to assess the areas explored by researchers, which can be used to analyze the trends and gaps. Continuous growth in the number of publications on various aspects of bamboo was observed. The number of publications rose from 176 to 2,226 from the year 2000 to 2021. Looking at the role of bamboo in sustainable development, researchers are exploring different areas of application. According to the Scopus database analysis, the number of journal articles about bamboo has been rising steadily since the year 2000, indicating a large number of technological innovations being undertaken. Figure 1 shows the increasing trend of publications on various bamboo-related aspects between 2000 to 2021.

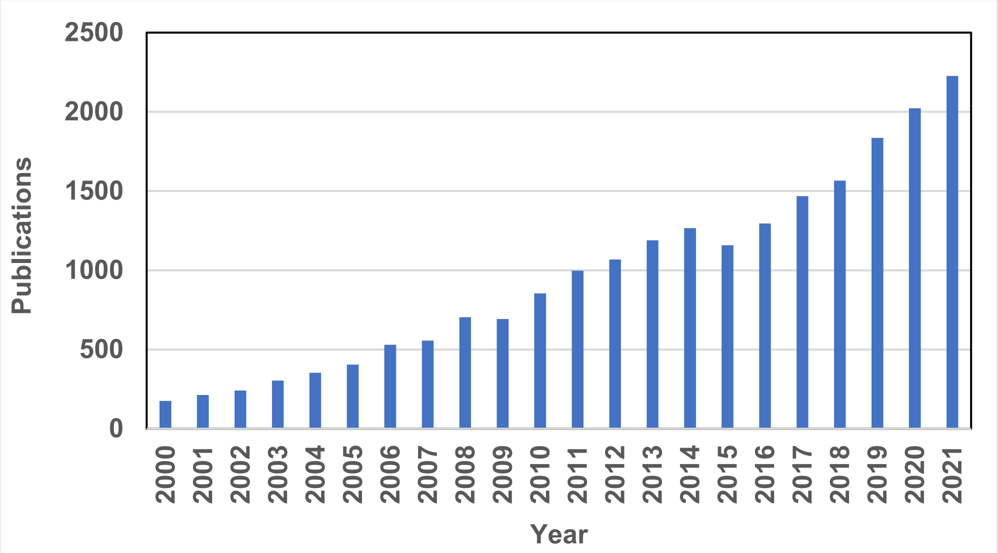

Fig. 1. Global trends and scientometrics analysis on bamboo

As shown in Fig. 2, the fields that researchers in the past have investigated are agricultural and biological sciences, followed by engineering and material science. In addition to this, the application of bamboo in biochemistry and medicines has also caught researcher's attention.

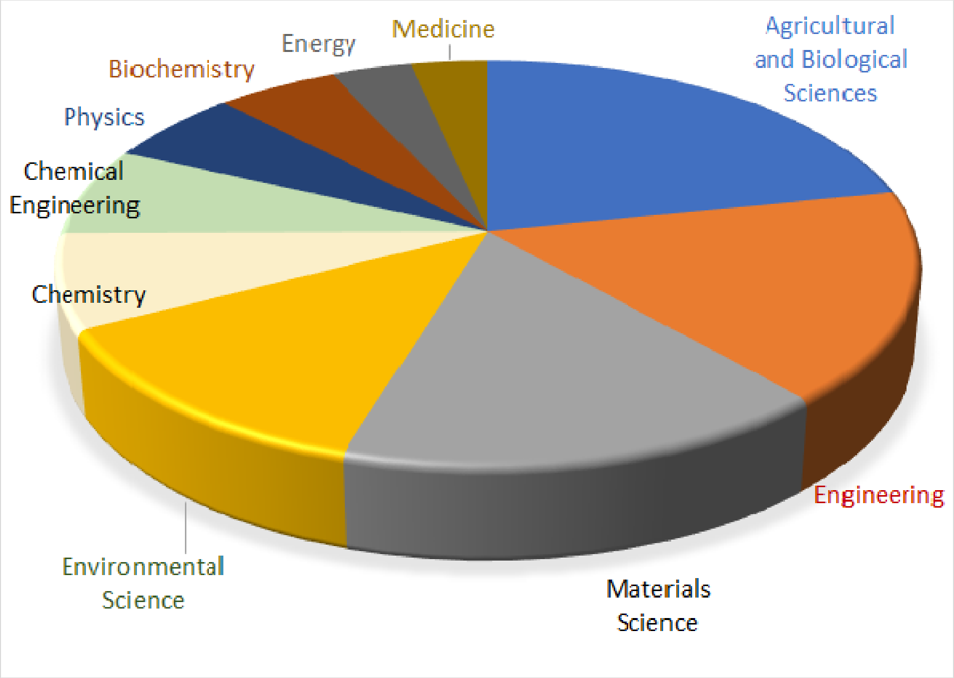

Fig. 2. Key areas for bamboo's applications explored by researchers

Further, limiting and refining the search to the past decade only, the most commonly used keywords for bamboo-based research were analyzed using VOS mapping software. This study focused on relevant articles published up through 2021. The statistical results include annual records of publications, national and institutional publication quantity, core countries, institutions, journals, and authors.

Based on the above-selected references, the application of bamboo can be broadly divided into two categories. Woven products, shoots, and furniture dominate the traditional treatments of bamboo. The study on emerging applications of bamboo is focused on a diverse range of fields, including bioenergy and biochar production. Bamboo-based research on biochar is limited to its usage in soil remediation and adsorption, with minute attention given to the medical field of application. Bamboo shoots are investigated for their fibrous and antioxidant properties. Engineered bamboo is studied to make composites, plywood, and fibers. Figure 3 shows the density visualization map of keywords for bamboo research.

Bibliographic coupling analysis was performed on the most researched keywords (57 in number) and their relations. In Fig. 3, each sphere represents a keyword, where larger circles and warmer colours represent more occurrences of that keyword.

The most commonly used keywords in literature are bamboo, giant panda, conservation, mechanical properties, adsorption, lignin, nitrogen deposition, and biochar. A few studies on the role of bamboo using keywords such as biodiversity, climate change, and carbon sequestration were also performed.

