# Merits of Bamboo Utilization in Earth Preservation, Water, and Wastewater Treatment: A Mini Review

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## GRAPHICAL ABSTRACT

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This paper reviews the positive attributes and challenges of bamboo usage in carbon absorption, water, and wastewater purification. Bamboo can serve as a habitat for a variety of creatures and supports a diversified ecology. Bamboo roots can cast a fibrous net into the ground to prevent soil erosion and degradation. As the water passes through this woven mesh, the bamboo roots act as a filter, drawing toxins and other contaminants out of the water. Bamboo can treat wastewater effectively in free-water surface, horizontal flow, and vertical flow constructed wetlands. Bamboo charcoal has exceptional filtering properties for cleaner drinking water and better air quality. Additionally, bamboo can be used to form cellulose-based membranes. Bamboo is a renewable resource for creating paper, furniture, and building materials. Bamboo has various benefits. Thus, bamboo forests offer opportunities for rural communities to thrive economically.

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## INTRODUCTION

Bamboo belongs to the Poaceae grass family and Bambusoideae subfamily, comprising 1,662 species within 121 genera (Canavan *et al.* 2016). Some common bamboo species include *Bambusa vulgaris*, *B. tulsa*, *B. ventricosa*, *Dendro-calamus giganteus*, and *Phyllostachys nigra*. Bamboo is renowned as the tallest grass species due to its distinctive rhizome-dependent system. Bamboo's significant carbon absorption ability makes it a crucial element in the endeavor to mitigate climate change and reduce the greenhouse effect, thereby contributing to the preservation of the world and the restoration of the atmosphere (Bakri *et al.* 2021). Certain bamboo species have a remarkable growth rate, surpassing 91 cm (36 in) within 24 h. This is equivalent to an impressive growth rate of nearly 4 cm (1.6 in) every hour, which means around 1 mm every 90 seconds or 1 inch every 40 min. These extraordinary characteristics position bamboo as the most rapidly growing plant on earth. It is a renewable resource because it can be harvested with little environmental harm and regenerates quickly.

The advantages of bamboo and growing bamboo are listed in many journals, books, and websites (Atanda 2015; Emamverdian *et al*. 2020; Zeng *et al*. 2020). Bamboo is well known for its capacity to absorb carbon, purify the air, and indirectly create essential habitats for various plant and animal species. It can support a diverse ecosystem and help protect biodiversity (Nath *et al*. 2015; Emamverdian *et al*. 2020). Current technology makes it more advantageous to clean polluted water using bamboo (Wang *et al*. 2020; Kuok *et al*. 2022a; Lamaming *et al*. 2022). Bamboo's thick web of roots and rhizomes makes it successful in its growth and longevity (Kuok and Chiu 2018; Huang *et al*. 2022). Bamboo can also prevent erosion, purify water, and gain a tenacious footing in the underground matrix, which is part of the natural ecosystem in the forest (Goswami *et al*. 2022). The bamboo roots work as a filter, pulling toxins and other pollutants out of the water as they flow through this tightly woven mesh (Bambu Batu 2022). This is a straightforward, organic method of handling contaminated runoff or domestic grey water. Bamboo charcoal offers outstanding purifying qualities for cleaner drinking water and better air (Lamaming *et al*. 2022; Kuok *et al*. 2023).

The article explores the diverse components of bamboo, including culms, shoots, leaves, roots, and rhizomes, as well as its by-products. It delves into the significance of bamboo across various domains, such as its role in carbon absorption, erosion prevention, and its use in wastewater treatment through bamboo macrophytes and constructed wetlands. Additionally, it examines bamboo charcoal's efficacy in water purification and discusses the potential of bamboo-based membranes. The article concludes by summarizing the multifaceted applications of bamboo and its promising prospects in various fields.

## BAMBOO COMPONENTS

Bamboo, which is widely utilized in Asian construction, remains a niche material in Europe and the United States. China and India have their standards, *i.e*. Indian Standard (IS) and Chinese Standard (GB/T), which utilize the use of bamboo construction and building materials. In Europe and the United States bamboo recently has gained popularity for flooring, kitchen tops, and chopping boards. However, its structural use in these markets is limited, often involving treatment with heat and chemicals, due to a lack of standard codes provided by the agencies in both Europe and the United States. Still, bamboo possesses several attributes that contribute to its immense value and versatility, with strength and renewability as pivotal qualities. Each segment of bamboo serves distinct purposes, encompassing bamboo culms, bamboo shoots, bamboo leaves, bamboo roots, and various by-products.

### Bamboo Culms

Bamboo stems or culms are long, round, hollow, and woody poles with a strength-to-weight ratio greater than steel. It is the most useful part of bamboo, with a hardness superior to pine and comparable to oak. Bamboo is an adaptable and sustainable supply of wood that may be used for various tasks, including building a dome (Fig. 1), making furniture, and making paper (Kaur *et al*. 2022). Bamboo plants take about 6 or 7 years to reach maturity compared to 20 to 30 years for trees. The massive poles of Guadua and

Moso bamboo are ideal for construction and processing into engineered lumber for building shelters, boats, and scaffolding (Fig. 2.)

**Fig. 1.** Bamboo Dome for G20 Bali Summit (Abdel 2022)

**Fig. 2.** Bamboo scaffolding (Neumann 2020)

Larger bamboo poles can be transformed into more advanced applications such as floor panels, fiber panels, and other engineered timber, as presented in Fig. 3, that meet the requirements set by municipal building codes and similar regulations. The bamboo culm was split into small thickness culm, while the waste was cut into small strands (Fang *et al.* 2018). Some are flattened using a press machine. At the same time, the size and thickness depend on the bamboo species and design. The bamboo is glued or atomized using conventional resin, which is used in timber industries, *i.e.*, polyurethane, epoxy, etc., and pressed using a hot press. Bamboo is a sustainable substitute for wood in various applications, alleviating the intense strain on forests. To accomplish this, larger bamboo poles were divided into strips, which were subsequently assembled into layers by lamination.

**Fig. 3.** Bamboo flooring (González-Lezcano *et al*. 2015)

Finer strands of bamboo are superb materials for crafting fishing poles and a variety of light crafts such as fencing (Fig. 4), curtain rods, flutes, and others. Bamboo poles are also well-suited for serving as garden stakes, whether for supporting a row of tomato plants or establishing a plantation of banana trees. To preserve the bamboo from biological attack and create a fire barrier, various laminating resins, fire retardants, chemical treatments, impregnation, and coatings are used to preserve the bamboo (Kaur *et al.* 2016; Rahman *et al.* 2021; Matin *et al.* 2022).

