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HARNESSING BAMBOO: THE GREEN REVOLUTION IN CLIMATE CHANGE MITIGATION AND ADAPTATION

Clara Manasa P. A[1], Supriya K Salimath[1], Ramakrishna Hegde[1] and Manjunath Gooli[2]

[1]College of Forestry, Ponnampet, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga, Karnataka, 571216, India
[2]Karnataka Forest Department, Karnataka, 571216, India
Corresponding E-mail: claramanasapa@gmail.com

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Abstract

Climate change is accelerating at an unprecedented rate, driven primarily by manmade greenhouse gas emissions, especially CO_2. Various mitigation strategies have been proposed to limit the global temperature rise to 2°C. While forests have been prioritized in carbon sink management within climate policies, bamboo-dominated systems remain underexplored. This review article highlights bamboo's potential for climate change mitigation and adaptation. Bamboo, often referred to as the "green gold" and "poor man's timber," has garnered the attention of researchers due to its unique qualities, including adaptability, rapid growth, flexibility, and ability to thrive in diverse soil conditions. It has significant potential for carbon substitution through biomass-based energy sources like biochar and bamboo-based wood products. Remarkably, bamboo can sequester more carbon in its early years of establishment than many forest trees. Moreover, bamboo's versatile growing nature, renewability, and wide range of uses make it an excellent option for climate change adaptation efforts. Its applications extend beyond environmental benefits to economic advantages, as bamboo cultivation can provide sustainable livelihoods for rural communities.

Keywords: Carbon dioxide, Carbon sequestration, Carbon trading, Fast growing, Green House Gas

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Introduction

Various natural factors contribute to the Earth's ongoing climate changes. Nonetheless, human-induced global warming, driven by the release of heat-trapping greenhouse gases (GHGs), is the leading factor behind the swift and dramatic shifts in climate patterns globally. This warming effect is linked to rising sea levels and increased climate variability, resulting in events like heat waves, severe droughts, and intense storms. The consequences of climate change and its variability are projected to adversely affect the economy, society, and the environment significantly (FAO, 2013). The primary driver of global warming is the emission of GHGs, with carbon dioxide (CO_2) and methane (CH_4) responsible for over 90% of these emissions. Major sources include the combustion of fossil fuels (coal, oil, and natural gas) for energy, alongside contributions from agriculture, deforestation, and industrial activities. There is unanimous agreement among national and international scientific bodies regarding the human influence on climate change.

Climate feedback mechanisms involve changes in carbon sinks on land and in oceans, the reduction of sunlight-reflecting snow and ice cover, and increasing water vapor (a GHG), among other factors (Mollah *et al*., 2021). Compared to the baseline average from 1951 to 1980, surface air temperatures from 2011 to 2020 have risen. Since the late 19th century, the global average temperature has increased by over 1.2°C (NASA, 2020). Several policies and measures have been introduced to tackle climate change. A notable initiative is the Intergovernmental Panel on Climate Change (IPCC), which addresses climate change adaptation and mitigation. The Clean Development Mechanism (CDM) under the Kyoto Protocol (KP) aims to support sustainable development in developing countries while helping industrialized nations meet their carbon reduction targets. The IPCC offers various recommendations (IPCC, 2007) to mitigate the rate of climate change, including the development of cleaner and more efficient energy sources, improvements in transportation, building practices, industry, and waste management, as well as modifications in agricultural practices to reduce methane from paddy fields and manure, and lower nitrous oxide emissions from fertilizers. Additionally, the IPCC suggests enhancing forest management, increasing afforestation and reforestation, reducing deforestation, and boosting the natural ability of ecosystems to absorb CO_2 to decrease atmospheric CO_2 levels (Quiroga *et al.,* 2013). Understanding the carbon sequestration capabilities of forests can enhance our grasp of their role in the global carbon cycle and inform the implementation of these strategies.

Carbon sequestration refers to a geoengineering method for capturing and storing CO2 that would otherwise enter the atmosphere (Manasa *et al*., 2016). Artificial carbon sequestration methods, such as capturing and storing CO_2 emissions from fossil fuel power plants in underground reservoirs, are gaining traction. However, biological carbon sequestration is also an effective natural mechanism. During photosynthesis, plants absorb CO2 and store the carbon within their tissues. According to Dixon *et al*. (1993) and Brown *et al*. (1996), increasing tree cover is a cost-effective way to mitigate climate change. Recent research on conservation, restoration, and improved land management suggests a potential for mitigating up to 23 $GtCO_2$. Efforts in this domain largely focus on reduced deforestation, reforestation, and better forest management, especially in tropical areas (Houghton, 2013; Canadell and Schulze, 2014; Grace *et al*., 2014; Houghton *et al*., 2015). This review paper aims to highlight the potential role of forests in carbon sink management within climate policies, with a particular emphasis on bamboo-dominated systems, which have received relatively less attention.