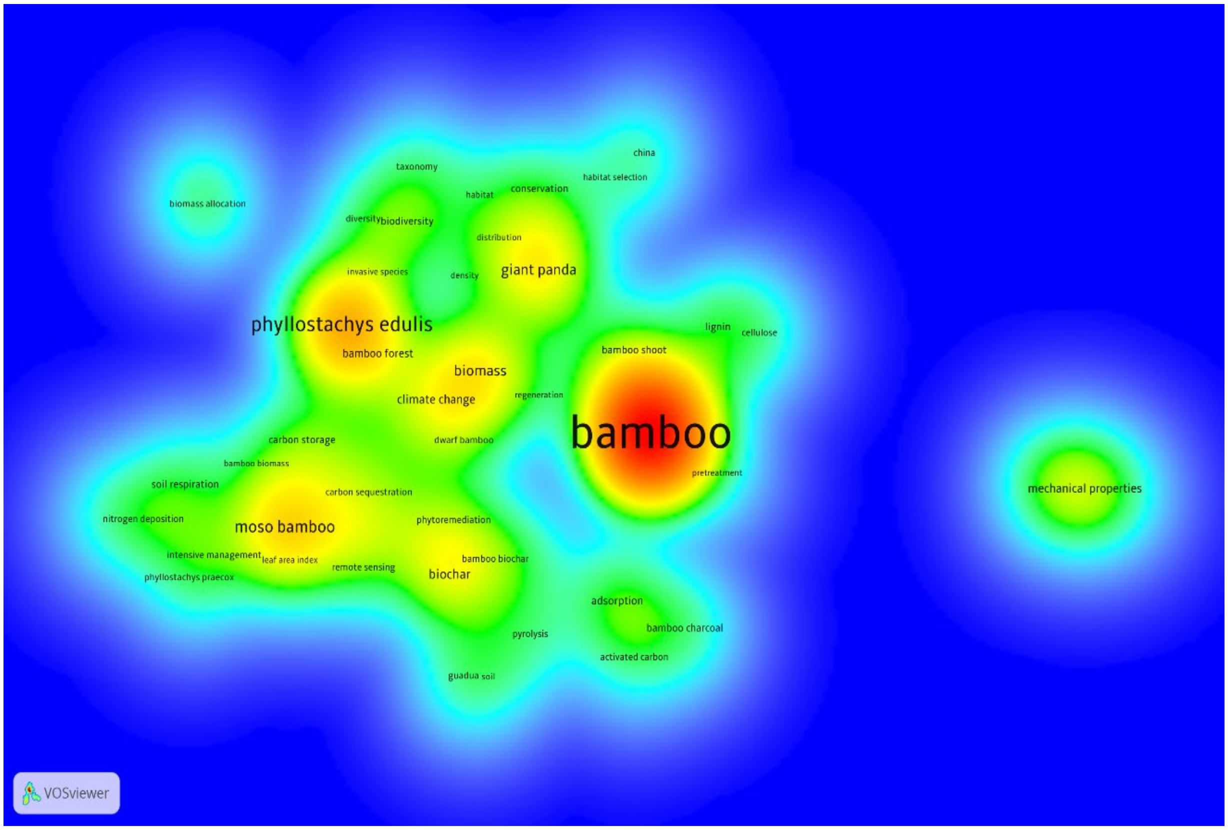

Fig. 3. VOS based keyword density visualization map

TRADITIONAL FIELD OF BAMBOO APPLICATION

Bamboo plays an essential role in many Asian societies. It has been used in multiple applications for a long period of time. Some of the conventional uses of bamboo are handicraft items, pulp for the paper industry, food, and medicine. Bamboo is also popularly used for building and construction purposes globally.

Construction Industry

Compared to steel, concrete, and timber, the more miniature bamboo can withstand greater loads. The density of solid bamboo culm is in the range of 700 to 800 kg/m^3. Thus, the culm can be used to produce strong panels and boards. The bending stress at failure is also 0.14 times mass per unit volume. Therefore it exhibits greater strength of bending failure. The tensile strength of *D. giganteus* and *B. vulgaris* bamboo species is as high as 135 and 170 MPa, respectively. The ability of bamboo to replace steel in the construction industry follows from the fact that the reinforcement of bamboo in the concrete led to an increase of 400% in the ultimate load applied (Ghavami 1995). Flooring, ceiling, walls, windows, doors, fences, housing roofs, trusses, rafters, and purlins can be made of bamboo (Yadav and Mathur 2021) As a structural material, it can be used to build bridges, boats, and skyscrapers scaffoldings. Bamboo-based buildings are eco-friendly, as they show insulation properties and consume less energy than conventional building materials (Lobovikov *et al.* 2007).

Pulp and Paper Industry

Three types of materials, namely wood, non-wood, and recovered paper, can be used to prepare the pulp. Bamboo is one of the primary materials used to prepare pulp and paper in India and China (Chen *et al.* 2011). It has more suitable chemical composition for such applications than other non-woody raw materials, including wheat straw, rice straw, and bagasse. Also, because of higher production capacity of fiber equivalent to hardwood in terms of fiber length, aspect ratio, and fibrous cell wall cavity ratio, bamboo is a preferable raw material for making pulp and paper. In China, the total production of bamboo pulp was 2,400,000 tons in 2017 alone. Chinese government further supports many bamboo-based plantation and storage drives to reach the annual production capacity of $1\text{x}10^6$ tons soon (Chen *et al.* 2011) As bamboo fiber is thin and long, it can be used to make a variety of papers such as writing, printing, and wrapping paper.

Table 1 shows that the maximum fiber length of bamboo pulp is suitable for the pulp and industry. The value of the rigidity coefficient is the ratio of the cell wall thickness ratio to the fiber diameter. A higher coefficient leads to less stiffness of the tensile strength of the paper (Sugesty *et al.* 2015).

Table 1. Properties of Bamboo Fiber (Sugesty *et al.* 2015).

S.No	Property	Bamboo (*Gigantochloa apus*)
1	Maximum fiber length (mm)	4.89
2	Minimum fiber length (mm)	1.20
3	Average fiber length (mm)	2.34
4	Outer diameter (µm)	14.54
5	Rigidity	0.29
6	Flexibility	0.42

Food

Bamboos are an indispensable part of the lives of rural people, especially in northeast India, as well as South-East and East Asian countries. Bamboo shoots contain high vitamins, carbohydrates, minerals, and proteins and provide nourishment to people at a meager cost (Singhal *et al.* 2013). Bamboo leaves and shoots are known for their nutritional properties. Researchers have reviewed the properties of bamboo leaves, and shoots (Nirmala *et al.* 2018). Various new products, including bamboo-based nuggets, crackers, chutneys, candies, chips, and buns, attract consumer's attention. In addition, bamboo leaves are used to feed cattle, pandas, and many birds during the dry season (Scurlock *et al.* 2000).

Medicines

Bamboo is a potential source of various bioactive compounds and antioxidants such as phenols, vitamins C & E, and trace minerals including selenium, copper, zinc, and iron. Such components allows bamboo to serve as a part of traditional medicines in various Asian countries. In Bangladesh, Tabasheer and Sitopaladi churna contain powder from bamboo nodes and are recommended to treat cold, cough, congestion, and sinus. Likewise, traditional Chinese medicine is made with Chenjin Wan, Gualou Zhishi Tang, and Jupi Zhuru Tang bamboo shavings. Meanwhile, Qinggong Tang and Zhuye Shigao Tang contain bamboo leaf powder for fever, cough, insomnia, and restlessness (Benjamin *et al.* 2021).

In India, while paste from *B. arundinacea* leaves is applied on fractured bones, decoction from its roots is used to treat kidney stones. Seeds of *B. bambos* are used for rheumatism treatment. In Malaysia, young shoots of *Bambusa* sp. are boiled and taken orally as a postpartum diet. Stems of *B. vulgaris* are given to trallergiesergy in the Philippines. *B. bambos* leaves are taken to treat constipation in Thailand, showing multiple medicinal uses of different parts of bamboo across Asia (Benjamin *et al.* 2021). Like Asian countries, Brazilian bamboo species were also investigated and exhibited antibacterial activity (Anselmo-Moreira *et al.* 2021). Scientific investigations have demonstrated the efficacy of various bamboo parts in treating chronic and cardiovascular diseases. Alzheimer's disease, Parkinson's disease, diabetes, and cancer can be cured using bamboo leaves, shoots, and other parts (Nirmala *et al.* 2018).