Upon harvesting the poles, the bamboo plant not only endures but flourishes. The life source of bamboo lies within its underground root system. As the culms are harvested, the roots will grow stronger and persistently generate robust shoots and new culms.

**Fig. 4.** Bamboo fencing (ONETHATCH 2023)

## Bamboo Shoots

Emerging early in the growing season, young bamboo shoots, shown in Fig. 5, are soft and suitable for consumption. A healthy and thriving bamboo grove exhibits an impressive capacity for producing fresh shoots. Bamboo is rich in nutrients, boasting high concentrations of protein, vitamins, and minerals. Throughout Asia, people have incorporated the soft, young bamboo growth into their diets for millennia. Before consumption, bamboo shoots require boiling or proper fermentation to eliminate natural toxins.

**Fig. 5.** Bamboo shoots (Dane 2019)

## Bamboo Leaves

Bamboo leaves serve as a primary dietary source for pandas and various mammals, including the mountain gorilla, the golden monkey, and the bamboo lemur of Madagascar. These animals particularly favor the soft and nutritious young bamboo shoots but also consume the leaves, which are abundant in silica. Beyond being a flavorful beverage with nutty notes, bamboo leaf tea is recognized for its capacity to fortify the body's connective tissues and provide relief from arthritis.

## Bamboo Roots and Rhizomes

Bamboo's vigorous roots and rhizomes are the vital core of the plant, rendering it renewable and resilient against eradication efforts. The extensive rhizome network is an effective erosion control method, particularly on slopes and along waterways. Furthermore, bamboo roots play a crucial role in capturing and storing significant amounts of carbon from the atmosphere, thereby mitigating the impact of climate change.

Figure 6 presents the roots of a bamboo groove. The lower segments of bamboo, where the roots commence, proved valuable for unconventional crafts. Skilled traditional woodcarvers have devised exquisite designs incorporating the smoothness of bamboo with the rugged and bushy texture of the roots.

**Fig. 6.** Bamboo roots (Ryan 2023)

## Bamboo By-products

Some bamboo by-products include bamboo clothing, bamboo paper, and bioethanol from bamboo. These bamboo by-products rely on the cellulose-rich pulp of the plant. Moso bamboo used to be the main source of pulp for bamboo clothing, especially in China (Dlamini *et al*. 2022). Figure 7 presents clothes made from bamboo. All bamboo species can produce bamboo paper and bioethanol. The thinner tops and side branches of the bamboo are ideal for making toothpicks, bristles for brooms, or other light crafts. Larger bamboo culms sheaths can be utilized to create rustic paper products or various handicrafts. All of these bamboo by-products offer essential alternatives to fossil fuels, deforestation, and pesticide-intensive agriculture.

**Fig. 7.** Bamboo clothing (Mahapatra 2017)

## BAMBOO IMPORTANCE AND MULTIFACETED APPLICATIONS

### Carbon Absorption

Bamboo exhibits a four times faster growth rate than most plants and surpasses trees in carbon absorption. This rapid growth rate occurs when individual culms are at their maximum during the growing season and under optimal growing conditions. A well-developed bamboo grove can provide 30 to 35 percent more oxygen than an equivalent area of forest (Espinoza 2023). In photosynthesis, bamboo absorbs carbon dioxide ($CO_2$) from the environment and generates oxygen ($O_2$). The plant then sequesters the carbon in its roots and above-ground biomass. Bamboo's significant role in combating global warming is noteworthy.

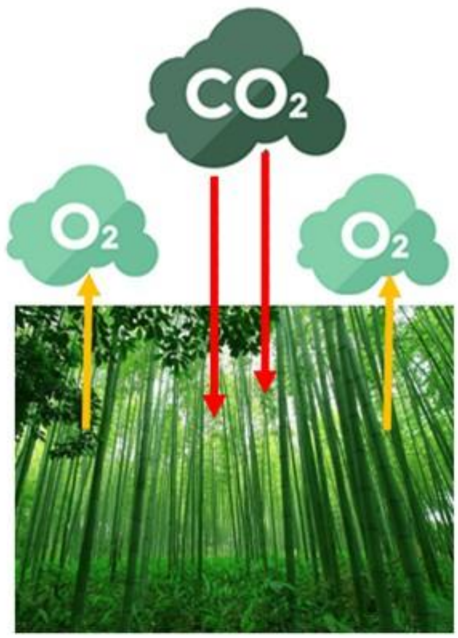


**Fig. 8.** Photosynthesis process that sequesters $CO_2$ and produces $O_2$

Bamboo's carbon absorption occurs alongside photosynthesis, where bamboo absorbs sunlight, water, and $CO_2$ to produce crucial nutrients, specifically sugar. The schematic diagram of the photosynthesis process is presented in Fig. 8. Meanwhile, bamboo simultaneously releases $O_2$ which is needed for humans. As such, existing carbon in the atmosphere will be absorbed, stored, or sequestered in the bamboo roots as carbon sinks through photosynthesis (Lou *et al*. 2010). Carbon sinks are vital in maintaining the balance of the earth's biosphere and stabilizing the atmosphere. The bamboo roots persist and retain the $CO_2$ even after the bamboo poles (culms) are harvested (Lou *et al*. 2010).

More carbon is released into the atmosphere when vast forests are logged or burned. Hence, bamboo is one of the best alternatives to replace cut trees to maintain the equilibrium of $O_2$ and $CO_2$ in the atmosphere. Bamboo likely has a higher capacity to convert $CO_2$ into $O_2$ than other vegetation types (Espinoza 2023). According to Japanese research, bamboo can absorb 12 metric tons of $CO_2$ per hectare annually, whereas Chinese estimates suggest a lower value of around five metric tons per hectare (Borowski *et al*. 2022). Researchers in Uganda have proclaimed that each square meter of bamboo can absorb 267 kg of $CO_2$ annually (Borowski *et al*. 2022). The numbers exhibit significant variation. However, all researchers proclaimed the superiority of bamboo in absorbing $CO_2$ and releasing $O_2$ through photosynthesis.

