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Biochar insights: Sustainable production, market evolution, and climate change mitigation

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Abstract

Biochar is a carbon-rich material obtained by heating biomass under limited oxygen conditions, and it has gained global attention for its role in addressing climate change, promoting sustainable agriculture, and supporting environmental protection. Its porous structure, large surface area, and stable chemical nature help improve soil health by enhancing soil structure, increasing nutrient and water retention, and stimulating beneficial microbial activity, which ultimately boosts crop productivity. Modern production methods such as fast pyrolysis, gasification, torrefaction, and hydrothermal carbonization allow biochar to be produced efficiently from diverse biomass sources and align well with circular bioeconomy concepts. In addition to its agricultural benefits, biochar is increasingly used for long-term carbon sequestration, wastewater purification, and the adsorption of environmental pollutants, thereby contributing to reductions in greenhouse gas emissions. Growing awareness of these benefits has led to a steady expansion of the global biochar market. Although India has substantial biomass resources and large agricultural areas that offer strong potential for biochar adoption, progress is limited by gaps in research integration and challenges related to large-scale implementation. This review examines the current and future role of biochar in climate change mitigation by integrating global perspectives on its development, production technologies, market trends, and mitigation potential.

Keywords: Biochar, soil, application, methods and market

1. Introduction

Rapid industrial growth and increasing global population have significantly intensified environmental pollution, making it one of the most serious threats to Earth's ecosystems and living organisms (Briffa *et al.*, 2020) ^[13]. Human-driven climate change, along with unsustainable agricultural practices, has further worsened environmental stress, leading to frequent droughts, nutrient losses through fertilizer leaching, and growing concerns over global food security (Glaser *et al.*, 2012) ^[34]. In the face of urgent and emerging global challenges, biochar has gained attention as a promising tool for building a more sustainable future and creating value within a circular economy framework. Researchers increasingly view biochar as an effective soil amendment capable of improving soil quality and enhancing the long-term sustainability of agricultural systems (Alling *et al.*, 2014) ^[5]. Key indicators of healthy soil include its texture, ability to support microbial activity, and capacity to retain nutrients and moisture, all of which play a crucial role in crop productivity (Novotny *et al.*, 2015) ^[83]. Traditionally, biochar has been applied in its raw form; however, recent studies suggest that physical and chemical modifications can further enhance its effectiveness in soil applications (Kim *et al.*, 2007) ^[59]. Numerous studies have demonstrated that biochar improves soil health and crop yields while maintaining the natural balance of the soil ecosystem (Bruun *et al.*, 2012) ^[15]. These benefits are largely attributed to biochar's high surface area, porous structure, strong adsorption capacity, water-holding ability, and cation exchange capacity. In addition, biochar is highly stable and resistant to physical, chemical, and biological degradation, making it a long-lasting amendment for both agricultural and environmental applications.

Because of its distinctive physicochemical characteristics, biochar has increasingly been applied to improve soil fertility and promote healthy plant growth (Yadav *et al.*, 2023) ^[116]. Beyond its

role in agriculture, biochar also contributes to climate change mitigation by enabling long-term carbon sequestration, lowering greenhouse gas emissions, and removing both organic and inorganic pollutants from soil, water, and air through processes such as adsorption and degradation (Shoudho *et al.*, 2024)^[97]. The Intergovernmental Panel on Climate Change (IPCC), in its 2014 assessment, highlighted serious concerns over the rising concentration of greenhouse gases in the Earth's atmosphere and emphasized the urgent need for mitigation actions. According to the report, global greenhouse gas emissions must be reduced by 40-70% by the middle of this century compared to 2010 levels. In response, a wide range of mitigation strategies and policy measures have been introduced worldwide to address climate change (Adnan *et al.*, 2018; Akram *et al.*, 2018; Rahman *et al.*, 2019; Hammad *et al.*, 2019; Zamin *et al.*, 2019; Nasim *et al.*, 2018)^[2, 4, 42, 80, 88, 119]. Given its wide-ranging benefits and long-term stability, biochar has attracted growing scientific interest as a viable and effective strategy for climate change mitigation both now and in the future.

2. Evolution of biochar

Biochar is a charcoal-like material produced by heating biomass at very high temperatures, and it also occurs naturally in soils as a result of vegetation fires. Humans have intentionally used biochar in agriculture for over 2,500 years, most notably in the Amazon Basin of South America. There, ancient farming communities created dark, charcoal-rich soils known as *terra preta* (black earth), which transformed previously poor and even toxic soils into highly productive farmland. These remarkable soils were first scientifically documented in the 1950s by Dutch soil scientist Wim Sombroek and are estimated to still cover nearly 10% of the Amazon Basin. Similar biochar-enriched soils have also been identified in regions of Ecuador, Peru, and parts of West Africa, including Benin and Liberia. Unlike typical tropical forest soils, which are generally low in fertility, the incorporation of biochar enabled soils to retain organic matter, essential plant nutrients, and moisture required for sustained crop growth. This innovation made it possible to cultivate the same land year after year, reducing reliance on slash-and-burn farming practices. The resulting improvement in soil fertility supported stable food production systems and enabled the development of large, permanent human settlements (Wayne, 2012)^[112].



Fig 1: Typical profiles of terra preta (left) and oxisol (right) (Glaser *et al.* 2001)^[35]

Since the beginning of the twenty-first century, biochar has emerged as a major focus of multidisciplinary research due to its unique properties, wide range of applications, and strong potential for future development. In response to growing concerns over food security, environmental pollution, and energy shortages, both fundamental and applied research on the use of biochar in agriculture, environmental management, and energy systems has increased substantially (Chen *et al.*, 2019)^[18]. Although interest in biochar has surged in recent decades, its use dates back at least 2,000 years (Hunt *et al.*, 2010)^[49]. Biochar was first formally recognized in Western agricultural studies during the mid-nineteenth century, though its practical use likely extends much further into history. The earliest known applications of biochar are closely associated with indigenous communities of the Amazon Basin, who intentionally modified soils to improve fertility (Lehmann *et al.*, 2009; Han *et al.*, 2020)^[44, 65]. These practices led to the formation of highly fertile soils known as *terra preta*, meaning “black soils of the Indians,” which serve as clear evidence of extensive biochar use by ancient civilizations (O'Neill *et al.*, 2009; Tenenbaum, 2009)^[84, 102]. These soils are characterized by exceptionally high concentrations of essential