Bamboo Resources and their Importance

Bamboo, often known as "green gold," "poor man's timber" or "timber from cradle to coffin" is a woody grass that belongs to the Poaceae family and plays a crucial role in many forest ecosystems. Over the past few decades, bamboo has garnered global attention due to its versatile utility, ranging from household items to rural housing and industrial raw materials (Dransfield and Widjaja, 1995). Traditionally, bamboo has been used for fuel, food, rural housing, shelter, fencing, tools, and other purposes. In certain regions of Asia, bamboo has been so intricately woven into the fabric of human culture and history that it is often referred to as a "bamboo civilization" (Nath *et al*., 2015). Consequently, the view of bamboo stands is undergoing a dramatic transformation, evolving from being seen merely as the "poor people's trees" to "high-tech industrial raw resources" that can substitute timber and other materials traditionally sourced from natural forests (Lobovikov *et al.*, 2009). The unique characteristics of bamboo, compared to other forest species, significantly enhance its utility.

Bamboo's flexibility and ability to thrive in varied soils make it suitable for re-greening degraded areas, wastelands, and other problematic regions. It is the fastest-growing species, maturing in four to five years. Most bamboo species can be harvested around this age due to their early maturity, with new culms adding to the clump annually, thus supporting the surrounding ecology. Bamboo's extensive rhizomatous root system helps hold soil and control landslides, making it suitable for planting near rivers and on steep slopes to prevent soil erosion (Manasa *et al.*, 2022). The leaf litter of most bamboo species is favored by earthworms and bacteria, aiding in transforming poor soil into rich soil. Bamboo groves have a superior ability to recharge groundwater and effectively purify local water compared to natural stands, thus playing a crucial role in regulating the water cycle. The lush green canopy of most bamboo species provides an excellent under storey, making them ideal for agroforestry systems. Consequently, bamboo is considered an asset that supports poverty reduction, economic development, and environmental conservation (Paudyal *et al.*, 2019).

Approaches for Climate Change with Bamboo

Bamboo has proven to be extremely important for humanity on numerous levels over time. It should be seen as a potential tool for addressing the issue of climate change adaptation and mitigation (Kuehl *et al.*, 2011). Globally, climate change is being addressed in various ways and the Strategies include:

1. Mitigation: Reducing GHG emissions and stabilizing atmospheric levels.
2. Adaptation: Adjusting to ongoing climate changes.

The International Network of Bamboo and Rattan (INBAR) has shown that managed bamboo can outperform some tree species in carbon sequestration (INBAR, 2009). Sustainable harvesting and durable bamboo products contribute to its effectiveness as a carbon sink (INBAR, 2009). Bamboo's rapid growth, renewability, and economic advantages make it a valuable tool for reducing greenhouse gas emissions and expanding bamboo forests (Sandhu *et al*., 2010; Tewari *et al*., 2016; Terefe *et al*., 2019).The schematic representation (Figure 1) below illustrates how bamboo can be used to address the issue of climate change through mitigation and adaptation (Kuehl *et al*., 2011).

Bamboo for Climate Change Mitigation

Mitigation with the help of bamboo can be approached in two ways:

a) Sequestration: Bamboo, as a woody perennial, has the potential to sequester atmospheric CO_2 and store it in its biomass as carbon. The biomass and atmospheric CO_2 sequestered by bamboo are also stored in the soil as organic carbon (Hinkle *et al*., 2019).

b) Substitution: Substituting bamboo for standing biomass acts as a long-term carbon sink by converting bamboo culms into durable products even after their harvest. To maintain its status as a net carbon sink, the bamboo system must ensure that carbon is stored in different forms so that the total carbon sequestered exceeds the amount released into the atmosphere. This is crucial because bamboo culms, which reach

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maturity in 5-10 years, decompose quickly afterwards, returning carbon from the biomass to the environment (Singh *et al.,* 2012; Kuehl *et al*., 2011).