The viability of bamboo as a carbon sequestration agent relies heavily on its transformation into durable products. This is analogous to the necessity of ensuring the longevity of grass within a meadow to maintain carbon levels. While bamboo's rapid growth and carbon absorption capacity are notable, its effectiveness as a carbon sink is contingent upon its utilization in long-lasting items. Harvested bamboo left to decay would release stored carbon, rendering it ineffective for carbon sequestration. Thus, processing bamboo into enduring commodities like furniture, flooring, and textiles is imperative to maximize its carbon sequestration potential. Stakeholders must emphasize not only bamboo's growth and uptake capabilities but also the importance of its utilization in ways that facilitate prolonged carbon storage, necessitating careful management throughout its lifecycle to prevent premature carbon release into the atmosphere.

## Erosion Prevention

Bamboo can grow close to waterways and in areas where water only passes intermittently. Bamboo has an extensive and vigorous rhizome root network (Huang *et al*. 2022). Bamboo roots usually grow towards moist soils, but not soggy and saturated areas. Apart from anchoring the plant securely to the ground, the tough web-like mesh roots minimize soil erosion and degradation by forming a fibrous net (Lou *et al*. 2010). Bamboo is a pragmatic and advantageous crop to cultivate on inclines and alongside watercourses, where erosion is prevalent. As such, bamboo emerges as a pragmatic and advantageous crop, particularly on slopes and along waterways, addressing the prevalent erosion issue. Additionally, bamboo's ability to retain soil makes it a superior pioneer crop (Zhou *et al*. 2005). In areas where soil erosion poses a threat, the survival prospects of seedlings become more challenging. By binding the topsoil, bamboo facilitates the establishment of other species, fostering a more resilient and diverse habitat (Tardio *et al*. 2018).

## Bamboo Macrophytes for Wastewater Treatment

The extensive bamboo roots and rhizomes network offers a persistent and secure foundation for wastewater purification. As the wastewater flows through the dense woven mesh, the bamboo roots function as a filtration system, extracting harmful substances and contaminants such as nitrogen and phosphorus, effectively purifying the water at riverbanks, lake shores, and areas that experience periodic fluctuation. It is a simple and natural method to purify contaminated runoff or domestic greywater.

Bamboo achieves maximum efficiency in purifying wastewater when the water table is one to two feet below the soil level (Xu *et al*. 2020). In this manner, the top layer of soil is not excessively saturated, while the root tips can access the water table for filtering. To optimize bamboo's water filtering capabilities without causing harm to the plant, one can manage and regulate the runoff flow within the bamboo grove (Tadio *et al*. 2018). To achieve optimal outcomes, it is advisable to channel the water through the bamboo patch and stop the flow once the roots are soaked (Fang *et al*. 2019).

The root network can filter water as it percolates through the mud, sifting and cleaning it. Because of its phytoremediation capabilities, bamboo may leach certain heavy metals and other pollutants from the water (Kuok and Chiu 2013; Bian *et al*. 2020). Bamboo can metabolize and filter water if it is not overly contaminated with harmful elements. Bamboo filtering will enhance the water quality for cattle and irrigate other food crops, but it will not be enough to treat toxic runoff into the potable water supply (Were *et* *al*. 2017). Hence, wastewater treated with bamboo is best suited for ferti-irrigation, which combines the watering and fertilizing processes by incorporating nutrients directly into the irrigation water, especially for irrigating the bamboo groves via irrigation canals (Chauhan and Kumar 2020). Ferti-irrigation allows for efficient nutrient delivery to the root zones of plants, thus enhancing nutrient absorption and minimizing waste. This is an ideal and affordable wastewater treatment method for developing countries that cannot afford to build proper wastewater treatment facilities.

## Constructed Wetland

According to Tilley *et al.* (2014), constructed wetlands can be categorized into a) Free-water surface constructed wetlands (Fig. 9), b) Horizontal flow constructed wetlands (Fig. 11), and c) Vertical flow constructed wetlands (Fig. 12). Bamboo can be the main wetland plant or macrophytes to replace the cattail wetland plants in Figs. 9, 11 and 12 for treating wastewater.

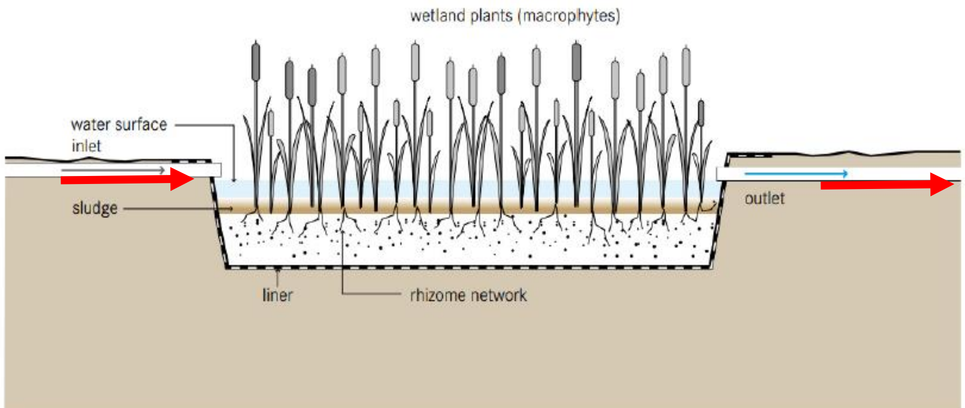


**Fig. 9.** Free-water surface constructed wetland (Tilley *et al*. 2014)

**Fig. 10.** Floating wetland treatment using (a) *Canna indica*, (b) *Ocimum tenuiflorum*, (c) *Chrysopogon zizanioides*, and (d) Hibiscus (Arivukkarasu and Sathyanathan 2023; Creative Commons Attribution License (CC BY 4.0))

The free-water surface constructed wetland is the most straightforward wetland, as there is about 0.6 m of free-standing water in the wetland throughout the year. It mimics the characteristics of authentic wetlands, marshes, or swamps. As the water moves slowly through the wetland, solid particles sink to the bottom and harmful microorganisms are eliminated. The bamboo grown in the wetland will uptake the nutrients, while the microorganism will biodegrade the organic material in the wastewater (Tilley *et al*. 2014; Kuok *et al*. 2015). Before treatment, it is vital to check the pollutant concentration and mitigate excessive sediment settling and system blockage.