nutrients such as potassium, phosphorus, and nitrogen (Chen *et al.*, 2019)^[18]. Owing to their dark, organic-rich nature, *terra preta* soils remain highly productive even after centuries of nutrient leaching under intense tropical rainfall (Hunt *et al.*, 2010)^[49]. Biochar should not be confused with *terra preta*, even though the two are closely related. *Terra preta*, also referred to as Amazonian dark earth, occurs naturally and can also be recreated through the deliberate addition of low-temperature charcoal mixed with organic materials such as compost, manure, plant residues, animal waste, and bones (Graham *et al.*, 2006)^[39]. In comparison, biochar differs from *terra preta* in both its overall composition and carbon structure (Igalavithana *et al.*, 2018). Importantly, scientific interest in biochar was largely stimulated by the discovery of the exceptional fertility of *terra preta* soils (Glaser *et al.*, 2002)^[36]. Biochar is present in soils across the globe due to natural processes such as forest and grassland fires (Krull *et al.*, 2008)^[63]. Regions with naturally high biochar content, including the North American prairies, are recognized among the most productive agricultural soils worldwide (Hunt *et al.*, 2010)^[49]. Historically, biochar has also been widely used in agricultural practices across various parts of Asia, particularly in Japan and

Korea. Insights gained from *terra preta* research during the mid-1990s revealed biochar's strong potential for carbon dioxide sequestration and emission reduction, positioning it as a promising tool for addressing climate change (Han *et al.*, 2020). Following the first International Biochar Initiative meeting held

in Australia in 2007, many countries established national biochar societies to promote research, field demonstrations, and knowledge exchange, leading to a steady growth in global biochar research efforts (Han *et al.*, 2020) [44].

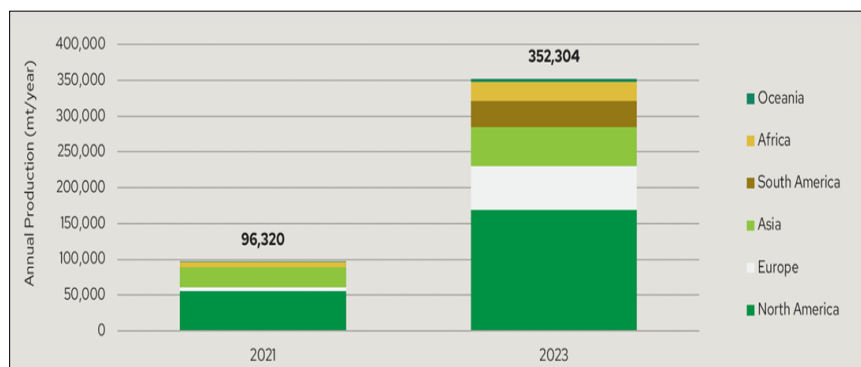


Fig 2: Global Annual Production (mt/year) by Region (2021 vs. 2023)

Fig 2. **Global biochar production:** Estimated annual global biochar production (in metric tonnes, Mt), categorized by producer type, based on reported values from biochar producers worldwide (Global Biochar Market Report, 2023)

3. Biochar production

Charcoal can form naturally through vegetation fires or be deliberately produced by humans using controlled burning

methods such as fire pits and simple handmade structures. Biochar, in contrast, is produced under anaerobic or oxygen-limited conditions, which allow biomass to undergo controlled thermal conversion. Based on the level of technological advancement, biochar production methods are broadly categorized into traditional and modern techniques, reflecting differences in efficiency, control, and degree of modernization (Gabhane *et al.*, 2020) [29].

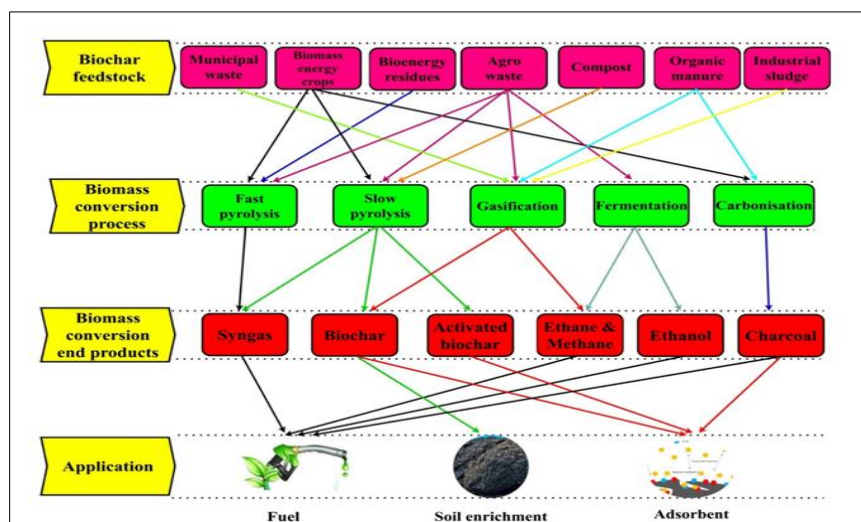


Fig 3: The overall conversion process of biomass into biochar and its application (Ravindrian *et al.*, 2024)

3.1. Traditional approaches

Archaeological records indicate that humans began producing and using biochar more than 2,500 years ago, with the earliest evidence originating from the Amazon Basin in South America (Glaser, 2007) [33]. These practices led to the formation of *terra preta* soils, which contain nearly three times higher levels of soil organic matter and nutrients compared to surrounding soils (Glaser *et al.*, 2001) [35]. Ancient communities typically produced biochar by slowly burning wood in soil-covered pits under little or no oxygen supply (Thines *et al.*, 2017; Barrow *et al.*, 2012) [8, 104]. In another approach, biomass was burned in open areas and the partially charred material was quickly covered with soil to limit oxygen exposure (Emrich, 1985; Reilly, 1925) [90]. To improve control over the process, early societies developed

simple, handmade reactors such as clay burners, firebrick pits, brick kilns, and iron retorts. Despite differences in materials, these systems shared a common design element—a pit enclosed by clay, bricks, or metal. Such modified production techniques allowed for the recovery and utilization of volatile compounds released during pyrolysis (Reilly, 1925) [90]. These traditional biochar-making methods remained widely used until the late nineteenth century, when more efficient, labor-saving steel ovens were introduced (Emrich, 1985; Reilly, 1925) [25, 90].