Handicraft

Bamboo can be split and processed using simple tools. It does not require any special skills or training to prepare simple crafts using bamboo. As it is readily available, producing and processing bamboo is affordable. It finds application in making household products such as handicraft items, tables, chairs, chopsticks, mats, poles, agricultural instruments, fishing tools, and musical instruments, *etc.* (Mohan *et al.* 2022).

EMERGING APPLICATIONS OF BAMBOO

Energy

Bamboo is a sustainable resource for biomass to generate bio-energy. A growing tree of bamboo sequesters CO_2 from the air and adds more cellulosic fiber at a fast rate. The bamboo plant is an effective carbon sink, meaning that it effectively mitigates the greenhouse effect (Banik 2000). As a high growth rate grass, its annual biomass generation capacity of 40 tonnes per hectare is much higher than that of timber. Both direct burning and gasification are practiced to create energy from bamboo. The power of 1 kWh of electricity can be produced from 1.2 kg of bamboo, which is equivalent to wood and better than other powdered agro-residues such as sawdust or peanut, coffee, and rice husk (Sharma *et al.* 2018). In addition, waste bamboo can be converted into several important by-products in a biorefinery. In particular, carbon-based bamboo products such as biochar, activated carbon, and charcoal are already creating niche markets in the health sector. By heating bamboo in the absence of air, the generation of liquid bio-oil, gaseous fuels, and bamboo charcoal is obtained as a by-product. The received product's yield and quality vary depending on the kiln's temperature, type of reactor used, and reaction conditions maintained. Lower temperature leads to an enormous amount of bamboo charcoal that can further be used as fuel.

Bamboo species having low ash and alkali content are suitable for biofuel production. Also, it has a lower heating value than other woody plants (Scurlock *et al.* 2000) The heating of any biomass to high temperature (300 to 900 ºC) in specially designed reactors can lead to the generation of three types of fuels, *i.e.*, solid (charcoal), liquid (bio-oil), and gaseous (syn-gas). While the temperature between 300 to 500 °C is suitable for the production of biochar, a medium-range temperature up to 700 °C is suitable for bio-oil production (Kaur *et al.* 2021). At temperatures above this, syn-gas can be obtained as the main product. Bio-oil is transportable and storable and a potential source of several valuable chemicals. Bamboo biomass can be used to produce bio-oil and as a promising alternative for oil-derived chemicals because of its wide availability and renewability. Wang *et al.* (2013) reported that it is challenging to convert bamboo biomass to bio-oil because bamboo is complex and needs pre-treatment processing. Isolating and purifying single products is difficult due to the complexities of bio-oil mixtures. At high temperatures (>700 °C), bamboo biomass is treated to produce syn-gas, a combination of carbon dioxide, methane, carbon monoxide, hydrogen, *etc.* (Wang *et al.* 2013).

Biochar

Activated carbon is known for its high adsorption capacity, porosity, thermal stability, and many active functional groups, which can act as a shield to protect the environment and human health.

Table 2. Comparison of Surface Area of Bamboo and Other Materials

Raw Material	Activation Process	Surface Area (m^2/g)	References
Bamboo chips	N_2 and $KHCO_3$	1693	(Li *et al.* 2020b)
Bamboo chips	KOH	720.69	(Jawad and Abdulhameed 2020)
Malaysian Selantik coal	KOH	1094.3	(Jawad *et al.* 2019)
Wood	KOH	167.8	(Danish *et al.* 2018)
Pineapple peels	K2CO3	680	(Foo and Hameed 2012)
Rice husk	KOH	752	(Foo and Hameed 2011)

The non-renewability and the high cost of conventionally used raw materials such as coal and petroleum coke make it expensive and non-eco-friendly to manufacture and use them. Thus, researchers are exploring non-expensive raw materials, including sawdust, agro-residue, like bagasse, rice husk, coconut husk, industrial waste (fly ash), chitosan, and peat, *etc*., as raw materials for the production of carbon-based adsorbents. Suitable reaction conditions can produce a sufficiently large surface area of 2123 m^2 /g (Ip *et al.* 2008).

Biochar produced using pyrolysis has a lower surface area. Using physical as well as chemical activations surface area of biochar can be greatly increased. As shown in Table 2, bamboo biochar (BC) is an excellent precursor for activated carbon. Different alkali chemical agents like KOH and NaOH can be applied to enhance surface functionality and negativity. Phosphoric acid (H_3PO_4), hydrogen peroxide (H_2O_2), and potassium carbonate (K_2CO_3) upgrade pore structure providing more active surface binding sites to the biochar (Shahib *et al.* 2022). Activated bamboo biochar can display a significantly higher surface area than wood charcoal and is effective for adsorption of pollutants due to its improved texture. Bamboo can be used to make green adsorbents by different methods with fine porous structure, more surface functional groups, larger specific surface area, and mineral components to perform a greater degree of adsorption than other adsorbents.

Studies on the optimization of process parameters to produce biochar of suitable properties have been conducted by different researchers. Sahoo *et al.* (2021) reported that by pyrolysis of 1 kg of bamboo biomass and pigeon stalk biomass in the range from 400 to 600 °C, biochar is produced in holding time and heating rate of 1 h and 13°C/min, respectively (Sahoo *et al.* 2021). It has shown that bamboo biomass had more cellulose, hemicellulose, and mass fraction of lignin than the agro-residue of pigeon pea stalk. Studies have revealed that black charcoal yield obtained at 700 and 850 °C carbonation temperatures have ranged from 27 to 33% with maximum pore distribution, strength, bulk density, density, and hydrophobic nature (DS *et al.* 2020b). Black charcoal obtained has about four times more cavities and adsorption rate, which may be used as adsorbents for removing carbon in the flue gas. A thermochemical process, slow pyrolysis, can be used for alternative traditional kilns, which release enormous gases to produce charcoal. In a fixed bed pyrolysis reactor by slow pyrolysis, 200 g of bamboo particles of *Dendrocalamus giganteus* of 5 years of age were heated in the temperature range from 300 to 600°C at the rate of 10 °C/min. Slow heating led to a higher char yield of 80% attained at 300 °C (Hernandez-Mena *et al.* 2014).

After processing, BC can be used as an ideal green adsorbent, depending on its specific properties. It can readily adsorb pollutants including harmful gases and radioactive materials, *etc.*, from the air. Likewise, dye, heavy metal ions, pesticides, nitrogen in fertilizers, *etc*., can be adsorbed from water to be used multiple times.

Dye pollutants removal

Industries such as paper mills, leather, food, pharmaceutical, textiles, and cosmetic sectors discharge dye-containing effluents, increasing the overall loading of chemical oxygen demand (COD), making the water unsuitable to use. Literature studies have shown that BC adsorbed different pollutant dyes efficiently. Reactive dyes are extensively used in the textile industry for its bright colors and dazzling shades. These dyes have many applications. However, their high solubility and poor biodegradable nature creates concerns about health and the ecosystem. The ultrasound technique was investigated to produce biochar of larger pore size and surface area. It increased biochar's surface area and pore volume from 56.3 to 141.2 m^2/g and 0.013 to 0.039 cm^3, which showed its highest adsorption capacity of 3.49 mg/g (Nguyen 2021).