Bamboo with inherent buoyancy can serve as a floating platform for terrestrial plants, including *Ocimum tenuiflorum*, Hibiscus, *Chrysopogon zizanioides*, and *Canna indica*, in a floating wetland treatment system (Arivukkarasu and Sathyanathan, 2023). Healthy terrestrial plants were affixed to floating rafts and set adrift, as presented in Fig. 10. The findings demonstrated that the implementation of floating wetland treatment with *Canna indica* exhibited the most effective removal rates for pollutants, including total suspended solids (96%), total phosphorus (98%), ammonia (95%), and dissolved oxygen (45%). *Chrysopogon zizanioides* had the highest rates of removal for many parameters, including turbidity (90%), total dissolved solids (48%), total nitrogen (85%), sodium (53%), potassium (74%), total phosphorus (92%), electrical conductivity (27%), chemical oxygen demand (93%), biochemical oxygen demand (95%), and *Escherichia coli* (47%). The study revealed that *Canna indica* and *Chrysopogon zizanioides* were the most effective terrestrial plants at removing a wide range of nutrients and pollutants from municipal sewage (Kuok *et al*. 2022b; Arivukkarasu and Sathyanathan 2023).

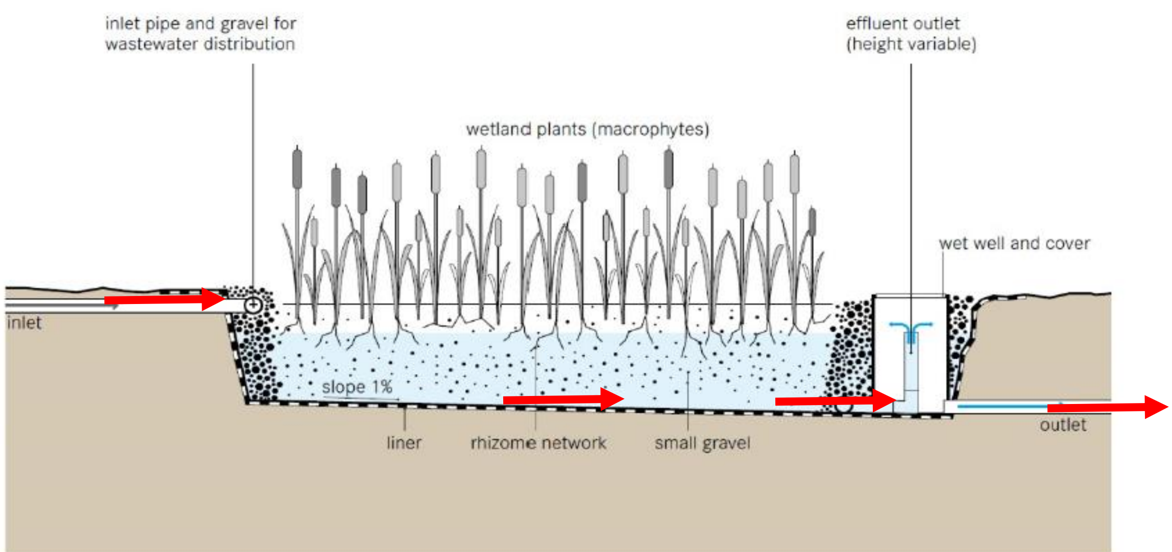


**Fig. 11.** Horizontal subsurface flow constructed wetland (Tilley *et al*. 2014)

A horizontal subsurface flow constructed wetland is filled with gravel and sand, designed explicitly for the growth of wetland macrophytes, which is bamboo. As the wastewater moves laterally over the basin, the filter material consists of sand and gravel, effectively removing particles, while microorganisms break down the organic matter. The wetland macrophytes will take up the nutrients in the particles.

A horizontal flow constructed wetland effectively eliminates a substantial quantity of contaminants from grey or black water before discharging into the groundwater, river, or natural wetland. This serves as a barrier against infections, germs, and non-biodegradable pollutants, effectively preventing their entry into the surface water. As a result, it contributes to maintaining a healthy ecosystem and improving sanitary conditions (Yocum 2006; Kuok and Chiu 2017).

The subsurface treatment method is highly environmentally friendly, with the system being discreetly concealed beneath the macrophytes that grow on top. These macrophytes, which are bamboo, can also serve as a decorative feature. Subsurface wetland systems have been found to effectively eliminate 65 to 85% of the biochemical oxygen demand (BOD) within 3 to 7 days. Vymazal (2010) stated that horizontal flow constructed wetlands usually require 5 $m^2$ per person. According to Crites and Tchobanoglous (1998), an area of approximately 174 $m^2$ is sufficient to treat the wastewater generated by a community of 400 families.

Yu *et al*. (2012) utilized horizontal flow constructed wetland planted with bamboo groves to treat wastewater for a village in southeastern China with a treatment capacity of 5 $m^3$/day. The results revealed that this bamboo groove wastewater treatment system had efficiently removed chemical oxygen demand, total nitrogen, and total phosphorus during a 6-month operation. The treated effluent met the Chinese sewage discharge standard and was indicated to be low-cost, operation-friendly, and applicable for sewage treatment in rural Chinese communities.