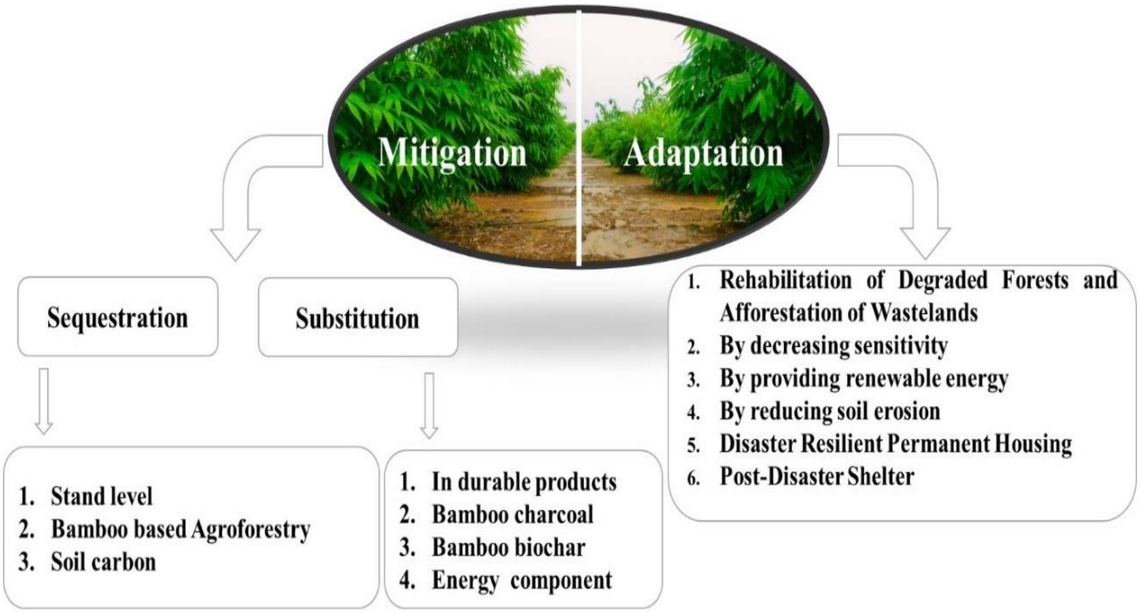

Figure 1: Schematic Representation Displaying the Approaches for Climate Change Mitigation with Bamboo

Bamboo for Sequestration

Sequestration at Stand Level

Human activities are estimated to produce approximately 30 billion tons of CO_2 equivalent annually. The rate of biomass production and storage in vegetation systems is crucial for quantifying system output and sustainability, thereby determining the carbon sequestration potential for mitigating climate change (Salimath *et al.,* 2022). Bamboo offers one of the most efficient methods for removing large amounts of CO_2 from the atmosphere and can generate up to 35 percent more oxygen compared to an equivalent stand of carbon-storing trees. Bamboo forests have the potential to produce biomass carbon storage ranging from 30 to 121 t ha^{-1}, with an annual sequestration rate of 6 to 13 t ha^{-1} (Andreola *et al*., 2022). Bamboo grows its full height in just a year, although it takes a few more years to mature, during which its biomass increases due to ongoing chemical and structural changes. Carbon sequestration in bamboo involves both the growth of new culms and the biomass in older ones. Early in its life, bamboo sequesters more carbon than trees (Yuen *et al.,* 2017; Hinkle *et al*., 2018). Studies show that *Guadua angustifolia*, a timber bamboo from Latin America, sequesters more carbon than three North American tree species (Hinkle *et al*., 2019), and Moso bamboo is 2.5 times more efficient than several fast-growing Asian woods (Nath *et al*., 2015). Managed bamboo stands can produce up to three times more biomass compared to unmanaged ones. For instance, managed Moso bamboo forests can sequester more carbon than fast-growing trees like Chinese fir (Kuehl and Yiping, 2012). Conversely, unmanaged bamboo stands have lower productivity and release stored carbon more quickly when older culms decay.

Managed bamboo can sequester up to 62 t CO_2 per hectare annually, while a young forest of similar size sequesters only 15 t CO_2. A *Guadua* plantation in Costa Rica absorbs about 17 t CO_2 per hectare each year (Janseen, 2000). A typical Moso bamboo ecosystem stores 106.36 t of carbon per hectare, with 34.30 t in above-ground vegetation and 72.20 t in the soil (Zhou and Jiang, 2004). Bamboo forests fix 5.10 t of carbon per hectare annually, surpassing tropical rainforests and Chinese fir at various growth stages (Zhao *et al*., 2009). Total carbon storage in bamboo forests increased from 318.60 Tg C (1950-1962) to 631.60 Tg C (1999-2003) (Chen *et al*., 2009). Bamboo, with its high carbon content, is highly effective for carbon fixation. Carbon storage capacity rises with culm diameter and density (Hauchhum and Singson, 2019). For *Guadua angustifolia*, above-ground biomass is about 200 tonnes per hectare, storing 100 tonnes of carbon, similar to some tree species like Chinese fir (Quiroga *et al.*, 2013). Carbon stocks vary among bamboo species, from 13.13 t C ha^{-1} in *Oxytenanthera abyssinica* to 67.78 t C ha^{-1} in *Phyllostachys aurea* (Barnabas *et al*., 2020), and range from 36.34 to 64.00 t ha^{-1} in *Bambusa tulda* and 50.11 to 65.16 t ha^{-1} in *Dendrocalamus longispathus* (Devi and Singh, 2021).

Sequestration in Bamboo-Based Agroforestry

Recently, the demand for bamboo has surged faster than its supply, making it necessary to expand bamboo cultivation both within and outside forested areas to meet this increasing demand. Agroforestry and farm forestry are viable approaches for sustaining bamboo supply for commercial use. Dev *et al.* (2020) highlight the significant potential for bamboo-based agroforestry due to its low capital investment requirements and resilience to extreme climatic conditions. There is also a focus on incorporating bamboo into agroforestry systems on harsh, eroded lands, and hill slopes to ensure productivity and rapid returns (Kishwan *et al.*, 2005). Additionally, bamboo is being considered for planting along riverine areas and irrigation canals as part of bund and boundary-based agroforestry systems (Manasa *et al.*, 2022). These systems are promising for Clean Development Mechanism (CDM) projects and climate change mitigation (Dhyani *et al*., 2016; Nath and Das, 2012).