Methylene blue is a cationic dye with an aromatic structure used in the printing and dyeing industries. Methylene blue dye displays poor biodegradability, and high chromaticity. Activated carbon with negative surface charges is found to be attracted to positively charged methylene blue dyes (Kuang *et al.* 2020). For instance, methylene blue dye (499 mg/g) got adsorbed by nitrogen-doped BC biochar modified using $KHCO_3$ (Li *et al.* 2020). G*igantochloa robusta* Kurz bamboo was pyrolyzed to 400 °C for 4 hours, and activated using KOH solution to result in an optimum methylene blue removal by 99.8% in 120 minutes of reaction. Table 3 shows BC's high dye removal efficiency compared to other waste materials.

Heavy metals pollutants removal

Contaminants such as heavy metals (Pb, Cu, Cd, Zn, *etc.*) resulting from industries in wastewater can cause harmful effects on humankind and the environment. BC's high surface area and positive charges facilitate the adsorption of various anions (*e.g*., $Cr_2O_7^{2-}$, CrO_4^{2-}, NO_3^{-}, and PO_4^{2-}) and oxygen-containing functional groups on its surface adsorb cations (*e.g*. Cu^{2+}, Cd^{2+}, Pb^{2+}, and Ni^{2+}). Chu (2019) studied the adsorption of Cd (II) and Cr (VI) simultaneously by bamboo-based oxidized biochar. The bamboo-based biochar was prepared by modifying moso bamboo with $ZnCl_2$ and pyrolysis at 500 °C. The prepared biochar was oxidized with $(NH_4)_2S_2O_8$ solution to obtain oxygen-containing functional groups. The highest adsorption capacities of the oxidized biochar for Cr(VI) and Cd (II) were 33.8 and 30.3 mg/g, respectively (Chu *et al.* 2019). Removal of heavy metals such as mercury can be achieved using biochar from different sources, including bamboo, coconut shell, and sugarcane bagasse, resulting in adsorption capacities up to 31.0, 11.5, and 15.2 mg/g, respectively (Goel 2004; Giraldo 2020).

Table 3. Methylene Dye Removal using Biochar from Different Sources

Source of Biochar	Modifier	Adsorption Capacity (mg/gm)	Reference
Bamboo	urea, $KHCO_3$	499	(Li *et al.* 2020b)
Cottonwood	Graphene	174	(Zhang *et al.* 2012)
AC/Palygorskite	$ZnCl_2$	351	(Zhang *et al.* 2012)
Date core	$ZnCl_2$	455	(Mahmoudi *et al.* 2015)
Corn stalks	200 $ml \cdot min^{-1}$ NH_3	436	(Lian *et al.* 2016)

Gaseous pollutants removal

The concentrations of greenhouse gases such as carbon dioxide, methane, nitrous oxide, chlorofluorocarbons, and ozone in the atmosphere have been increasing, leading to global warming, rising sea levels, and ecosystem imbalance, threatening the existence of many organisms. Substantial research has been carried out to find suitable low-cost technologies to capture gaseous pollutants and preserve the environment.

Table 4. Adsorption Capacity of Various Pollutants by Modified Bamboo Biochar

Adsorbents	Modified	Pollutants	Maximum Adsorption Capacity	References
Water bamboo *(Zizania latifolia)*	Ultrasonic irradiation	Reactive Black 5	3.49 mg/g	(Nguyen *et al.* 2021)
Bamboo biochar	-	Rhodamine B	0.638 mg/g	(Alcântara *et al.* 2016)
Bamboo shoot shell	Hydrothermal carbonization	Rhodamine b	85.8 mg/g	(Hou *et al.* 2019)
Mayan bamboo *(Giganchlotoa robusta Kurz)*	KOH	Methylene blue		(Efiyanti *et al.* 2020)
Moso bamboo *(Phyllostachys edulis)*	-	Methylene blue	1667 mg/g	(Ma *et al.* 2019)
Waste bamboo scaffolding	-	Methylene blue	0.99 mmol/g	(Mui *et al.* 2008)
bamboo biochar	H_3PO_4	Yellow 161dye	2.401 mg/g	(Wang and Yan 2011)
Moso bamboo	$ZnCl_2$	Cd(II)	30.3 mg/g	(Chu *et al.* 2019)
Moso bamboo	$ZnCl_2$	Cr (VI)	33.8 mg/g	(Chu *et al.* 2019)
bamboo leaf	-	Hg (II)	27.11mg/g	(Mondal *et al.* 2013)
bamboo leaf	Triton X-100	Hg (II)	28.1mg/g	(Mondal *et al.* 2013)
bamboo leaf	Sodium dodecyl sulphate	Hg (II)	31.05 mg/g	(Mondal *et al.* 2013)
Moso bamboo	-	CO_2	78.64 mg/g	(Wang *et al.* 2008)

The Intergovernmental Panel on Climate Change (IPCC) has mentioned that the adsorption of contaminants using carbon-based porous materials such as biochar is one such potential technology. Adsorption using activated charcoal has its advantages and limitations. Capturing noxious pollutants such as CO_2 using inexpensive waste biomass-based adsorbents with high recyclability has been anticipated to be a sustainable technology to improve environmental conditions (Metz Bert *et al.* 2005).

Huang (2014) reported moso bamboo carbonized temperatures of 600, 700, 800, 900, and 1000 °C with nitrogen gas used as the carrier gas at a constant flow rate (300 mL/min) for comparing the quality of bamboo charcoal (Huang *et al.* 2014). Treatments at 600 and 1000 °C produced the highest (32.2%) and lowest (27.4%) average charcoal yields. The highest adsorption of 78.6 mg/g was obtained at a carbonization temperature of 1000 °C. As shown in Table 4, the adsorption capacity of bamboo is sufficiently high to utilize waste bamboo for detoxification purposes.

Medicinal applications

Bamboo biochar is biodegradable, biocompatible, low cytotoxic, non-toxic, hard, thermally stable, emits far-infrared rays, and is highly oxidation preventive. These advantages motivated researchers to produce various composites to be used in biomedicines (Li *et al.* 2020a; Zhang *et al.* 2022).

Research work on BC-based composites for biomedical applications has shown encouraging results. Studies on the biocompatibility of BC and ultra-high molecular weight polyethylene (UHMWPE) were tested for biocompatibility by using seeds of fibroblasts and were observed for two days. Survival of all cells for this period indicates the safety of BC for biomedical applications. BC/UHMWPE composite showed a low friction coefficient, high protein adhesion, and high cell proliferation because of BC's high hydrophilicity and specific surface energy (Li *et al.* 2020a).

A high level of bilirubin in blood causes a disease known as hyperbilirubinemia. In hyperbilirubinemia patients, a high level of albumin is found in the blood, and it can act as a toxic substance (Hsieh *et al.* 2007). During blood detoxification, chitosan-BC beads averted the probability of liberation of minute particles (Khandegar *et al.* 2021; Suri *et al.* 2021). A homogenous composition was formed between BC and chitosan. The activated carbon of BC may contain large pores. These pores were found to act as adsorbent sites for bilirubin when exposed to plasma. Blood toxin removal by activated carbon depends on the surface area of the adsorbent. Bamboo charcoal beads provide a large surface area for the adsorption of toxic materials. During the pulverization of natural bamboo, the size distribution and pore geometry disintegrate. BC didn't damage any of the macrophage cells. They were independent of the size of BC particles or their doses.