Pyrolysis: Pyrolysis is a thermochemical process in which biomass is heated under anaerobic or oxygen-limited conditions, resulting in the formation of gaseous products, liquid by-products, and solid char residues commonly referred to as biochar (Basu,

2010) [9]. Agricultural biomass mainly consists of cellulose, hemicellulose, lignin, and silica, each of which decomposes at different temperatures during pyrolysis. Cellulose typically degrades around 350 °C, while lignin breaks down over a broader temperature range and begins decomposing above 350 °C (Czernik and Bridgwater, 2004) [21]. As a result, an effective temperature window for pyrolysis generally lies between 300 and 700 °C (Suarez-Abelenda *et al.*, 2017) [101]. Although pyrolysis occurs in the absence of oxygen, external heat sources are required to sustain the process, including hot gases, heated solids, liquid heat-transfer media, or heat generated through controlled oxidation and partial oxidation reactions (Li *et al.*, 2016; Xie *et al.*, 2015) [60, 67, 115]. Over time, pyrolysis technologies have evolved significantly. Based on operational parameters such as temperature, heating rate, and residence time, pyrolysis can be categorized into different modes, most commonly slow and fast pyrolysis, which are associated with traditional production methods. In contrast, advanced techniques such as flash pyrolysis, vacuum pyrolysis, and microwave-assisted pyrolysis incorporate modern technological innovations. Accordingly, slow and fast pyrolysis are classified under traditional approaches, while flash, vacuum, and microwave pyrolysis are grouped under modern biochar production methods.

Slow pyrolysis: As its name suggests, slow pyrolysis is a time-intensive process that typically takes several hours to complete and results in biochar as the primary product. Also referred to as

conventional pyrolysis, this method involves heating biomass at temperatures ranging from 300 to 600 °C using a relatively low heating rate of about 5-7 °C min⁻¹ (Lai *et al.*, 2013) [64]. Slow pyrolysis generally produces a higher proportion of biochar, accounting for approximately 35-45% of the total output, along with by-products such as bio-oil (25-35%) and syngas (20-30%) (Lai *et al.*, 2013; Méndez *et al.*, 2015; Verma *et al.*, 2015) [64, 76, 110]. A wide variety of feedstocks have been successfully utilized for biochar production through slow pyrolysis, including *Conocarpus* wood waste (Moussavi *et al.*, 2012) [78], cotton stalks (Shen *et al.*, 2015) [95], and agricultural residues such as coconut shells, palmyra nutshells, and rice husks (Jegajeevagan *et al.*, 2016) [53].

Fast pyrolysis: Fast pyrolysis is a highly efficient thermochemical process designed primarily for the conversion of biomass into biofuels (Dai *et al.*, 2017) [22]. This process operates at temperatures exceeding 500 °C, with very high heating rates of more than 300 °C min⁻¹ under oxygen-free conditions. Unlike slow pyrolysis, fast pyrolysis occurs rapidly and is typically completed within a few seconds. The product distribution from fast pyrolysis generally consists of about 60% bio-oil, 20% biochar, and 20% syngas (Dai *et al.*, 2017; Huang *et al.*, 2016) [22, 48]. Due to its high efficiency and rapid processing capability, fast pyrolysis is commonly applied in large-scale biochar and biofuel production systems (Liu *et al.*, 2016) [67, 70].

Table 1: Different methods of biochar preparations

S. No.	Methods	Temperature (°C)	Heating Rate (°C s ⁻¹)	Residence time	Syngas (%)	Bio-oil (%)	Biochar (%)	References
1	Slow pyrolysis	300 to 550	1-10	Several Hours	35	30	35	Shahbaz <i>et al.</i> (2022) [94]
2	Fast pyrolysis	450 to 600	10-1000	10-30 s	13	75	12	Thomas <i>et al.</i> (2019) [105]
3	Flash pyrolysis	750 to 1000	Less than 1	Less than 2 s	-	-	-	Thomas <i>et al.</i> (2019) [105]
4	Gasification	More than 800	1-0.8	10-20 s	85	5	10	Zaied <i>et al.</i> (2020) [117]
5	Torrefaction	450 to 550	-	Less than 2 h	5	20	75	Amalina <i>et al.</i> (2022) [6]
6	Microwave-assisted pyrolysis	400 to 800	1000 +	-	-	-	-	Zaker <i>et al.</i> (2019) [118]
7	Hydrothermal carbonization	Less than 200	Less than 1	1 to 16 h	35	30	35	Brown <i>et al.</i> (2020) [14]

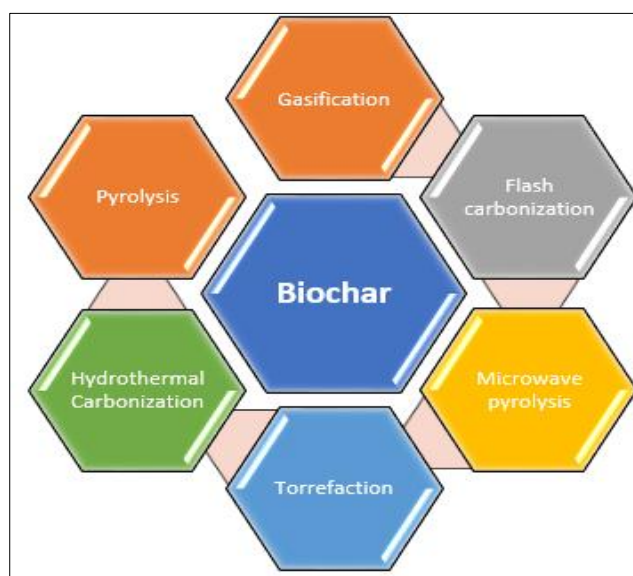


Fig 4: Different methods of thermochemical conversion process

3.2. Modern approaches

By the end of the twentieth century, significant advancements and modifications in biochar production methods emerged. Over time, a variety of modern approaches have been developed, including advanced pyrolysis techniques such as flash, vacuum, and microwave pyrolysis, as well as gasification, torrefaction, hydrothermal carbonization, and electro-modified methods (Gabhane *et al.*, 2020)^[29].