In the context of climate change, agroforestry has emerged as a highly attractive economic and ecological strategy for mitigating greenhouse gas emissions (Dhyani *et al*., 2016). Nath and Das (2012) explored the ecological benefits of integrating bamboo into village agroforestry systems as a global climate change mitigation strategy. In homegardens managed by farmers, where fresh culms are not harvested, the carbon sequestered by bamboo can be considered a net gain, demonstrating that smallholder bamboo farming systems can effectively sequester carbon while fulfilling essential rural needs through the harvest of mature culms. In Northern Ethiopia, older culms of *Oxytenanthera abyssinica* stored more carbon than younger culms, with 3.80, 3.90, and 3.50 kg of carbon per culm for age classes less than one year, and one to three years, respectively (Darcha and Birhane, 2015). The carbon storage potential of traditional agroforestry systems in waterlogged conditions in northeastern India was documented by Sarkar *et al.* (2021), identifying these systems as excellent carbon sinks and promising components for climate change mitigation.

Sequestration under Bamboo Soil

Soil carbon sequestration (SOC) is a vital strategy for mitigating the increasing CO_2 concentrations in the atmosphere due to climate change. Bamboo soils, like those in tropical forests, play a significant role in this process. Carbon sequestration in bamboo stands varies significantly, with storage levels between 54.39 and 89.28 tons of carbon per hectare, averaging 66.52 tons per hectare. The organic carbon content is approximately 2.90% (Borisade *et al*., 2018). In the North East region of India, the carbon content in forest floor material is approximately 115.3 kilograms per hectare. Here, leaf litter contributes the largest amount at 76.32 kilograms of carbon per hectare, followed by sheath and branch material at 35.34 and 3.64 kilograms of carbon per hectare, respectively, based on data from 100 home gardens and 40 bamboo groves (Nath and Das, 2012). Additionally, research by Sirsat *et al.* (2021) indicates that carbon storage in the soil is influenced by the age of bamboo plantations, with surface layer carbon stocks ranging from 13.52 to 22.97 tons per hectare and subsurface layer stocks ranging from 12.44 to 22.34 tons per hectare. This indicates that older bamboo plantations tend to have higher carbon sequestration potential. Zhuang *et al.* (2011) reported significant carbon accumulation in *Phyllostachys praecox* f. *prevernalis* soils when large volumes of organic material were used for mulching.

In North East India, bamboo-based agroforestry systems demonstrated a SOC rate of 0.59 t ha^{-1} yr^{-1}, which was compared favorably with other tropical agroforestry systems at similar soil depths (Nath *et al.*, 2015). Dev *et al.* (2017) confirmed an increase in organic carbon content over time in bamboo-based agroforestry systems. Similarly, extensively managed Moso bamboo plantations in subtropical China were found to enhance soil organic carbon, aggregate stability, and amorphous iron, indicating that increased soil carbon stocks were attributed to greater carbon input and improved preservation due to enhanced shrub diversity (Yang *et al*., 2021).

3.1.2 Bamboo for Substitution

Bamboo species mature and degrade quickly, releasing carbon from their biomass into the atmosphere (Liese, 2009). This process leads to a stable level of above-ground carbon, where emissions from older culms balance the carbon capture. To keep bamboo as a net carbon sink, it is crucial to store carbon in various forms to ensure that retained solid carbon exceeds what is released into the air (Singh *et al*., 2012).

Substitution: In Durable Products

In bamboo forests, culms are regularly harvested for product manufacturing. Consequently, the forest's carbon sequestration capability relies on the usage, longevity, and durability of the harvested material and its products (Kuehl *et al*., 2011). Bamboo is highly efficient in minimizing waste, as nearly every part can be used in production. Durable bamboo products can sequester carbon for extended periods, maintaining carbon storage until the products are discarded or incinerated. INBAR reports that bamboo has over 10,000 recognized uses globally, with its use and market expected to grow significantly. Bamboo's strength and stiffness surpass those of wood, brick, and concrete, and it exhibits tensile strength comparable to steel. The absence of rays and knots in bamboo's stem results in more uniform yield stress strength compared to wood (Baghel and Thakkar, 2017). Its qualities—such as pest resistance, durability, flexibility, and availability—make it ideal for various construction applications, including walls, piers, roofs, floors, and room dividers. These structures are valued not only for their aesthetic appeal but also for bamboo's exceptional engineering properties (Ogunbiyi *et al.*, 2015). Nath *et al.* (2009) reported that bamboo's tensile strength is 17 percent greater than steel, 27 percent greater than red oak, and 13 percent harder than hard maple.