Oxidative treatment was given to BC to enhance its hydrophilicity. Also, its mechanical properties were observed by researchers (Nitayaphat *et al.* 2009). The composite contained both chitosan with nitric acid-modified BC and unmodified BC. Many pores in BC make it an excellent source for infrared rays adsorption. It was observed that chitosan-modified BC (1% w/w) showed better tensile strength than chitosan-unmodified BC. An increase in the hydrophilic nature of BC was reported, resulting in more adsorption of water. This composite was suggested to be applied to remove toxins in the blood.

Bamboo vinegar produced during pyrolysis of bamboo also influences growth hormones. The study done by Chu *et al.* (2013) used a mixture of BC and bamboo vinegar given as the basal diet for the swine population. Although the concentrations of cholesterol, triglyceride, low-density lipoprotein cholesterol, high-density lipoprotein cholesterol, and total protein were not affected by this diet, blood urea nitrogen, low-density lipoprotein, and cortisol were crucially affected (Chu *et al.* 2013). Immunoglobulin G and IgA levels were also affected by the addition of BC in a diet showing a high amount, but the BC didn't affect immunoglobulin M level. The study highlighted the potential of BC and bamboo vinegar as a replacement for commercial antibiotics to increase bacterial protection and reduce stress in animals.

Ciprofloxacin belongs to a group of antibiotics known as fluoroquinolones that are used to treat bacterial infections such as conjunctivitis, ear infection, and chest infections (Wang *et al.* 2015). Bamboo waste was impregnated in phosphoric acid, followed by a carbonization process to prepare BC. The obtained bio-char was washed and dried, followed by impregnation in potassium carbonate. At 25°C, the kinetic properties and adsorption equilibrium on bamboo-based activated carbon of ciprofloxacin were determined. Impregnation of BC in phosphoric acid resulted in microporosity in activated carbon. Hydrolysis of lignocellulosic acid was caused by phosphoric acid. This causes biomaterial swelling, resulting in mesopore formation. At 750 °C, the specific surface area of bamboo-based activated carbon attained a maximum value (2125 m^2/g).

Bamboo charcoal beads coated with chitosan, a linear polysaccharide, non-toxic, biodegradable polymer, were invested for pharmaceutical applications. Poly(methacrylate) (PMAA) was used to coat activated carbon. A chemotherapeutic drug called doxorubicin can be adsorbed by chitosan, poly(methacrylate) (PMAA), and BC (Caminos-Peruelo *et al.* 2017). Moso bamboo species were used to extract BC, then combined with chitosan and PMAA to produce BC beads. Direct use of BC for haemoperfusion (filtration of blood outside the body to remove toxins) could lead to emboli (air bubbles or blood clots) in blood vessels. Thus, a coating BC by chitosan was incorporated. Also, PMAA and chitosan coating on BC led to enhanced hydrophilic properties. The composite bead (surface area: 681 m^2g^{-1}) successfully adsorbed polar compound creatinine (15%) from the contaminated aqueous solution. (Caminos-Peruelo *et al.* 2017; Khandegar *et al.* 2021; Suri *et al.* 2021).

Ankle injury comprises approximately 10% of all sports injuries. A nano-TiO_2 modified BC was used to make ankle guard material (Lu *et al.* 2021). The hydroxyl ions were released by exposing TiO_2 to light, which resulted in the denaturation of their protein components. Gradual recovery in pain and swelling symptoms was observed by using a nano BC ankle guard. Also, nano-BC particles could absorb all moisture, keeping ankle lesions dried and breathable. Far-infrared wavelength was followed by BC ankle guard, which maintained heat on the concerned area, promoting blood circulation, dilating skin capillary, relieving pain, dissipating congestion, and promoting the recovery of ankle joint function.

Drug delivery in chemotherapy

Many of the safe and effective anti-cancerous drugs are not used commercially due to their poor aqueous solubility and lower bioavailability, limiting tissue distribution and half-life. To further improve the therapeutic effect of these compounds, bamboo charcoal of size in nano-scale (BCNP) with a large surface area (surface area: 348 m^2/g) for drug absorption was explored. Bamboo is non-toxic, highly porous (increases drug delivery capacity), relatively cheap, and possesses a high photothermal efficiency (Dong *et al.* 2016). For combined photothermal therapy (PTT) and tumor chemotherapy, BCNP was used as a drug carrier for the chemotherapeutic drug doxorubicin (DOX). Studies have shown that the drug resistance against MCF-7 cancer cells and drug potency was enhanced as cellular uptake was promoted. The small size of BCNP and its mesoporous structure favored drug delivery demand. BCNP was found to be an effective and promising nano-carrier for drug delivery in chemotherapy.

Curcumin (found in turmeric) was loaded on BCNP by Xie (2017) to observe its antitumor effects in chemotherapy. TPGS (a water-soluble derivative of vitamin E) and BCNP with curcumin were used as reactive oxygen species (ROS) scavengers for radioprotection. TPGS-BCNP was found to possess a high photothermal effect. The drug delivery method was studied by drenching TPGS-BCNP in curcumin solution. After centrifugation of TPGS-BCNPS, the color change of curcumin from yellow to colorless indicates its loading on TPGS-BCNP. The amount of curcumin released without near infrared (NIR) irradiation in 80 min was 17.6% (Xie *et al.* 2017).

In contrast, 61.2% of curcumin was released from TPGS-BCNP under NIR irradiation. The anticancer effect was attained by treatment of TPGS-BCNP +curcumin + NIR. Curcumin bioavailability was increased, leading to improvement in therapeutic effect. Treated mice showed complete tumor eradication and 99.8% of tumor growth inhibition with no reappearance of cancer.

Table 5. Enhanced Surface Properties of Modified Bamboo Charcoal Nanocomposites

Composite	Plasma Treatment	Surface Area BET (m^2/g)	Pore Volume (cm^3/g)	References
BC/Ag	Untreated	169	-	Bardhan 2014
BC/Ag	Untreated	171	0.07	Fu *et al.* 2009
BC/Ag	Untreated	171	-	Fu *et al.* 2009
BC/Ag	BC	870	0.44	Vignesh 2015
	Untreated BC/Ag	966	0.48	
	BC/Ag - Air plasma treatment	970	0.49	
	BC/Ag oxygen plasma treatment	992	0.52	
BC/ZnO	Untreated BC/ZnO	956	0.47	Vignesh 2016
	BC/ZnO - Air plasma treatment	975	0.49	
	BC/Zn- Oxygen plasma treatment	973	0.48	
BC/TiO_2	Untreated BC/TiO_2	631	0.52	Vignesh 2016
	BC/TiO_2 - Air plasma treatment	401	0.58	
	BC/TiO_2- Oxygen plasma treatment	265	-	
BC/ZnO/ TiO_2	Untreated BC/ZnO/TiO2	1020	0.51	Vignesh 2016
	BC/ZnO/TiO2 - Air plasma treatment	1035	0.52	
	BC/Zn/TiO2- Oxygen plasma treatment	1037	0.53	
BC/ Chitosan	Untreated	659	-	Caminos-Peruelo 2017
BC/ Chitosan/ PMAA	Untreated	681	-	

Safety evaluation results revealed low toxicity and good biocompatibility. Also, a well-built free radical scavenging ability was observed, which could be utilized for radiation protection in healthy tissue.