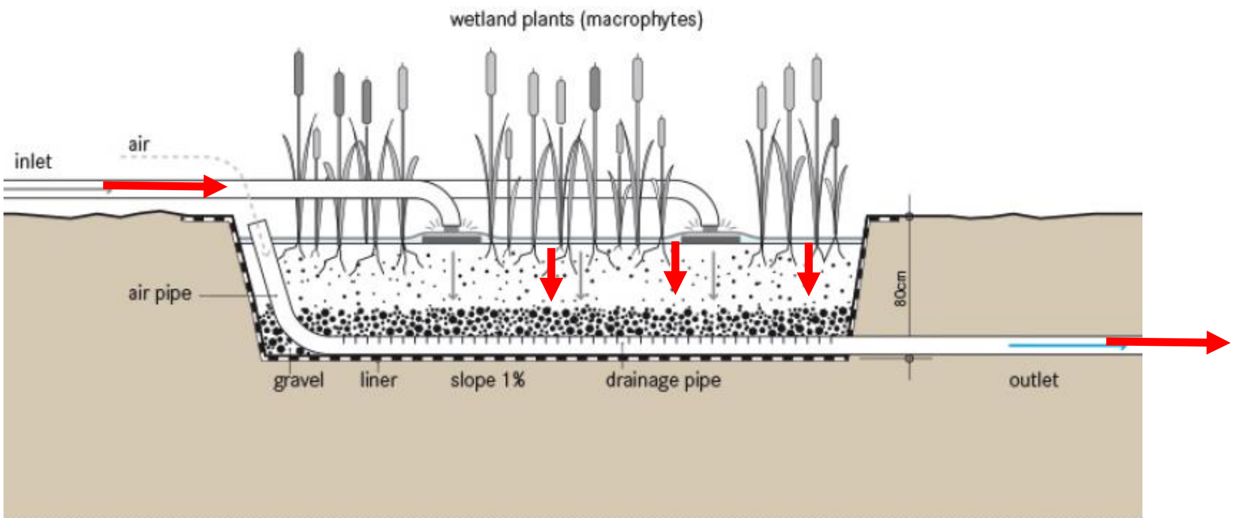


**Fig. 12.** Vertical subsurface flow constructed wetland (Tilley *et al*. 2014)

The vertical subsurface flow constructed wetland process involves pouring water from the top onto the wetland. The wastewater will pass through the filtration media to remove particles. This filter media, made of gravel and sand, provides a surface for bacterial growth and allows bamboo roots to establish themselves. The wastewater is added in stages, allowing for alternating periods of saturation and desaturation, leading to both anaerobic and aerobic digestion.

The vertical subsurface flow constructed wetland system required less area, which is 1 to 3 $m^2$ per person, compared to the horizontal flow constructed wetland (Tilley *et al*. 2014). Nevertheless, there are additional maintenance expenses in comparison. Meanwhile, the vertical subsurface flow constructed wetland system also required expert design and accurate dosing to treat the wastewater properly.

The French patented technology Bambou-Assainisse-ment® based on vertical subsurface flow constructed wetland system to treat effluents from the food industry under the BRITER-WATER project (CORDIS 2013). With a full-scale size of 1500 $m^2$, this innovative bamboo wastewater treatment system received about EUR 720,000 from European Union (EU) funding and was completed in 2012. This project investigated the performance of intensified bamboo-based phytoremediation for dairy and other food industry greywater applications. The system is designed to treat greywater, consisting of a high concentration of organic matter generated by the Délifruits factory near Valence in France (CORDIS 2013). The bamboo plant was chosen for this project because it has a very dense root system and is a fast-growing rustic plant capable of resisting many environmental stresses, such as too little or too much water or extremely low temperatures.

Piouceau *et al*. (2020) adopted a vertical subsurface flow constructed wetland system with bamboo groves to treat pig slurry on Réunion Island, a French overseas territory in the western Indian Ocean. Three field plots were designed on an agricultural area and planted with 40 bamboo clumps on each plot for phytoremediation of pig slurry. Results show that the concentration of nitrogen, phosphorus, and potassium was reduced significantly after the treatment.

PHYTOREM®, a French company specializing in phytoremediation, has patented an innovative technology using temperate bamboo to treat wastewater in vertical subsurface flow-constructed wetlands (Arfi *et al*. 2009). Experiment results revealed that soil–the soil-bamboo system had successfully removed 99% of the organic matter and 98% of the nutrients.

Osei *et al*. (2019) studied the pollutant removal potentials and growth dynamics of two bamboo species, namely *Bambusa vulgaris* and *Cymbopogon nardus*, for pollutant removal in a vertical subsurface flow constructed wetland. Results show that both species demonstrated appreciable pollutant removal efficiency >80% for the organic, reactive phosphorus, ammonia-nitrogen, total suspended solids, and total volatile solids.

## Bamboo Charcoal for Water Purification

Bamboo charcoal is an outcome of pyrolyzing bamboo. It is a porous material with excellent adsorption, electromagnetic shielding, and infrared emitting capacity. Figure 13 illustrates the environmental benefits of bamboo charcoal. Bamboo charcoal possesses remarkable cleansing and detoxifying attributes, which contribute to the enhancement of air quality and the purification of drinking water (Jiang *et al*. 2014). Bamboo's high water absorption capacity makes it an excellent option for phytodepuration or phytoremediation, an ecological method that utilizes plants to treat, alleviate, and purify polluted soil, water, or air.

With advanced technology, bamboo water filter charcoal sticks can be produced and purchased in many department stores or online (Chien *et al*. 2017). Bamboo charcoal filters are extremely effective in removing ammonia ($NH_3$), lead (Pb), mercury (Hg), cadmium (Cd), copper (Cu), chlorine (Cl), and chlorides ($Cl^-$) from water due to their high surface area (Lamaming *et al*. 2022). Calcium (Ca), potassium (K), and magnesium (Mg) are minerals found in bamboo charcoal that are good for human health (Nongdam and Tikendra 2014). Bamboo charcoal may release these minerals when mixed with water, enhancing the water's overall quality. Bamboo charcoal may help balance the pH of water, making it less acidic or alkaline, and the water taste better.

Bamboo charcoal can extract all the pollutants once immersed in a pitcher of water for an hour, producing a superbly refreshing glass of water. Bamboo charcoal filters are economical and do not require exorbitantly priced in-home filtering systems. Bamboo charcoal does not leave any residue or provide any unpleasant flavor to the water. Bamboo charcoal was used to "sweeten" the water for tea in ancient China and Japan (Kamath 2011).