In managing carbon sinks amid climate change, key factors include (i) the sustainability and renewability of the product, (ii) its carbon sink capacity, and (iii) the longevity of the stored carbon. Traditional bamboo products, despite retaining substantial CO_2, often have a short lifespan, which limits their effectiveness in long-term carbon sink management (Ray *et al*., 2020). Therefore, effective preservative treatments are essential for extending the lifespan of bamboo products. The carbon transfer rate affects the carbon stock in bamboo products: higher carbon stocks are achieved with better carbon transfer ratios during production. Since boiling and carbonizing processes can lead to significant carbon loss, improving these methods can enhance carbon retention and reduce the carbon footprint of bamboo products (Baghel and Thakkar, 2017). Efficient preservative treatments can extend product durability, thereby increasing the longevity of sequestered carbon. Advances in technology have enabled the creation of more durable bamboo items, ensuring that stored carbon remains sequestered for longer periods and enhancing bamboo's carbon storage potential (Terefe *et al.*, 2019).

Substitution: Bamboo Charcoal

Bamboo charcoal, a by-product of anoxic bamboo pyrolysis, has a range of applications, including the potential to replace coal in thermal processes (Chen *et al*., 2016). Pyrolyzing 38 tonnes of dry bamboo biomass can produce approximately 9.5 tonnes of charcoal, assuming a conservative charcoal yield of 25 percent. The net calorific value of bamboo charcoal is 25,000 MJ t^{-1} (Ganesh, 2003). Compared to wood charcoal, bamboo charcoal is three times more porous, releases more energy, and provides a substantial fuel backup (Hossain *et al.*, 2015). Bamboo charcoal is also beneficial for nutrient conservation and heavy metal stabilization due to its high adsorption capabilities. Chen *et al.* (2010) found that adding bamboo charcoal to pig manure composting effectively reduced total Kjeldahl nitrogen loss and controlled the mobility of copper (Cu) and zinc (Zn). Similarly, Li *et al*. (2017) perceived that bamboo charcoal decreased the bioavailability of Cu and Zn in chicken manure composting, thereby reducing the co-selection pressure from heavy metals. Furthermore, bamboo charcoal briquettes are commercialized in Asian and African countries, primarily for cooking and heating applications (Montaño and van Dam, 2021).

Substitution: Bamboo Biochar

Biochar, durable solid rich in pyrogenic carbon, can persist in soil for millennia. When biochar is produced through anaerobic combustion and integrated into soil, it sequesters roughly half of the carbon initially present in the biomass. Bamboo biochar, in particular, stands out as an effective long-term carbon sink, benefiting both energy production and agricultural practices. By converting biomass into biochar, we enhance the retention of carbon in the soil, as it mitigates CO_2 emissions by offsetting the rate of organic matter decomposition (Lehmann and Joseph, 2015; Maulana *et al*., 2021). Compared to traditional wood charcoal, bamboo biochar is far superior, offering about five times greater porosity and ten times higher absorption capacity. It also demonstrates exceptional performance in environmental applications. For instance, a bamboo biochar and montmorillonite composite has been shown to effectively treat industrial effluents or wastewater, particularly those contaminated with anionic pollutants like nitrates (Viglašová *et al*., 2018). Moreover, bamboo-derived porous biochar holds promise as a desulfurization adsorbent, aiding in the production of ultra-clean fuel oils (Yang *et al.,* 2018). Its diverse applications accentuate its value in both environmental management and resource recovery.

Substitution: Other Energy Components

Bioenergy is a low greenhouse gas emitter with minimal net radiative forcing on the atmosphere. Bamboo, with its substantial biomass production, presents a compelling bioenergy source in tropical regions (Fielden, 1999). Utilizing bamboo for bioenergy helps conserve carbon sequestered in fossil fuels and it can contribute to preserving natural forests (Seethalakshmi *et al*., 2009). Recently, bamboo has gained recognition as a key player in bioenergy production due to its availability and socio-economic feasibility (Sharma *et al.,* 2018). Rathour *et al.* (2022) advocate for promoting bamboo as a potential feedstock because of its high biomass yield, making it a viable commercial source for producing next-generation biofuels like bioethanol. Bamboo can be utilized as an energy source through various methods, enhancing its role in bioenergy. Several bamboo biomass energy conversion processes are discussed below (Figure 2) (Dube, 2008; Truong and Le, 2018).