Gasification: Gasification is a thermochemical process in which biomass is converted into biochar, bio-oil, and syngas by applying high temperatures above 750 °C in the presence of oxygen, air, or steam, using the heat generated from biomass decomposition (Ravindiran *et al.*, 2024)^[89]. This method is widely employed for producing syngas from various solid fuel sources. Compared to conventional techniques such as pyrolysis, combustion, and fermentation, gasification offers higher syngas yields and lower leveled emissions. Hydrogen is a major component of the

syngas produced through gasification (Gonzalez *et al.*, 2008)^[38]. Overall, gasification serves as an efficient thermochemical approach to converting biomass into energy while generating biochar as a valuable byproduct (Guan *et al.*, 2016)^[41].

Torrefaction: Torrefaction is a thermal treatment process in which biomass is heated at moderate temperatures ranging from 300 to 550 °C, with a heating rate of approximately 50 °C min⁻¹ and residence times of 20 to 40 minutes, producing biochar along with bio-oil and syngas (Manyà *et al.*, 2014). This process is commonly used as a pre-treatment to reduce biomass moisture content, thereby enhancing its subsequent thermal conversion efficiency. Biochar yields from torrefaction typically range between 30% and 70% (Enaime *et al.*, 2020)^[26]. During torrefaction, the hemicellulose fraction of the biomass decomposes, resulting in carbon-rich, stable solid products and volatile compounds that are more energy-dense and suitable for further applications (Prins *et al.*, 2006)^[87].

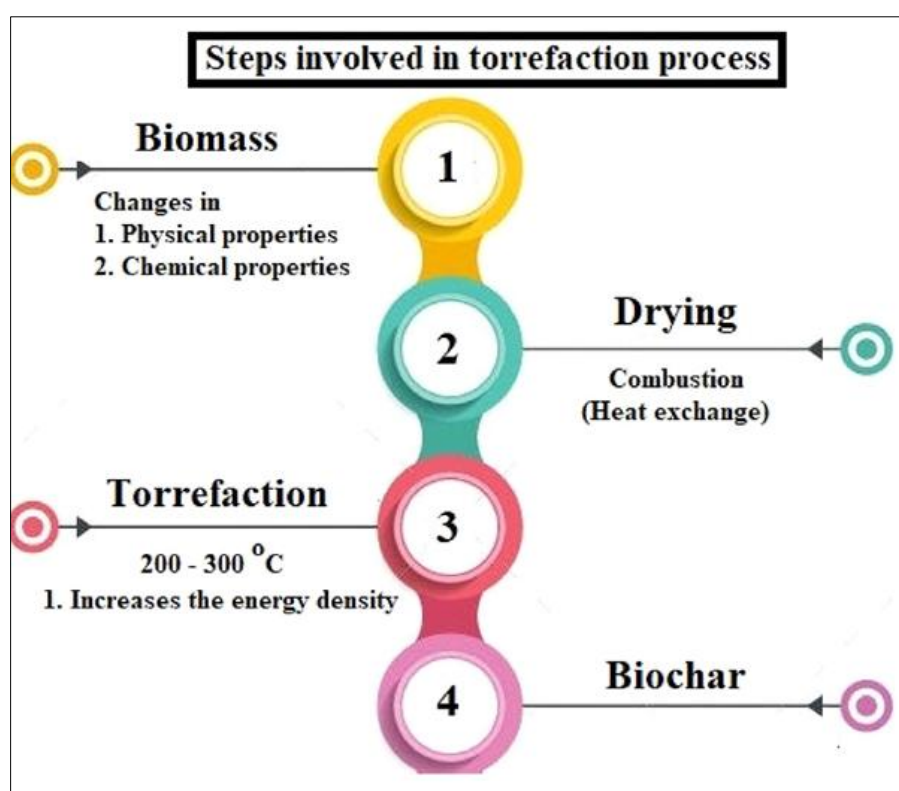


Fig 5: Steps involved in torrefaction process

Flash pyrolysis: Flash pyrolysis is an advanced variation of fast pyrolysis, characterized by extremely rapid thermal decomposition of biomass at very high temperatures, typically above 1000 °C, within a very short time usually less than a minute. Heating rates can exceed 1000 °C per second, and the process is generally conducted at temperatures between 900 and 1200 °C, which can be reached almost instantaneously (Li *et al.*, 2013; Demirbas *et al.*, 2002)^[23, 68]. This combination of extremely high temperature, rapid heating, and short vapor residence time favors the production of bio-oil in high yields. However, the rapid conversion conditions result in comparatively lower biochar yields (Tripathi *et al.*, 2015)^[108].

Microwave assisted pyrolysis: Microwave-assisted pyrolysis (MAP) is a modern advancement in thermochemical conversion technologies. In this method, microwaves are used to efficiently convert uniform biomass waste into energy-rich feedstocks (Ge *et*

al., 2021)^[32]. Unlike conventional heating, where energy transfers from the surface inward, MAP delivers energy directly within the biomass, enabling rapid and uniform pyrolysis throughout the material (Liu *et al.*, 2021b)^[71].

Hydrothermal Carbonization (HTC): Hydrothermal carbonization (HTC) is a method used to convert high-moisture feedstocks, such as sewage sludge, animal manure, and compost, into biochar-like products called hydrochar (Titirici *et al.*, 2007)^[106]. Unlike conventional biochar, which is produced through dry pyrolysis, hydrochar is formed under wet conditions, where biomass undergoes thermal treatment in a mixture of solid and liquid phases. Consequently, the properties of hydrochar differ from those of traditional biochar, reflecting the differences between dry and hydrothermal carbonization processes (Kambo & Dutta, 2015)^[55].

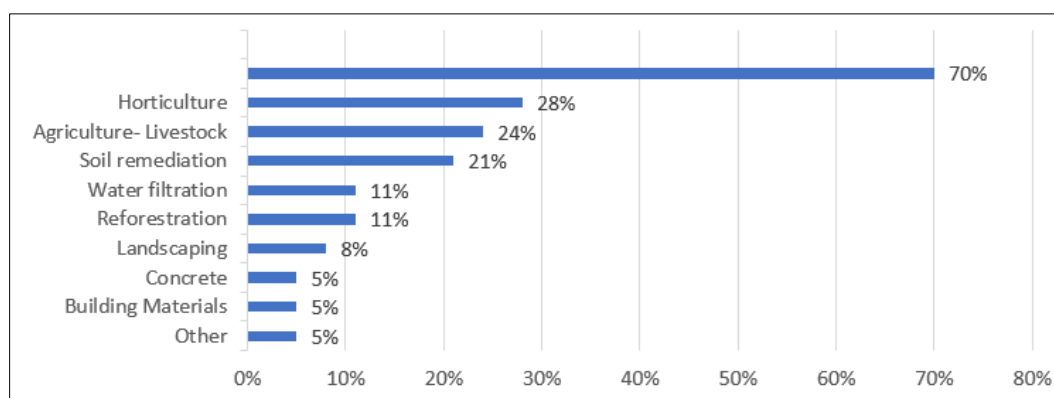
Table 2: Emerging technologies for biochar production in India (Sigh, *et al.*, 2025)