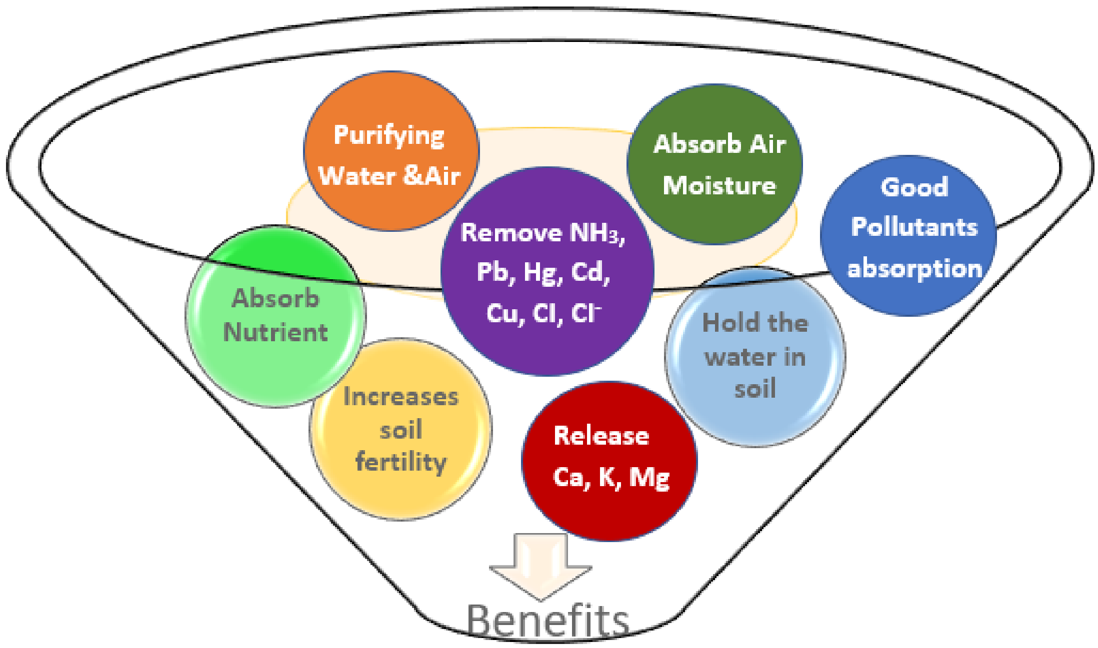


**Fig. 13.** Environmental benefits of bamboo charcoal

Bamboo charcoal can be activated to form activated bamboo charcoal, which is extremely effective in treating water and wastewater. Bamboo-activated carbon is successfully combined with orthophosphoric acid to remove colored dyes from wastewater effectively (Wang and Yan 2011; Suwanasing and Poonprasit 2014; Koo *et al*. 2015). Waji (2018) absorbed 99.8% of lead ions from wastewater at pH 5 using bamboo-activated carbon. Awoyale *et al*. (2012) removed lead (Pb) and copper (Cu) ions from wastewater using activated bamboo charcoal and cocoa pod husk activated charcoal. Santana *et al*. (2017) effectively absorbed pesticides, including Furadan, 2, 4-dichloro phenoxy acetic acid, and metribuzin from wastewater using bamboo-activated carbon.

Organic concentration quantified as chemical oxygen demand was effectively reduced from 378 to 142 mg/L within the first 4 h using bamboo-activated carbon (Ademiluyi *et al*. 2009). Wang *et al*. (2010) found that bamboo charcoal can absorb 40 % of Cadmium (II) in the first 5 min and the remaining portion within 6 h from aqueous solutions. Chen (2010) found that bamboo charcoal can adsorb lanthanum (III) from aqueous solutions endothermically and spontaneously.

Mui *et al*. (2010) found that bamboo charcoal can absorb acid blue 25, acid yellow 117, and methylene blue dyes from aqueous solutions. Wang *et al*. (2011) proclaimed that superior adsorptive qualities were obtained using activated bamboo charcoal to adsorb dimethyl sulfide from an aqueous solution. Liao *et al*. (2012) and Santana *et al*. (2018) observed that bamboo charcoal can adsorb acid orange and methylene blue dyes from aqueous solutions. Baruah *et al*. (2014) modified the indigenous rural water filter for arsenic mitigation using different bamboo charcoals.

Chien *et al*. (2017) discovered that the purification yield for bamboo-activated charcoal was between 58% and 90% for coliforms, nitrogen, nitrites, total harness, turbidity, and iodine. Lin *et al*. (2017) utilized bamboo-activated carbon prepared from bamboo charcoal to purify water using a multi-layer filtration method. Nguyen *et al*. (2021) developed biochars derived from water bamboo (*Zizania latifolia*) shoot husks using pyrolysis and ultrasound-assisted pyrolysis for the treatment of Reactive Black 5 (RB5) in wastewater. Jamali and Rahman (2022) designed and developed a portable mini water bamboo filter using bamboo-activated carbon to treat tap, pond, and river water.

*Properties of bamboo charcoal*

Bamboo charcoal can appear in different shapes, as presented in Fig. 14, including a) round, b) sliced, c) particle, and d) powder.


**Fig. 14.** Different shapes of bamboo charcoal

The chemical composition and physical structure of bamboo charcoal are highly porous, allowing it to absorb and retain contaminants readily. The substance comprises 85-98% carbon, which is also utilized in most contemporary filtration techniques. Bamboo charcoal contains abundant minerals such as potassium, magnesium, salt, and calcium. The minerals present in the water are dissolved through the filtration process, enhancing its mineral content. Bamboo charcoal consists of microbes for decomposing toxic substances like tri halo methane and chlorine. These microbes are also an anti-bacterial and anti-fungal bioagent that bonds naturally to bamboo. Thus, the water treated with bamboo charcoal is naturally cleared of toxic substances, bacteria, and fungi. Bamboo charcoal emits Far Infrared Waves (FIR), an electromagnetic radiation with wavelengths between 4 and 16 micrometers. The FIR produces a warming effect on the human body and can improve blood circulation. Bamboo charcoal can dissipate Electromagnetic (EM) waves that are harmful to the human body in large amounts. EM waves are produced by electrical appliances such as computers, microwave ovens, cell phones, and televisions.

*Other usages of bamboo charcoal*

Bamboo charcoal may be used as a supplement to enhance soil structure and fertility (Ding *et al*. 2016). It has minerals like calcium, potassium, and magnesium that may improve the soil and encourage the development of healthy plants (Ding *et al*. 2016).

Because of its capacity to absorb and hold water, bamboo charcoal may assist in minimizing the frequency with which plants need to be watered (Chaturvedi *et al*. 2023). It may improve gardening productivity and aid in water conservation. Bamboo charcoal may absorb extra minerals and release them gradually over time, aiding in the retention of nutrients in the soil (Kuok *et al*. 2022). It also may guard against nutrient leaching and provide a constant supply of nutrients for plants.

