Review Article

BIOCHAR PRODUCTION FROM PLANT RESIDUES: A SUSTAINABLE APPROACH FOR CARBON SEQUESTRATION AND SOIL FERTILITY IMPROVEMENT

Abstract

This review article explores the sustainable practice of producing biochar from plant residues, effectively transforming green waste into a valuable resource commonly referred to as “green gold”. It discussed mainly on the pyrolysis process of biochar production, and the impact of different pyrolysis methods on the resulting biochar's properties, including surface area, porosity, and nutrient holding capacity. Further, the review analyzes the multifaceted benefits of biochar for soil health and plant growth. It highlights how biochar can improve soil structure, increase water retention, and enhance nutrient availability, leading to healthier and more productive agricultural lands. Additionally, the review explores biochar's potential in influencing the soil microbial community, potentially promoting beneficial organisms and suppressing harmful pathogens. It also explores biochar's role in mitigating climate change by capturing and storing atmospheric carbon, effectively reducing greenhouse gas emissions. However, a balanced perspective is maintained by acknowledging potential drawbacks associated with biochar use, such as the need for further research to optimize production methods and potential negative impacts on certain soil fauna. This review highlights biochar's promise as a sustainable, cost-effective solution for agriculture and environmental issues. Biochar adoption can lead to a greener future through carbon capture, soil health, and waste management.

Keywords: Pyrolysis, plant leftovers, Sustainable agriculture, Carbon sequestration, Soil improvement

INTRODUCTION

To support sustainable agricultural systems and the growth of the rural economy, agricultural production management requires innovation. Soil erosion, greenhouse gas emissions, soil deterioration, and soil organic matter loss are often higher when comparing conservation agriculture strategies to standard crop management systems (Haider *et al*., 2022). Turning plant waste and leftovers into biochar can combat climate change in three ways. First, it reduces reliance on fossil fuels. Second, it traps carbon in the soil for long periods. Ultimately, it reduces the release of nitrous oxide, a potent greenhouse gas more harmful than carbon dioxide (Tomczyk, 2020). Due to its extended longevity, utilizing biochar, which stores carbon, in soil is proposed as a potential approach to diminish atmospheric CO_2 levels (Rawat *et al.*, 2019). Biochar's vast surface area makes it effective in attracting and holding onto both organic and inorganic pollutants. Additionally, its properties allow it to stay put in the soil, preventing contamination from spreading (Laghari *et al.*, 2016). Soil microorganisms in biochar can break down more labile soil organic matter (SOM) and accelerate soil stabilization. The higher mineralization of biochar provides important nutrients for plant growth (Fischer and Glaser, 2012; Laghari *et al.*, 2016). Biochar's distinctive physicochemical characteristics, particularly its high capacity for carbon sequestration and metal immobilization, render it a valuable tool for soil remediation efforts. It can reduce the stress that plants experience from their surroundings (Jawaria *et al.*, 2014).

Bulk plant wastes are utilized as biomass, animal feed, and biofuel after harvest. To achieve sustainable production and protect the environment, we need to find innovative ways to convert waste materials into biochar. Carbonizing leftover agricultural residue to create biochar has emerged as a novel method of using residues (Askeland *et al.*, 2019; Kumari *et al.*, 2023). Made from biomass via pyrolysis, biochar is a carbon-rich, finely divided material with a highly porous structure (Gell *et al.*, 2011). While pyrolysis breaks down organic material at high temperatures with minimal oxygen, creating biochar, it is important to note that biochar itself does not necessarily sequester carbon. In fact, if left to decompose naturally, one ton of biochar could release 3.6 tons of CO_2 (Babu *et al.*, 2023; Lehmann and Joseph, 2015; Li *et al.*, 2022). There are two main methods for creating biochar from various materials: slow pyrolysis and hydrothermal carbonization (low heat and high pressure). The surface area, functional groups, pH, porosity, and content of the finished product are determined by the manufacturing temperature and feedstock.