Technology	Description	Advantages	Status in India	Example
Microwave-assisted pyrolysis	Microwave radiation is used to provide rapid and consistent heating during the pyrolysis process	Quick processing, higher energy efficiency, and customized biochar characteristics	Mostly in the research phase, few pilot projects exploring potential.	Company: Indian Institute of Technology (IIT) Bhubaneswar Location: Kansapada, Odisha
Flash carbonization	Biomass is rapidly heated to high temperatures before being quenched.	Increased surface area biochar with tailored functional groups for various purposes.	Under research, some lab-scale and pilot-scale trials investigating commercialization.	Company: ICAR-Central Research Institute for Dryland Agriculture (CRIDA) Location: Hyderabad, Telangana
Gasification and biochar co-production	Fractional burning of biomass to produce syngas and charcoal as byproducts	Enhanced energy recuperation, greater economics, and syngas consumption potential	Research and demonstration phase, pilot projects exploring integration.	Company: Anulekh Agrotech Pvt. Ltd. Location: Mumbai, Maharashtra
Hydrothermal carbonization (HTC)	Wet biomass is converted into hydrochar at high temperatures and pressure in water	Wet feedstocks are efficiently processed, with the potential for nutrient recovery.	Research ongoing, pilot-scale projects evaluating feasibility for specific applications.	Company: Indian Institute of Technology (IIT) Kharagpur Location: Kharagpur, West Bengal
Biochar functionalization	Post-treatment procedures to improve biochar characteristics for certain applications	Expanded application range, tailored biochar properties for specific uses.	Increasing research and development activities, some projects exploring commercialization.	Company: APChem-Agile Process Chemicals Location: Navi Mumbai, Maharashtra

4. Biochar applications

Biochar contains a higher carbon content compared to commercially available activated carbon, making it a valuable tool for environmental management and various pollution control

applications. Its versatility extends across multiple sectors, including biofuel production, soil enhancement, construction materials, carbon sequestration, and the improvement of composting processes.

**Fig 6:** Existing end-use market (global biochar market report, 2023)

Biochar for soil structure and enrichment: In agriculture, biochar is often referred to as “black gold” due to its remarkable benefits for soil health and crop productivity. Intensive land use and modern farming practices have altered soil properties, leading to numerous ecological challenges (Ravindiran *et al.*, 2024)^[89]. Incorporating biochar into soils can enhance their physical structure by increasing porosity, surface area, water retention, oxygen availability, and adsorption capacity (Janus *et al.*, 2015; Chan *et al.*, 2007)^[17, 52]. The expanded surface area and pore network also provide habitats for beneficial bacteria and fungi, which facilitate nutrient absorption from the soil (Chan *et al.*, 2007)^[17]. Higher soil porosity helps maintain moisture and aeration, supporting microbial activity and stimulating nitrification processes (Zhang *et al.*, 2013; Mukherjee *et al.*, 2013)^[79, 120].

In addition to physical improvements, biochar positively influences soil chemical properties, including organic matter, nitrogen, carbon, and pH levels. It also contains essential micronutrients such as nitrogen, phosphorus, potassium, calcium,

magnesium, and sulfur, which, when added to soil, enhance nutrient availability and plant growth (Glaser *et al.*, 2001)^[35]. Several studies have shown that enriched biochar, compared to raw biochar, further improves soil fertility by maintaining higher levels of organic matter and releasing greater amounts of micronutrients (Kizito *et al.*, 2019)^[60].

Biochar as a source of nutrients: Biochar can serve as an important source of essential micronutrients such as boron, molybdenum, potassium, phosphorus, and calcium, all of which play a key role in the nodulation process of Rhizobium bacteria (Randon *et al.*, 2007). When applied together with compost, biochar markedly improves nutrient availability in the soil, leading to enhanced crop growth and higher productivity (Fischer and Glaser, 2012)^[28, 34]. Numerous studies have consistently reported that biochar application has a positive effect on soil fertility and supports yield improvement across a wide range of crops (Agegnehu *et al.*, 2015; Fischer and Glaser, 2012; Liang *et al.*, 2014)^[3, 28, 34, 69].

Effects of biochar on microbial diversity and soil enzyme:

Biochar is known to supply several essential micronutrients, including boron, molybdenum, potassium, phosphorus, and calcium, which are crucial for effective *Rhizobium* nodulation in leguminous crops (Randon *et al.*, 2007). Its combined application with compost has been shown to improve soil nutrient availability, thereby promoting better crop growth and increased yields (Fischer and Glaser, 2012) [28, 34]. A growing body of research confirms that biochar enhances soil fertility and contributes to productivity gains in a wide range of agricultural crops (Agegnehu *et al.*, 2015; Fischer and Glaser, 2012; Liang *et al.*, 2014) [3, 28, 34, 69].

Biochar amendment suppresses plant diseases: Beyond its well-recognized role in carbon sequestration, nutrient enrichment, and improvement of soil physical and biological properties, biochar has also been shown to reduce the severity of plant diseases and enhance resistance against a range of pathogens. Several studies have reported that biochar application can suppress disease incidence and stimulate plant defense mechanisms by influencing microbial diversity and extracellular

enzyme activity in the soil (Elad *et al.*, 2010; Meller *et al.*, 2012; Spokas *et al.*, 2012; Wang *et al.*, 2016; Bhaduri *et al.*, 2016; Huang *et al.*, 2017) [10, 24, 47, 75, 100, 111].

Biochar for wastewater treatment: Growing population pressure and rapid industrialization have led to the discharge of large volumes of wastewater into natural ecosystems. Among the most frequently encountered and hazardous contaminants in these effluents are dyes and heavy metals, which are persistent in nature and can cause serious environmental damage even at very low concentrations, such as 1 mg L^{-1} . A range of treatment methods is therefore used to remove these pollutants, including coagulation, reverse osmosis, ion exchange, membrane filtration, and biosorption (Gabhane *et al.*, 2020) [29]. In this context, biochar has attracted increasing attention due to its properties that closely resemble those of activated carbon. Its high carbon content, porous structure, large surface area, and abundance of surface functional groups make biochar an effective and promising material for wastewater treatment applications (Oliveira *et al.*, 2017) [85].