By lowering acidity or alkalinity, bamboo charcoal may assist in bringing the pH of soil into equilibrium (Hamidi *et al*. 2021). It may contribute to improving the environment for plant development. Due to its ability to deter certain insects and pests from plants, bamboo charcoal has been demonstrated to have some pest management capabilities (Wang *et al*. 2015). It may lessen the use of chemical insecticides. Bamboo biochar is a charcoal-like product in which the carbon is fixed and stabilized. When applied to the earth, biochar increases soil fertility (Ding *et al*. 2016) and creates a carbon sink that can last centuries. It is an efficient and beneficial use for bamboo offcuts or whole bamboo poles in regions without a well-developed value chain for bamboo products.

Many air-purifying products also utilize this purification property (Kaur *et al*. 2022). Bamboo charcoal-made cushions or gel are also ideal for reviving the sock drawer or purging the air in the refrigerator. Because of its porous nature, bamboo charcoal can efficiently absorb and retain airborne contaminants, allergies, and smells (Huang *et al*. 2014). It may aid in lowering the concentrations of dangerous pollutants in the air, making breathing safer and more enjoyable. Bamboo charcoal acts as a system that removes volatile organic compounds (VOCs) from indoor air that may be regenerated on-site while using less energy (Huang *et al*. 2016). It also creates fewer maintenance services, indirectly generating significant environmental and economic interest.

Bamboo charcoal can control the humidity in the air by soaking up extra moisture or releasing it when required. As a result, mold and mildew would not be able to develop, which is good for human health. Bamboo charcoal can emit negative ions into the atmosphere, which may help balance out positive ions from sources like electronics and other sources (Chaturvedi *et al*. 2023). It may lessen the chance of respiratory issues and improve air quality. Bamboo charcoal has a long lifespan and may be recycled several times by simply reactivating its absorption capabilities in the sunshine. It makes it a priced and ecologically responsible method of regulating humidity and air quality.

## Bamboo-based Membranes

Esfahani *et al*. (2020) utilized the waste fiber output from the bamboo construction industry as a sustainable raw material for producing cellulose-based membranes (refer to Fig. 15). This was achieved by employing 1-butyl-3-methylimidazolium chloride [C4mim] [Cl] as an ionic liquid (IL) solvent. The lignin and hemicellulose components of the bamboo waste fibers were eliminated, and the extracted cellulose was used at the concentrations of 3wt%, 5wt%, and 10wt% to produce membranes using the phase inversion technique. The intrinsic properties of the fabricated membranes, including morphology, crystallinity, surface charge, roughness, and chemistry, were assessed using scanning electron microscopy, powder X-ray diffraction (XRD), zeta potential analysis, atomic force microscopy (AFM), and water contact angle measurements, respectively.

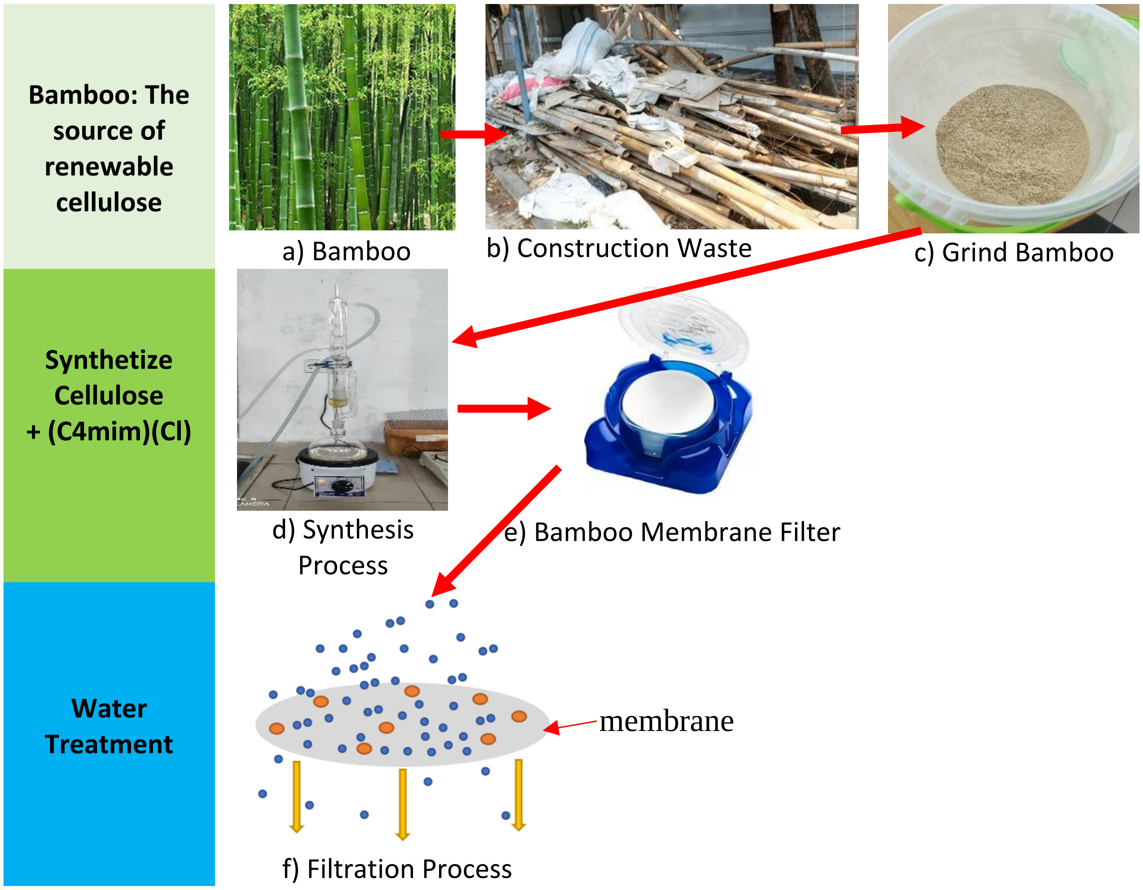


**Fig. 15.** Flowchart of transformation of bamboo construction waste into sustainable cellulose-based membranes

Each membrane exhibited a distinct transformation from cellulose I to cellulose II, with varying crystallinity indexes, depending on the initial concentration of cellulose digested by [C4mim] [Cl]. The study evaluated the efficacy of bamboo-based membranes in removing several dyes from water, including methylene blue, methylene orange, and crystal violet. The assessment considered membrane permeance, antifouling properties, and rejection rates. Overall, the bamboo-derived membranes exhibited comparable or superior performance to cellulose-based membranes regarding water flux, antifouling, and rejection. This confirms the successful conversion of waste materials, which are bamboo waste fibers, into a valuable membrane using sustainable green technology.