Specific applications of bamboo charcoal composites

Bamboo biochar (BC) on loading with other nanoparticles such as silver helped enhance their medicinal properties. BC/Ag composite prepared by chemical reduction was evaluated for its antibacterial activity against the gram-negative pathogen (*E. coli*) and gram-positive bacteria (*S. aureus* and *B. subtilis*). A good bonding was observed between BC and silver nanoparticles, resulting in a high zone of inhibition with the destruction of all pathogens. BC-Ag composite was tested on textile fiber, and it was found to be an excellent source of antibacterial fabrics (Yang *et al.* 2009).

Table 6. Anti-pathogen Activity of Bamboo Biochar Nanocomposites

Pathogen	Composite	Treatment	Minimum Inhibitory Composition	Zone Inhibition	References
S. aureus	BC/Ag	-	0.3	14.4	(Bardhan *et al.* 2014; Vignesh *et al.* 2016; Yang *et al.* 2009)
	BC/Ag	-	1	23.3	
	BC/Ag	-	<0.4	14±0.2	
	BC/Ag	-	-	11.1 to 20.3	
	BC/TiO_2	-	-	19	
	BC/TiO_2	Air plasma treatment (Jia *et al.* 2022)	-	19	
	BC/TiO_2	Oxygen plasma treat.	-	20	
P. aeruginosa	BC/Ag	-	0.3	22.2	(Bardhan *et al.* 2014; Vignesh *et al.* 2016; Yang *et al.* 2009)
	BC/Ag	-	0.3	14.6	
	BC/Ag	-	4,000	13±0.2	
	BC/Ag	-	-	11.1 to 20.3	
	BC/TiO_2	-	-	16	
	BC/TiO_2	Air plasma treatment	-	17	
	BC/TiO_2	Oxygen plasma treat.	-	19	
E. coli	BC/Ag	-	0.3	13.3	(Bardhan *et al.* 2014; Vignesh *et al.* 2016; Yang *et al.* 2009)
	BC/Ag	-	-	11.1 to 20.3	
	BC/TiO_2	-	-	18	
	BC/TiO_2	Air plasma treatment	-	18	
	BC/Ag	Oxygen plasma treat.	-	20	
K. pneumonia	BC/TiO_2	-	-	22	(Vignesh *et al.* 2016)
	BC/TiO_2	Air plasma treatment	-	23	
	BC/TiO_2	Oxygen plasma treat.	-	24	
S.mutants	BC/TiO_2	-	-	21	(Vignesh *et al.* 2016)
	BC/TiO_2	Air plasma treatment	-	21	
	BC/TiO_2	Oxygen plasma treat.	-	23	
E. coli	BC/Ag	-	0.3	14.0	(Yang *et al.* 2009)
E. coli	BC/Ag	-	-	22.1	(Yang *et al.* 2009)

B.subtilis	BC/Ag	-	-	21.1	(Yang *et al.* 2009)
S. aureus	BC/Ag	-	0.3	14.2	(Yang *et al.* 2009)
P. aeruginosa	BC/Ag	-	0.3	13.6	(Yang *et al.* 2009)
C. albicans	BC/Ag	-	-	20.3	(Yang *et al.* 2009)

As shown in Table 6, researchers have further used different modification techniques to enhance the antimicrobial activity of these composites. Plasma treatment was found to be an effective method for changing the surface property of BC-Ag nanocomposites (Vignesh *et al.* 2016).

A composite prepared using BC and silver to ameliorate the properties of silver nanoparticles was tested against pathogens (*P. aeruginosa, E. coli, S. aureus, P. putida*). It was observed that the antimicrobial effect depended on the amount of Ag^+ ions released. Ag acts as inert in its metallic state, but when exposed to moisture, it releases Ag^+ ions, leading to damage and mortality of the pathogen cell. Based on the diameter of the zone of inhibition, the antibacterial property of pathogens against BC-Ag composites was evaluated. It was found that all selected pathogens were inhibited by the treatment BC-Ag composite (Bardhan *et al.* 2014). Table 6 shows the anti-pathogenic activity of various BC nanocomposites.

Nanoparticle particles ($Ni_{0.5}Zn_{0.5}Fe_2O_4$ and silver) coated bamboo charcoal and showed a ferromagnetic effect (Wu *et al.* 2006). Researchers have performed UV absorption testing of bamboo fiber. It was found that the lignin component of bamboo is responsible for its UV absorption capacity. Various polar fluids such as water and ethanol extracted bamboo fibers exhibited high extraction ability and UV responsiveness. Extracted fibers are appropriate to be used in the textile industry to shield UV rays (Afrin *et al.* 2012).

Electromagnetic interference (EMI), consists of many unwanted radiated signals, threatening digital security and human health. Scholars are investigating the efficiency of various materials to block EMI and protect pieces of equipment in industries and defense. Presently, expensive metals, including aluminum and copper, are used for EMI shielding, and these have additional corrosivity problems (Jia *et al.* 2022). Lignocellulosic materials obtained from bamboo have been investigated for electromagnetic wave absorption capacity and were found to have a reflection loss of only 50.05 dB. This shows bamboo's excellent electromagnetic wave absorption property (Cai *et al.* 2022).

As a green adsorbent, castor oil-based polyurethane foam was reinforced with multi-walled carbon nanotube (0.75 wt%), cupric oxide (1.5 wt%), and BC (1.5 wt%). Researchers produced BC-based composite foam (density: 0.063750 g/cm^3) with excellent EMI shielding effectiveness of 27.08 dB at 8 to 12 GHz frequency. The results of this study are promising for the development of BC-based composite foams as a suitable substitute for metal in radio and satellite communication systems (Subramanian *et al.* 2021).

ROLE OF BAMBOO IN CIRCULAR ECONOMY

Literature analysis highlights the abundance of bamboo, with many species present in almost all continents. Globally, the bamboo forest is spread over 36 million hectares (MHa), nearly 0.92% of the world's total forest area (Lobovikov *et al.* 2007). China, European countries, Indonesia, and Vietnam are among the biggest exporters of bamboo (INBAR 2017). Bamboo grows successfully in Africa, Asia, and Central and South America, Europe, and North America (Soderstrom and Ellis 1988; Banik 2000). The abundance of availability of bamboo at low cost with flexible properties and numerous species makes it a material of choice for diversified fields of applications. Based on an environmental assessment of bamboo compared to steel, timber, and concrete, bamboo culm has been found to be 20 times more sustainable than others (van der Lugt *et al.* 2006). The carbon storage potential of one tonne of bamboo is around 140 kg higher than the same amount of wood (Xu *et al.* 2022).

The conventionally used linear economy in various business models is based on the use, throw, and waste model. However, the sustainability paradigm is based on the hypothesis of a circular economy, where there is a closed-loop system. Every part of the life-cycle of a product should be used, leading to zero waste. Resources consumed should ultimately return to nature. Bamboo-based products are biodegradable and are sustainable to be included in the circular economy cycle. The culm has a fast growth rate to allow new culm to grow while one is in use and can replace abiotic materials multiple times.