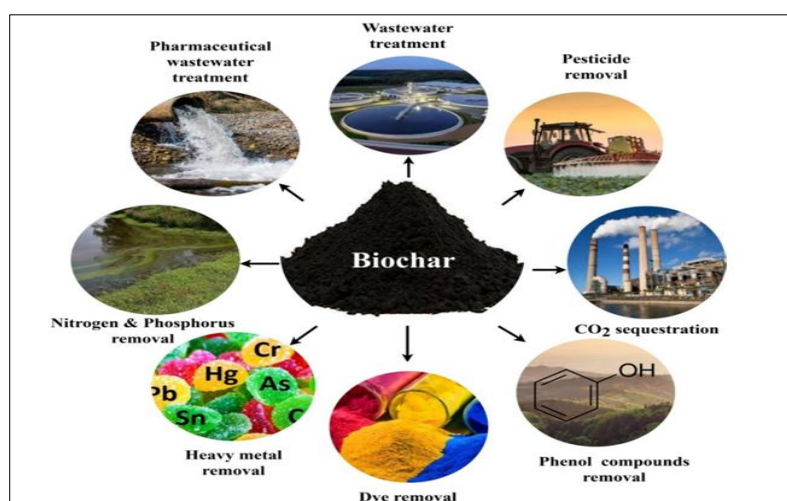


Fig 7: Application of biochar in wastewater treatment

5. Biochar and global climate change

Research conducted between 1998 and 2010 highlighted the benefits of biochar in improving soil carbon storage and reducing greenhouse gas emissions, demonstrating its potential role in mitigating global climate change. During this period, studies showed that converting waste biomass into biochar was an effective way to sequester carbon (Gaunt and Lehmann, 2008; Roberts *et al.*, 2010; Woolf *et al.*, 2010) [31, 91, 114]. Compared to raw biomass, biochar decomposed more slowly and remained stable in soils over the long term (Masiello and Druffel, 2003; Nguyen *et al.*, 2009; Zimmerman, 2010) [74, 82, 122].

Between 2011 and 2015, research in this area expanded significantly, providing detailed insights into biochar stability. Factors such as higher hydrothermal treatment (HTT), longer reaction times, larger particle size, and higher lignin content in the biomass were found to produce more stable biochar (Fang *et al.*, 2014; Harvey *et al.*, 2012; Many *et al.*, 2014; Singh *et al.*, 2012; Windeatt *et al.*, 2014) [27, 72, 98, 113]. Mineral additions, including kaolin, calcite, and calcium dihydrogen phosphate, were also shown to enhance biochar stability, suggesting new strategies for producing biochar with high carbon sequestration potential (Li *et al.*, 2014) [66].

Beyond carbon storage, biochar influences soil biochemical

processes. For example, it can increase methane (CH_4) uptake (Karhu *et al.*, 2011) [56], reduce the abundance of nitrifying microbes, enhance denitrification and N_2 fixation, and adsorb ammonium (NH_4^+), leading to lower N_2O emissions (Anderson *et al.*, 2011) [7]. These findings help explain how biochar contributes to the reduction of climate-relevant greenhouse gases through changes in soil microbial communities.

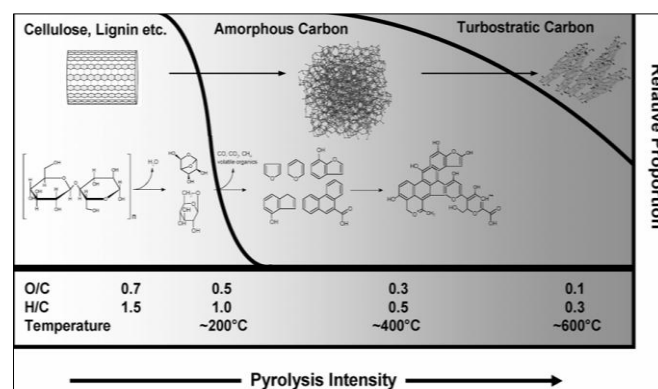


Fig 8: Role of biochar in mitigation of climate change

Fig. 2. A schematic representation illustrates how organic materials, using cellulose as an example, transform during pyrolysis as temperature increases. At lower temperatures, dehydration reactions lead to the formation of compounds such as levoglucosan and anhydrides (Mok and Antal, 1983) [77]. As the temperature rises, poly-aromatic and heterocyclic carbon structures rich in oxygen are formed, while significant amounts of carbon are released in gaseous and liquid forms (Knicker, 2007) [61]. At even higher temperatures, these intermediate structures break down into amorphous carbon (Kercher and Nagle, 2003) [58], which can then reorganize into highly ordered structures containing reactive radicals and heterocycles (Harris, 2005) [45]. These transformations summarize the progressive chemical changes during pyrolysis (Hammes and Schmidt, 2009; Krull *et al.*, 2012; Keiluweit *et al.*, 2010) [43, 57, 62].

Cornelissen *et al.* (2013) [20] suggested that the sorption of N_2O to anhydrous biochars could be a key mechanism for reducing N_2O emissions. Similarly, Van Zwieten *et al.* (2014) [109], using ^{15}N stable isotope techniques, showed that biochar amendment in Tenosol soils reduced N_2O emissions by creating favourable conditions for the enzyme nitrous oxide reductase (nosZ). Overall, the reduction of greenhouse gas emissions (CO_2 , CH_4 , N_2O) in biochar-amended soils occurs through a combination of abiotic and biotic mechanisms, with the extent of mitigation influenced by the specific properties of both the soil and the biochar.