The primary mechanism for dye rejection was found to be size exclusion, while solute diffusion was determined to be the predominant transport mechanism in the bamboo-based membranes. The rejection of substances is determined by the membrane's physical structure, namely its dense layer, as well as the size of the dye molecules. On the other hand, the antifouling capability of the membranes is influenced by their surface charge and hydrophilicity. The membranes of 10% bamboo and 3% bamboo exhibited the highest dye rejection rate of 87% and water flux of 600 LMH, respectively.

Li *et al*. (2023) adopted a cross-linking coating modification approach to create an eco-friendly composite nanofiltration membrane based on bamboo cellulose (CL-NF-BCM), with bamboo cellulose serving as the supporting material. The cellulose membrane was cross-linked with alginate (ALG) and carboxymethyl cellulose (CMC) effectively, as evidenced by the results of solid-state Nuclear Magnetic Resonance (13C NMR). In addition, X-ray Photoelectron Spectroscopy (XPS) studies verified the transfer of chemical components. Upon cross-linking coating modification, the bamboo cellulose membrane transforms its microscopic morphology. The formerly uniform porosity structure is replaced by a polymerized layer characterized by an interwoven network structure.

Furthermore, the Brunauer-Emmett-Teller (BET) analysis reveals that the average pore size of the as-prepared CL-NF-BCM is around 1.1 nm. The performance testing findings indicate that the CL-NF-BCM cellulose membrane exhibited a rejection rate of 48% when tested against a 500 ppm NaCl solution. Additionally, the membrane demonstrated a flux of 17 $L \cdot m^{-2} \cdot h^{-1}$ under a nanofiltration setting with an operating pressure of 0.5 MPa. This work enhances the application of bamboo products with high added value and offers a fresh approach to modifying membrane surfaces.

## Bamboo's Socio-economic Effects

Bamboo has various good implications for social development and economic growth, which can vary according to the context and region. The general impacts on society and the economy are:

1. Employment and Livelihoods: Bamboo cultivation, harvesting, processing, and production can generate employment opportunities, particularly in rural areas where other job options could be restricted. This can assist in enhancing livelihoods and alleviating poverty for bamboo producers in remote areas.
2. Income Generation: Bamboo products have a wide range of uses, including construction, furniture, handicrafts, and even food. Selling these products can generate income for small-scale farmers and communities, creating a sustainable life and reducing dependency on subsistence agriculture.
3. Environmental Benefits: Bamboo is a fast-growing and renewable resource that can help mitigate deforestation and land degradation. Its cultivation can also contribute to carbon sequestration and biodiversity conservation. Its broad root system helps avoid soil erosion and promotes water conservation. The root also can assist in water and wastewater treatment.
4. Carbon Sequestration: Bamboo trees absorb carbon dioxide and release oxygen into the atmosphere, helping alleviate climate change by sequestering carbon.
5. Biodiversity Conservation: Bamboo forests provide habitats for numerous plants and animals, contributing to biodiversity conservation.
6. Cultural and Social Significance: Bamboo is firmly rooted in many cultures and holds important traditional significance. Bamboo is utilized for different purposes, including construction, crafts, rituals, ceremonies, and daily living. Bamboo can help conserve cultural history and strengthen social relationships.
7. Infrastructure and Housing: Bamboo is a versatile material used in buildings. Its usage in housing can lead to cost-effective and sustainable building solutions, especially in locations prone to earthquakes and other natural calamities.
8. Economic Development: Bamboo products are often traded globally, contributing to the economy through exports and trade. This can also generate opportunities for international cooperation and partnerships.

Bamboo is replete with an abundance of advantages and benefits. Despite its versatility, bamboo is not widely recognized and renowned as a lumber source on a global scale, primarily due to insufficient information and education about the plant. Sometimes, bamboo is perceived as a low-value, traditional, and outdated material, affecting its marketing appeal. The lack of defined regulatory frameworks and standards for bamboo goods hinders their marketing in specific regions or industries. Moreover, bamboo also confronts competition from other materials like wood, plastic, and metal, which may have better-established research data, codes or standards, marketing strategies, and market share. As a result, numerous potential consumers lack awareness of the advantages and flexibility of bamboo, posing a challenge in efficiently marketing bamboo products. Therefore, concerted efforts are required from industry players, governments, non-government organizations, communities, and other stakeholders to enhance awareness, optimize the supply chain, and advocate for the advantages of bamboo as a sustainable and versatile material for sustainable development.

## CONCLUSIONS

1. This article provides a detailed summary of the possibilities and advantages of bamboo in environmental preservation, water treatment, and wastewater treatment. The essential scientific developments in bamboo in recent years in water and wastewater treatment are critically highlighted. The water purification process focuses on utilizing activated bamboo charcoal to eliminate various contaminants found in water, such as colored dyes, lead ions (Pb and Cu ions), pesticides (including adsorbed Furadan, 2, 4-dichloro phenoxy acetic acid, and metribuzin), Cd (II), lanthanum (III), acid blue 25, acid yellow 117, acid orange, methylene blue dyes, dimethyl sulfide, Reactive Black 5 (RB5), coliforms, nitrogen, nitrites, total hardness, turbidity, and iodine. A portable tiny water bamboo filter can be created by combining bamboo-activated carbon, gravel, and sand. This filter is designed to effectively purify tap water, pond water, and river water.
2. Bamboo macrophytes are also efficient for wastewater treatment in free-water surface-constructed wetlands, horizontal-flow-constructed wetlands, and vertical flow-constructed wetlands. Within floating wetlands, bamboo acts as a floating platform for terrestrial plants, enabling them to cleanse contaminated water and process wastewater. Recent research has shown that bamboo waste fiber generated by the bamboo construction industry can be effectively utilized as a sustainable source material to produce cellulose-based membranes. The research findings suggest that bamboo is poised to play a prominent role in the urban, green building, and gardening sectors, contributing to the nation's economic growth.
3. Given the numerous benefits and prospects associated with bamboo, the presence of bamboo forests in rural regions could potentially foster opportunities for economic expansion. Bamboo forests may assist in generating employment in the forestry and industrial sectors and serve as a source of revenue by selling bamboo goods. Communities may enhance their revenue, lessen their environmental effect, and generate new opportunities by investing in the cultivation and processing of bamboo.

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