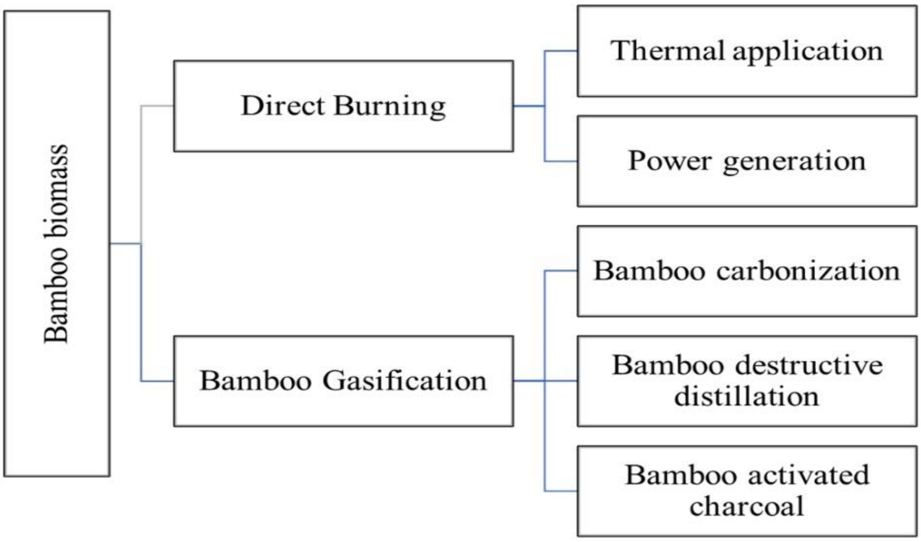

Figure 2: Bamboo Bioenergy Conversion Processes *(Source: Dube, 2008)*

Bamboo biomass, like any other biomass, can be directly burned for heat and electricity generation. It has the potential to replace coal in thermal applications. With a net calorific value of 16 GJ t^{-1} dry matter, a CO_2 emission factor of 96.1 t CO2 TJ^{-1} (IPCC, 2006), and a 75 percent thermal conversion efficiency, bamboo can achieve an emission reduction of 44 t CO2 ha^{-1} per rotation. Each rotation's biomass from a hectare of bamboo crop contains 608 GJ of energy, which can generate 56 MWh of power, assuming a power-generating efficiency of 33 percent (Dube, 2008).Bamboo gasification is an industrial technology where heated bamboo produces goods without or with a limited air supply. Bamboo is heated in brick kilns or mechanical kilns with limited air, using heat from burning firewood to pyrolyze bamboo and make bamboo charcoal. The carbonization and activation processes of bamboo determine its usage and can impact structural qualities like surface area, pore volume, adsorption, and conductivity (Isa *et al.*, 2017). Carbonized bamboo, often used for flooring, is considered an environmentally favorable building material because it matures in three years and regenerates without replanting. The charcoal manufacturing process softens bamboo fibers by 20% - 30%, and the fibers must be treated for strength and endurance (Willard, 2017). Bamboo activated carbon is produced by heating bamboo material in a brick kiln and an activated kiln. Khuong *et al.* (2021) found that hydrothermal treatment can efficiently convert bamboo and its solid byproducts into porous carbon using CO2 for physical activation. The resulting solid residue is particularly promising for producing activated carbon because of its low ash content.

Bamboo is an appealing resource for bioethanol production due to its rapid growth and plentiful, sustainable supply in tropical regions (Kuttiraja *et al.*, 2013). Bioethanol derived from bamboo is both technically and economically comparable to gasoline. Nevertheless, new strategies are required to lower bioethanol production costs to enhance its feasibility. These approaches may involve improving sugar extraction through more efficient pre-treatments and reducing enzyme usage, securing affordable bamboo feedstock, or choosing feedstocks with higher or more readily available cellulose content (Littlewood *et al*., 2013). Barathi (2018) reported that four kilograms of bamboo can yield 1.20 liters of ethanol, and an acre of bamboo can produce 10,000 liters of ethanol annually.

Bamboo for Climate Change Adaptation

The IPCC describes adaptation as "modifications in ecological, social, or economic systems in response to present climate shifts and their impacts." It involves altering existing practices or preparing for future environmental changes to adapt to a changing climate. The aim is to decrease our susceptibility to the negative consequences of climate change, such as rising sea levels, extreme weather events, and food scarcity. Bamboo, with its capacity to flourish in diverse climates and environments, renewability, and multiple applications, presents an excellent choice for climate change adaptation strategies.

Adaptation through the Restoration of Degraded Forests and Afforestation of Wastelands

Bamboo can be instrumental in restoring productive and functional ecosystems, especially in areas affected by climate change or unsuitable for traditional cultivation (Baghel and Thakkar, 2017). Ideal for deforested and degraded lands, bamboo plantings improve soil quality and boost the productivity of surrounding crops. In an INBAR project near Allahabad, India, bamboo species were used to restore soil damaged by brickfield mining. Within a few years, bamboo cultivation on the residual soil significantly improved its quality (Dwivedi *et al.*, 2019). Projects in India and Nepal have demonstrated bamboo's effectiveness in converting degraded regions into economically viable systems, enhancing soil quality, raising water tables, and reducing dust storms (Yiping *et al*., 2010; Gautam *et al*., 2018). Bamboo cultivation on such lands supports diverse agricultural systems, including medicinal plants and fisheries.In Central India, Eco-Rejuvenation Technology (ERT) using five bamboo species—*Bambusa balcooa* Roxb., B. *vulgaris* var. vittata, *B. vulgaris* var. *striata* (Yellow), *B. nutans* Wall. ex. Munro, and *Dendrocalamus asper* Backer—was implemented to reclaim and restore degraded land. This approach significantly increased soil biomass and carbon sequestration capacity within a year (Singh *et al*., 2020).Bamboo's role in eco-restoration of degraded lands has garnered significant attention from foresters, ecologists, and soil scientists. Consequently, bamboo plantations positively impact soil erosion control, biodiversity preservation, and enhancement of capacities in degraded land restoration (Mishra *et al.*, 2014).