6. Market analysis of biochar

A word on this market research: Industry composition (Global Biochar Market Report, 2023)

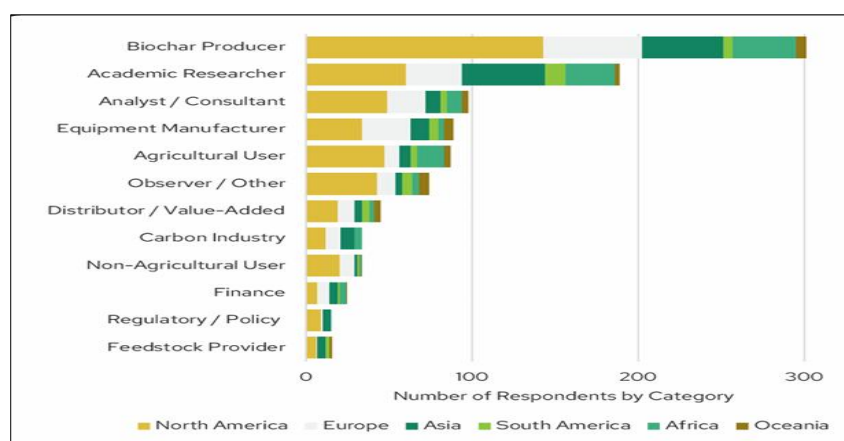


Fig 9: This report provides insights gathered through 007 survey responses from just over 100 countries and multiple stakeholder group within the biochar industry

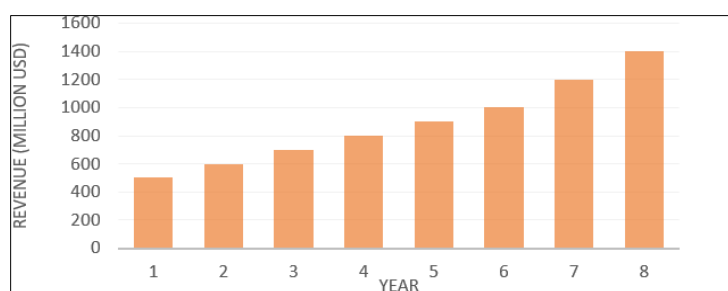
a. Global market overview-biochar market size and trends

Biochar is increasingly recognized as a critical resource for achieving a net-zero carbon society. In 2024, the global biochar market was valued at approximately \$877.15 million and is projected to reach \$3,111.96 million by 2034, growing at a compound annual growth rate (CAGR) of around 13.5% (Precedence Research, 2024) [86]. Its expanding use in organic farming, along with its proven benefits for soil fertility and crop productivity, are key drivers of this growth. Earlier projections indicated the global market would reach USD 541.8 million in 2023, with a CAGR of 13.9% between 2024 and 2030 (Regional Analysis, 2024).

In Europe, countries such as Austria and Switzerland have recently adopted the European Biochar Certificate, which allows for the direct incorporation of biochar into agricultural soils (Abu-Rumman *et al.*, 2016) [1]. Factors such as growing environmental awareness, lower raw material costs, and supportive government waste management policies are expected to create further opportunities for market expansion (Zorpas, *et al.*, 2020) [123]. The

biochar industry comprises both organized and unorganized sectors, reflecting the presence of large-scale manufacturers alongside a rising number of small and medium-sized producers, particularly in North America and Europe (Growth Analysis Report, 2024).

However, adoption remains slower in the Middle East and Asia-Pacific due to limited awareness of biochar and its long-term benefits (Biochar Market Growth, Size, Share, Trends, Forecast 2033 | Brainy Insights, n.d.). In countries such as rural China, Japan, Brazil, and Mexico, significant quantities of biochar are produced in collaboration with research institutions and organizations (Shi *et al.*, 2021) [96]. Beyond improving soil properties, biochar contributes to carbon sequestration (He *et al.*, 2024; Li *et al.*, 2014) [66], further strengthening its market potential across multiple sectors. With the increasing global emphasis on carbon neutrality and circular economy initiatives, the demand and application of biochar are expected to expand significantly in the coming years.



(a)

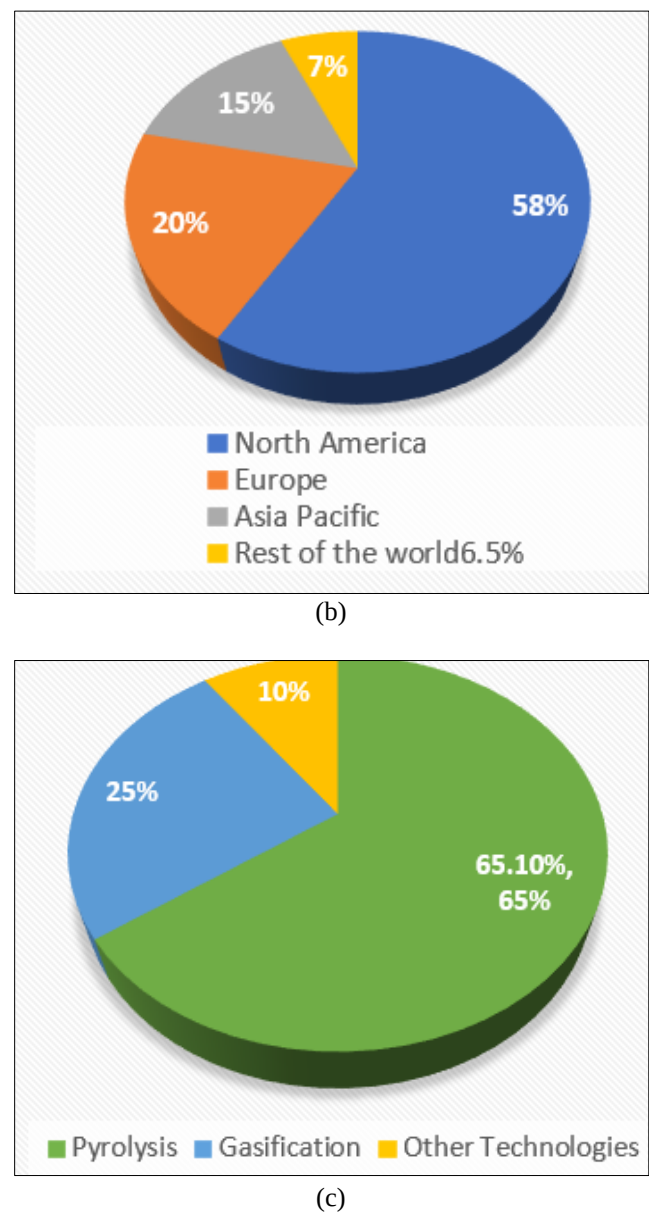


Fig 10: Market analysis of biochar: a) Global biochar market overview, b) production technology insights, and c) biochar regional revenue share. (Global Biochar Market Report, 2023)

The biochar industry remains in its early development stage and is highly fragmented, comprising a small number of producers with production capacities ranging from small to large scale. Market participants often compete by offering high-quality biochar products at competitive prices in the global marketplace (Garcia *et al.*, 2022)^[30]. North America hosts over 80% of the world's large and medium-scale biochar manufacturers, surpassing the numbers in Europe and the Asia-Pacific region. By 2023, agriculture emerged as the dominant application segment, accounting for more than 77% of total revenue. Meanwhile, applications such as water treatment and waste management are experiencing growing demand, particularly in emerging economies like China and India.