Bamboo can be integrated into the circular economy context when every bamboo product should also follow a closed-loop system, producing no waste at the end of the life cycle of any bamboo product. There are a few exemplary case studies in which the successful implementation of a circular economy in bamboo-based enterprises has been considered. For instance, in Canada, waste bamboo chopsticks on compression are bound using resin and are converted into high-end home decoration items and furniture. The company has claimed to recycle about 49.6 million chopsticks with a carbon storage potential of about 68,000 kg (https://chopvalue.com/). Figure 4 shows an example from a Chinese company where bamboo plants were grown to make furniture and floor panels and provide food to farm animals. Waste culms from the sector were further sent to separate lignin and cellulose. While lignin was fed to the ceramic and dye industries, cellulose was sent to the paper industry. The sawdust collected from all these operations was used to produce 40,000 tonnes of activated carbon annually. By-products of this process were bamboo vinegar and bamboo tar. All the left-over waste was mixed with agro-residue to make pellets to provide energy to industries. The overall process is based on the zero-waste model and is an excellent example of the bamboo industry as environmentally-begin, sustainable and circular economically (van der Lugt and King 2019).

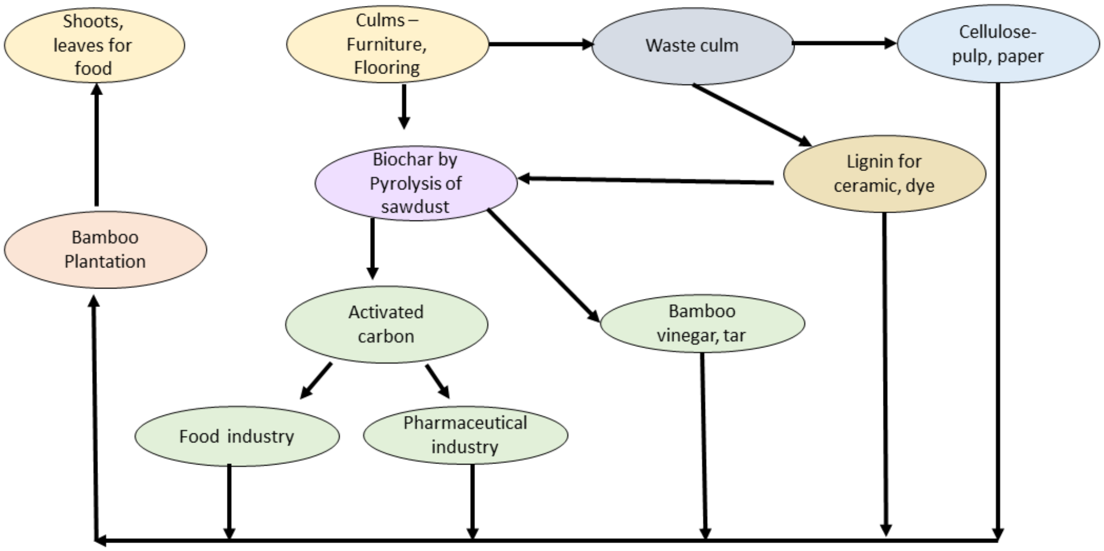

Fig. 4. Use of bamboo in the furniture industry as a part of the circular economy

Bamboo is used globally for traditional and modern engineering applications, leading to the generation of a large amount of waste biomass with unique properties that can be used for multiple applications, including food, pharmaceutical, and environmental remediation. Abundance, low cost, and ecological footprints associated with the usage of bamboo make it a sustainable and environment-friendly alternative as a raw material for numerous applications. Life-cycle analysis studies manifest the carbon neutrality of the bamboo plywood industry (Mohan *et al.* 2022).

The impact of bamboo on 2.5 billion people with an international trade value of 68.8 billion USD in 2018 shows its importance from an economic perspective. Bamboo has been considered an industrial material since the early 1990s in many countries, especially India, China, and Indonesia (Lobovikov *et al.* 2007). International organizations, including INBAR have emphasized bamboo's immense potential to lead rural industrialization and generate large-scale employment (Charlotte and Wu 2021).

Figure 5 presents an overview of the consumption of bamboo forest for multiple products, including food, fodder, furniture, pulp, incense sticks, briquettes, pulp, and paper products. Recovery of resources at every step can lead to the evolution of novel value-added by-products from waste bamboo via several treatment processes. The most crucial part is to perceive the biodegradability of all products obtained at all stages, which can go back to the soil on completion of their service life (van der Lugt and King 2019).

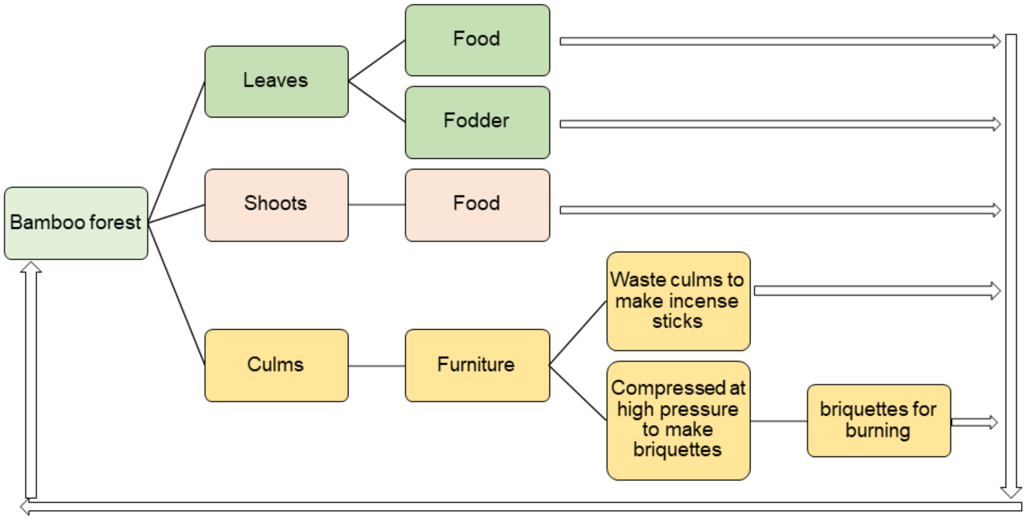

Fig. 5. Application of circular economy in bamboo forest

CHALLENGES

Based on the above analysis, the major strength, weaknesses, opportunities, and threats analyses are shown in Fig. 6.

Short Life Span

Bamboo's major constituents are lignin, cellulose, and starch. The minor constituents include resin, gums, and tannins (Kaur *et al.* 2016). The presence of starch makes it susceptible to attack by brown rot fungi such as *O. placenta*, white-rot fungi such as *T. versicolor*, pests, and subterranean termites, causing severe losses under storage conditions (Kaur *et al.* 2016c). There are specific traditional methods of bamboo preservation, including smoke treatment and water leaching in the water of flowing rivers (Kaur *et al.* 2016b).