Adaptation by Reducing Sensitivity

Developing adaptation strategis for a changing climate is a prolonged, ongoing process. Bamboo, being a rapidly growing species, helps establish productive stands within a few years, with culms ready for harvest in 3–6 years depending on the species. This swift establishment enhances flexibility in management and harvesting practices in response to climate changes and reduces susceptibility to external threats such as fires or severe weather (Kuehl *et al*., 2011). For instance, flooding in 2010 inundated fields in four Village Development Committees in Madi, within Chitwan National Park, Nepal. The flood destroyed banks, causing extensive property damage. In response, the Adoption of Bamboo and Rattan Initiatives (ABARI) and WWF launched the Hariyo Ban project in October 2014, planting 10,000 bamboo clumps for biodiversity conservation and land restoration, using 24 bamboo species for ecosystem management (FAO and INBAR, 2018).

In the winter of 2008, heavy snowfall in central and southern China caused numerous bamboo culms to break. By 2010, the forest had been restored, with new culms replacing the damaged ones (Kuehl *et al.,* 2011). Similarly, after forest fires, bamboo can recover more swiftly than trees and other crops. The underground rhizome survives the fire, and its stored resources enable vigorous regrowth, allowing bamboo to outcompete other plants for space in the burnt area (Ferreira *et al.,* 2020).

Adaptation by Providing Renewable Energy

With rising energy demands in many developing countries, deforestation for domestic energy has become a significant contributor to greenhouse gas emissions. Bamboo charcoal and firewood are increasingly recognized as environmentally friendly alternatives to meet the energy needs of rural and urban populations. They can help mitigate deforestation by offering a more sustainable energy source compared to traditional wood. Bamboo, like other biomass, can be converted into liquid, solid, or gaseous fuels, as well as other chemical compounds, heat, and power through various conversion processes (Montaño and Van Dam, 2021). Integrating multi-purpose perennial bamboo crops into Indonesia's energy systems could significantly help the country achieve its renewable energy targets (Sharma *et al.,* 2018). Additionally, it can support land restoration efforts by offsetting the substantial costs associated with meeting the Bonn Challenge's restoration goals.

Adaptation by Reducing Soil Erosion

Bamboo is particularly valuable in areas prone to runoff, such as steep slopes, riverbanks, or degraded fields, due to its extensive root and rhizome systems that stabilize the soil, holding up to 6 m^3 of soil. As an evergreen plant, bamboo provides a dense canopy and ground cover, preventing direct splash erosion and enhancing infiltration. Its deep roots assist in soil absorption, making it advantageous for riverbank stability. Furthermore, bamboo can collect and store rainwater for later use, reducing water flow in streams and rivers and minimizing erosion. Planting bamboo along riverbanks for five years can reduce soil erosion by up to 85 percent *(Singh et al., 2021)*. The bamboo species *Ochlandra spirostylis* is particularly suited for riverbank stabilization. The biological interaction between microorganisms in the topsoil and the fibrous root systems of *Ochlandra* species produces water-stable macroaggregates. Consequently, pure reed patches of *Ochlandra* species are considered a stable vegetation climax capable of improving soil's physical properties, stabilizing slopes, and preventing land degradation (SijiMol *et al.,* 2016).

Disaster-Resilient Permanent Housing

One of the key aspects of climate change adaptation is enhancing resilience against unpredictable natural disasters in the context of future climate conditions. During the reconstruction phase, a mix of technical, economic, and social factors is used to ensure that new structures are not only earthquake-resistant but also sustainable and livable. It is crucial that earthquake-resistant construction techniques become a standard practice among builders and homeowners. Bamboo emerges as a promising material for this purpose, with its potential to improve architectural design, making it more functional, durable, safe, eco-friendly, climate-responsive, and socially acceptable. However, to fully realize its potential, bamboo must be treated with technical measures to qualify as a structurally safe and long-lasting building material (Baghel and Thakkar, 2017). In India, various bamboo house designs demonstrate its versatility and cultural importance. Examples include the Chang

Ghar, a bamboo hut elevated on stilts; bamboo huts built directly on the ground; and the Ekra house, also known as the Assam-type house, which combines bamboo with other local materials (Das and Mukhopadhyay, 2018). Each of these constructions illustrates how bamboo can be integrated into various architectural styles and adapted to different environmental conditions, underscoring its role in sustainable building practices.