Fig 11: Indian Biochar Market 2024-2032

b. Biochar price data

Biochar market prices have declined significantly over the past decade, falling from approximately \$2,740 per ton in 2013 to a range of \$600-\$1,300 per ton by 2021 (Thengane *et al.*, 2021; Zilberman *et al.*, 2023)^[103, 121]. In the US, prices have historically varied widely, from \$270/t to \$13,480/t, with an average of \$2,740/t in 2013 (Cheng *et al.*, 2020)^[19], and a slightly lower value of \$2,512/t in 2014 (Campbell *et al.*, 2018)^[16]. According to IBI reports, the price remained around \$2,062/t in subsequent

years (Jirka & Tomlinson, 2015)^[54]. The market began experiencing a notable decline starting in 2017, with surveys reporting prices as low as \$661/t, an average of \$1,137/t, and a most frequently cited price of \$1,764/t (Groot *et al.*, 2018)^[40]. Recent studies recorded biochar prices of \$1,600/t in 2018 and \$1,044/t in 2019 (Nematian *et al.*, 2021; Sahoo *et al.*, 2019)^[81, 93]. Prices have since stabilized at approximately \$1,300/t, reflecting more consistent production levels in recent years (Thengane *et al.*, 2021; Zilberman *et al.*, 2023)^[103, 121].

Table 3: Biochar prices evolution (2013-2021) (Trapero *et al.*, 2025)^[107]

Year	Actual Prices (\$/t)	Reference
2013	2740	Cheng <i>et al.</i> (2020) ^[19]
2014	2512	Jirka and Tomlinson (2013)
2015	2062	Jirka and Tomlinson (2013)
2016	Missing value (1865 ^a)	-
2017	1764	Groot <i>et al.</i> (2018) ^[40]
2018	1600	Nematian <i>et al.</i> (2021) ^[81]
2019	1044	Sahoo <i>et al.</i> (2019) ^[93]
2020	Missing value (1253 ^a)	-
2021	1300	Zilberman <i>et al.</i> (2023) ^[121]

^a Interpolated values by means of a quadratic regression.

The biochar prices reported in Table 3 align closely with those presented by Campion *et al.* (2023). Despite this relative price stabilization, biochar remains considerably more expensive than conventional charcoal, which limits its competitiveness in the market. As noted by Mardoyan and Braun (2015)^[73], economic incentives and supportive policies are essential for encouraging biochar adoption, especially in regions where cheaper charcoal alternatives dominate. In the absence of targeted subsidies or carbon credit schemes, the high production costs of biochar continue to constrain its large-scale commercial deployment.

c. Indian market dynamics: The Indian biochar market was

valued at USD 71.91 million in 2024 and is projected to reach USD 183.95 million by 2033, growing at a compound annual growth rate (CAGR) of 11.0% during 2025-2033 (IMARC Group) (Fig. 11). This growth is driven by rising demand for sustainable soil enhancement, carbon sequestration, and waste management solutions, supported by government initiatives, increased adoption in agriculture, and growing interest in bio-based alternatives. Key applications include farming, forestry, and environmental remediation, positioning India’s biochar market for rapid expansion and significant opportunities in climate change mitigation and sustainable agriculture.

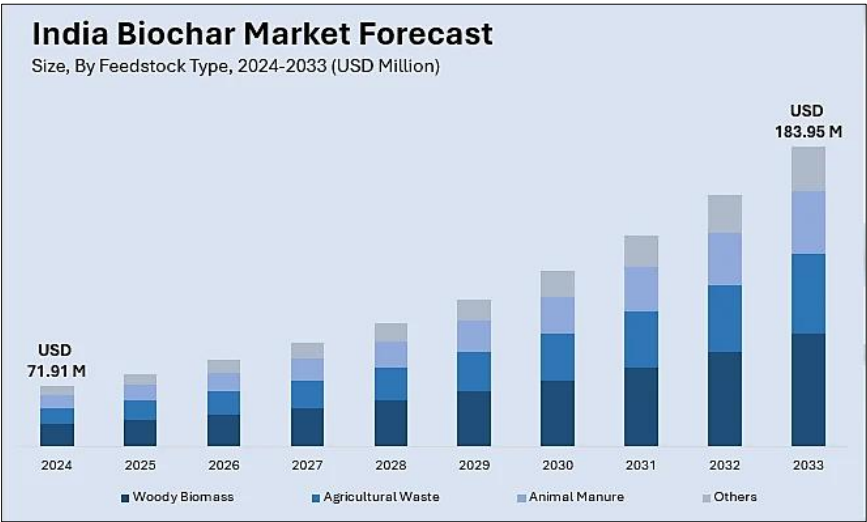


Fig 12: India biochar market forecast with compound annual growth rate 11% (India Biochar Market Size, Share and Industry Report 2033)

Although still in its early stages, the biochar market is experiencing growing interest and adoption across various industries. Market research suggests that the Indian biochar sector is poised for strong growth, with a projected compound annual growth rate (CAGR) exceeding 15% during the forecast period. The emerging technologies employed for biochar production in India are summarized in Table 1. Beyond its established use in agriculture, biochar is increasingly being investigated for potential applications in water purification, remediation of

contaminated soils, enhancement of concrete properties as an additive, and as a supplement in animal feed.

Conclusion

Biochar has emerged as a well-established and versatile material with the capacity to tackle several interconnected issues, including climate change, declining soil quality, environmental contamination, and sustainable use of natural resources. Its role in improving soil health, storing carbon for extended periods,

lowering greenhouse gas emissions, and removing pollutants demonstrates its wide applicability in both agricultural and environmental contexts. Ongoing improvements in production methods, along with increasing market interest, have further reinforced its importance within the circular bioeconomy. However, broader adoption-especially in countries such as India-will require coordinated research, economically viable large-scale production, and strong policy support with appropriate incentives. With such integrated efforts, biochar has the potential to contribute significantly to long-term climate resilience and sustainable development.

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