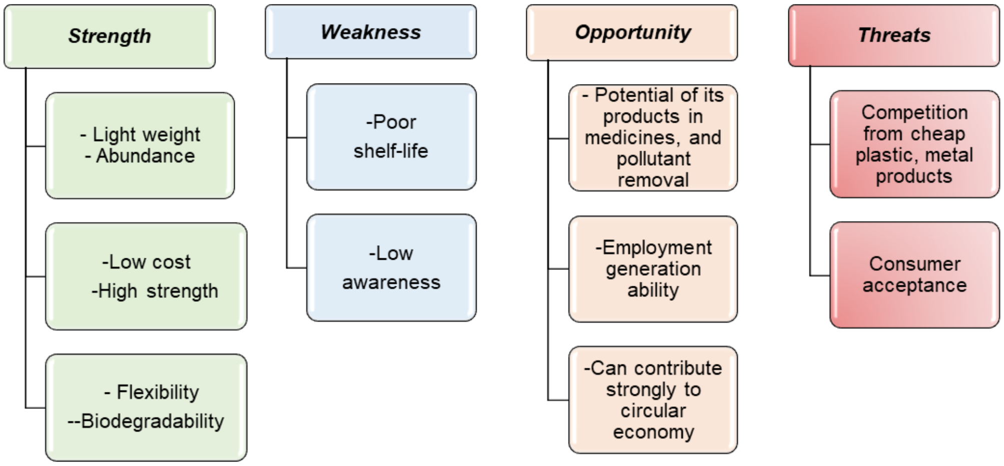

Fig. 6. SWOT analysis of bamboo and its products

These methods are safe but insufficient to provide long-term durability to the culm. Thus, chemicals such as CCA, boric acid, and CCB are used to treat the culms. The presence of toxic substances such as chromium and arsenic makes its usage hazardous for the artisans handling it (Kaur *et al.* n.d.). Boric acid is non-toxic, but there are problems related to its high solubility in water, such that it is not suited for outdoor usage. Research on various plant extract-based preservatives, including neem oil, cashew nut shell oil, and cedar oil, is underway (Kaur *et al.* 2016). Scale-up of studies on the same is lacking in the literature. As per Mehra and Mehra's reports (2007), although India shared 45% of the world's bamboo production, its share in the global market was only 4.5% due to the lack of post-harvest management and preservation techniques of bamboo culms (van der Lugt *et al.* 2006). Two principles of circular economy are maximum service life and minimum losses of product at every stage of the life-cycle, which needs serious consideration from the service-life of bamboo and its consequences in environmentally benign ways.

Difficulty to Standardize

Also, the literature suggests that the properties of bamboo vary with species. Even the same species grown in different climatic conditions exhibit variable properties. For instance, *D. strictus* species grown in India, *i.e.*, Haryana and Uttar Pradesh, differed significantly. A higher value of lignin content is related to the strength of bamboo culms. The lignin content of bamboo has been found to be comparable to wood. *B. pallida*, Bangalore and *D. strictus*, Gurgaon have the lowest and highest lignin content, respectively. Bamboo species with the lowest lignocellulose content in *B. arundinacea*, Allahabad, were most desirable for the pulp and paper industry. *B. pallida*, Bangalore, was the most susceptible to fungal attack. The study suggested using the lowest decay resistance and highest lignin content *D. strictus* bamboo species in the housing sector (Kaur *et al.* 2016a). Researchers have highlighted the difficulty of standardizing the process, as physicochemical properties vary globally. There is a need to address the species-specific application development for the industrial and large-scale application of engineered bamboo.

Working Challenges

Bamboo has a high elastic modulus, making it appropriate for building and construction as earthquake-resistant material. Though bamboo possesses tensile strength comparable to steel, owning its highly flexible vascular bundles, one significant limitation lies in its poor ability to create joints. While steel consumes 50 times higher energy, in concrete, bamboo reinforcement is six times stronger than steel. Howbeit, bamboo's failure in compression hinders its wider usage. The shrinkage of bamboo in loose soil needs suitable interventions (Mohan *et al.* 2022). Also, there is a need to perform studies on joints while designing bamboo wall panels (Lugt *et al.* 2006).

As research on bamboo’s subsections is increasing, new engineered products are being explored, and gluing of bamboo with other bamboo and wood is required. Waxy layers on bamboo, in addition to the impermeability of bamboo material, make it difficult to glue. Hydrophobicity of bamboo skins, coupled with a high amount of starch, silica, wax, and high specific gravity, pose obstruction for the penetration of adhesive and processing of bamboo and subsequently lead to poor bond formation. Special treatment techniques, such as chemical and steam, are required to improve bamboo’s bonding performance (Nkeuwa *et al.* 2022).

A significant impediment to implementing bamboo in buildings is the lack of standards and regulations, as the available measures for construction NTC2018 are valid for steel, wood, and concrete. Lately, International Organization on Standardization (ISO) has published a technical standard (ISO22156) that provides specific guidelines for building bamboo culms (Donini *et al.* 2022).

Consumer Acceptance

Bamboo has tremendous potential, and the sector possesses numerous opportunities to utilize every component of the bamboo product in the commercial market. It is an indispensable part of the socio-economic life of people, contributing to sustainable development and revenue and employment generation (Solomon *et al.* 2020). However, consumer's perception of bamboo as a “poor man's timber” or “invasive weed” detracts from its popular appeal. There is a lack of awareness about the usefulness and socio-economic benefits associated with bamboo-based products, which restricts their acceptance for high-end applications (Sarfo *et al.* 2017; Tambe *et al.* 2020). Due to these factors, cheap plastic and metal products can replace bamboo with ease (Gauli *et al.* 2018).

CONCLUSION AND FUTURE DIRECTION

The harmful effects of the linear economy based on unsustainable resource consumption, wastage, and product redundancy call for exploring renewable multi-facet biomass resources such as bamboo. Bamboo is a low-cost, abundantly available, eco-friendly bioresource that can be valorized into a diverse range of products from food, and handicrafts, to engineered high-end products such as biochar of specific properties. Every part of bamboo finds application in various applications, making it appropriate for the development of the circular economy. An overall zero-waste, closed-loop model for bamboo industries can pave the way for sustainable development.

The high amount of cellulose, hemicellulose, and lignin makes it a rich carbon source to generate biochar and bio-energy. By heating bamboo under controlled conditions in the absence of air, the generation of liquid bio-oil, gaseous fuels, and bamboo charcoal is obtained. The higher surface area of bamboo charcoal provides it was a higher adsorption capacity, *i.e.*, 613 mg/g.

Porous, structured bamboo-based charcoal allows the separation of solute from solvent and can be used to detoxify the air, water, and soil. The enhanced surface functional groups can be used in greenhouse gas-capturing applications, UV, microwave, and EMI shielding effects. Bamboo-based charcoal also has exceptional medicinal values and has tremendous potential for small and medium enterprises. It is expected that drug delivery based on non-toxic, biocompatible renewable BC may revolutionize the chemotherapy treatment for cancer patients.

However, the development of bamboo as an eco-friendly raw material for an industrial-scale application is characterized by various constraints. While bamboo's biodegradability on the one hand makes it eco-friendly, on the other hand, this reduces the shelf-life of its products and jeopardizes its usage as an advanced engineering material. As bamboo is susceptible to microbial and insect attacks, its shelf-life may be of concern. Chemical toxic preservatives could cause handling and disposal problem due to toxin constituents. The current usage pattern of commercial chemical preservatives has various ill effects on humans and the environment. The imperative is to explore alternative strategies that involve the valorization of eco-friendly treated bamboo species. There are additional constraints related to joints, bonding, and improving the compressive strength of bamboo culms.

There is an immediate need to address the issues of policy implementation or development of bamboo policy regulation on the universal understanding of the industrial perspective of bamboo to boost the country's economy (Okokpujie *et al.* 2020). Focused research on awareness generation will also lead to higher acceptability of bamboo substitutes for non-renewable resources. Following suitable global policy level interventions, a shift from a non-renewable linear economy towards a highly productive, zero-waste renewable circular society can be achieved. It is hoped that developing suitable policies for using bamboo as traditional material and a modern engineering material can help efficient biomass utilization, employment generation, and attainment of the global circular economy.

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