Post-Disaster Shelter

Bamboo is an excellent material for post-disaster shelter construction due to its rapid growth, sustainability, and strength. Its natural flexibility makes it highly resistant to earthquakes, reducing the risk of structural collapse (INBAR, 2011). Following the Lombok earthquake in 2018, a unique prototype of a temporary bamboo house, called Akin, was developed to assist local populations in rebuilding their homes (Fajrin *et al.*, 2021). In Assam, India, annual floods create a critical need for effective post-disaster shelters. According to Dev and Das (2020), traditional tents become uncomfortable in the hot and humid weather following floods and increase the risk of vector-borne diseases. Thus, developing housing structures using bamboo, with wall cladding made from woven bamboo mats measuring 120 cm × 250 cm, was essential. In terms of construction, bamboo offers excellent insulation properties, helping to maintain comfortable temperatures inside shelters. Its natural hollow structure allows for effective ventilation, enhancing the living conditions for occupants. The aesthetic appeal of bamboo also contributes to the psychological well-being of disaster survivors, promoting a sense of stability and normalcy. Sil (2016) highlighted that bamboo composites are attractive due to their low embedded energy (the energy required for manufacturing), particularly compared to materials like aluminum and steel. Furthermore, bamboo composites offer excellent impact resistance, thermal and acoustic insulation, and corrosion resistance, making them ideal for construction. Additionally, bamboo bio-concrete (BBC), made by combining bamboo particles, conventional Portland cement, and materials like metakaolin and fly ash, offers a valuable climate change adaptation option by enhancing carbon storage and reducing operational carbon (Caldas *et al.*, 2019). In regions where bamboo is abundant, BBC provides a viable solution for mitigating and adapting to the adverse effects of climate change (Caldas *et al.*, 2020).

Opportunities for Carbon Trading and Carbon Farming

Carbon has become a marketable commodity due to the growing climate financing mechanisms (Salam and Dube, 2009). Carbon trading is a market-based approach to reducing greenhouse gas (GHG) emissions. It involves the buying and selling of carbon credits, which represent the reduction, removal, or avoidance of one metric ton of carbon dioxide or its equivalent in other GHGs. Companies or entities that exceed their emission reduction targets can sell their excess credits to those that are unable to meet their targets, creating a financial incentive for reducing emissions. Carbon farming, on the other hand, refers to agricultural and land management practices that increase the amount of carbon stored in soil and vegetation. It encompasses activities like reforestation, agroforestry, and the use of cover crops, all aimed at enhancing carbon sequestration and improving soil health (Sileshi and Nath, 2017; Smith *et al.*, 2014). Carbon farming not only helps mitigate climate change but also offers co-benefits such as increased biodiversity, improved water retention, and enhanced soil fertility.

The inclusion of bamboo in carbon trading schemes offers several opportunities:

1. *Increased Carbon Credit Generation*: Due to its fast growth and high biomass production, bamboo can generate more carbon credits per unit area compared to many other crops or trees. This makes it an attractive option for landowners and farmers looking to participate in carbon trading markets.
2. *Sustainable Land Use*: Bamboo can be grown on degraded or marginal lands that are not suitable for conventional agriculture. This not only restores the land but also provides an additional income stream through carbon credits, promoting sustainable land use practices.
3. *Integration into Agroforestry Systems*: Bamboo can be integrated into existing agroforestry systems, providing multiple benefits. It can act as a windbreak, improve soil health, and offer additional products such as bamboo shoots for food and bamboo poles for construction, all while sequestering carbon.
4. *Corporate and Governmental Partnerships*: Companies and governments seeking to offset their carbon emissions can invest in bamboo plantations. Such partnerships can provide funding and resources for large-scale bamboo projects, enhancing their feasibility and impact.

Challenges and Solutions for Bamboo Carbon Projects

Despite its potential, there are challenges to the widespread adoption of bamboo for carbon trading and farming: Accurately measuring and verifying the carbon sequestration potential of bamboo can be complex due to its botanical classification as a grass rather than a tree (Yiping *et al.*, 2010). Developing standardized methodologies and protocols is crucial for ensuring credibility and transparency in carbon trading markets. Bamboo-based carbon credits may face challenges in gaining recognition and acceptance in existing carbon markets. Additionally, establishing bamboo plantations requires initial investment and time before realizing returns through carbon credits.To maximize the potential of bamboo, continued investment in research, policy support, and capacity building is essential. Governments, private sector stakeholders, and international organizations must collaborate to create enabling environments for bamboo-based carbon projects. By doing so, the full potential of bamboo as a powerful tool for carbon sequestration, climate resilience, and sustainable development can be unlocked.

Conclusion

When addressing environmental issues and climate change, bamboo is frequently the "forgotten answer." Its ability to store CO_2 has been well-documented and acknowledged globally. Bamboo has the potential to be highly effective in sequestering carbon due to its rapid growth and flexibility. As a fast-growing and sustainable resource, bamboo can function as a significant carbon sink, aiding efforts to mitigate and adapt to the consequences of climate change when managed strategically and scientifically. Additionally, bamboo can play a vital role in regreening degraded regions, thanks to its high growth rate and dense canopy. Its versatility extends beyond environmental benefits; bamboo is also a valuable resource in construction, offering a sustainable alternative to traditional building materials. As the world seeks solutions to climate change, recognizing and leveraging the full potential of bamboo could make a substantial difference in our global efforts to create a more sustainable and resilient future.

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