Biochar produced at cooler temperatures has more sorption capacity and surface area than biochar generated at higher temperatures (>550°C) (Ahmad *et al.*, 2014; Babu *et al.*, 2023). Higher treatment temperatures reduce biochar production from the feedstock. Achieving the desired biochar properties for agricultural and environmental applications necessitates optimizing the pyrolysis process, particularly by carefully selecting feedstock type and temperature. (Jawaria *et al*., 2014). The source plant material plays a crucial role in determining biochar's pH level. For instance, biochar made from mulberry leaves has a much higher pH compared to biochar derived from cinnamon bark (Ahmad *et al.*, 2014). Biochar can lower greenhouse gas emissions by 12% and boost agricultural output by 11% on a global scale. In soil, it can sequester around 0.7–1.8 g of CO_2 per year and store C in a solid state. Biochar application enhances soil health, promotes agricultural yield, and promotes plant development (Jawaria *et al.*, 2014). Biochar's rich organic carbon content significantly boosts the soil's ability to store carbon, potentially reaching up to 90% depending on the feedstock used in its production (Lehmann and Joseph, 2015).

Biochar stands out from other soil organic matter due to its exceptionally high content of aromatic carbon and condensed aromatic structures (Yeboah *et al.*, 2020). The aromatic structure has a considerable impact on the formation of porous structures and the initiation of chemical reactions in soil (Qiu *et al.*, 2022). Biochar has an array of impacts on different types of soil; hence, its impact on crops and yield is likely to vary (Fischer and Glaser, 2012). Biochar is rich in both total and organic carbon, boasting a balanced composition of macro and micronutrients (Lehmann *et al.*, 2006). Considered "green gold," biochar has enormous potential to solve different pressing issues. This review paper explores the method of producing biochar from plant leftovers, emphasizing its environmental advantages, potential uses and obstacles.

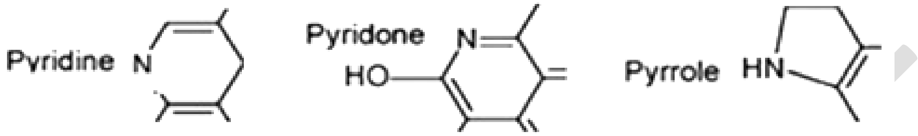

Fig. 1. *Biochar possesses chemically active groups on the surface of graphene sheets* (Tomczyk, 2020)

BIOCHAR PRODUCTION

Biochar is a dark substance with a porous and fine-grained texture, lightweight nature, substantial surface area, and a pH level that positively influences soil (Laghari *et al.*, 2016). Biochar production provides a sustainable alternative by utilizing a variety of waste organic materials, including sludge, manure, food scraps, agricultural and forestry leftovers (Cantrell *et al.*, 2012; Haider *et al.*, 2022; Ohtsuka *et al.*, 2021). Biochar, a versatile product, originates from diverse agricultural waste like grasses, manure, wood chips, and other organic residuals. Biochar is composed of minerals and components in the ash fraction (hydrogen, carbon, oxygen, sulphur and nitrogen) (Lewandowski *et al.*, 2010). During the biochar production process, oil, CO_2, H_2, CH_4, and CO form, giving sustainable energy. The gasification process differs from pyrolysis in the formation of biochar (Qiu *et al.*, 2022; Yeboah *et al.*, 2020). The amount of biochar produced using pyrolysis and hydrothermal carbonization processes is heavily influenced by the operation parameters, reaction media, and biomass type. Before being used, the dry waste is chopped into pieces before being used (Cantrell *et al.*, 2012; Lewandowski *et al.*, 2010).

Pyrolysis is the oldest known and most used method of biomass thermal process (Arif *et al.*, 2017). The classification can be made into fast and slow pyrolysis, depending on factors such as the temperature used, residence time, and rate of heating, as shown in **Figure 2** (Agarwal *et al.*, 2022; Cantrell *et al.*, 2012). Slow pyrolysis is most frequently used and produces more biochar but less liquid fuel than other chemical and thermal techniques, whereas fast pyrolysis produces around 75% liquid fuel and generates more biofuel (Liu *et al.*, 2013). 25%–35% of biochar is produced during intermediate and slow pyrolysis (Qiu *et al.*, 2022). Pyrolysis yields three products: biochar, synthetic gas, and bio-oil as shown in **Table 1** (Buss *et al.*, 2015; Yeboah *et al.*, 2020). The range of temperatures, pressure, reaction time, feedstock composition and moisture content affect how much each of these product's forms (Buss *et al.*, 2015).

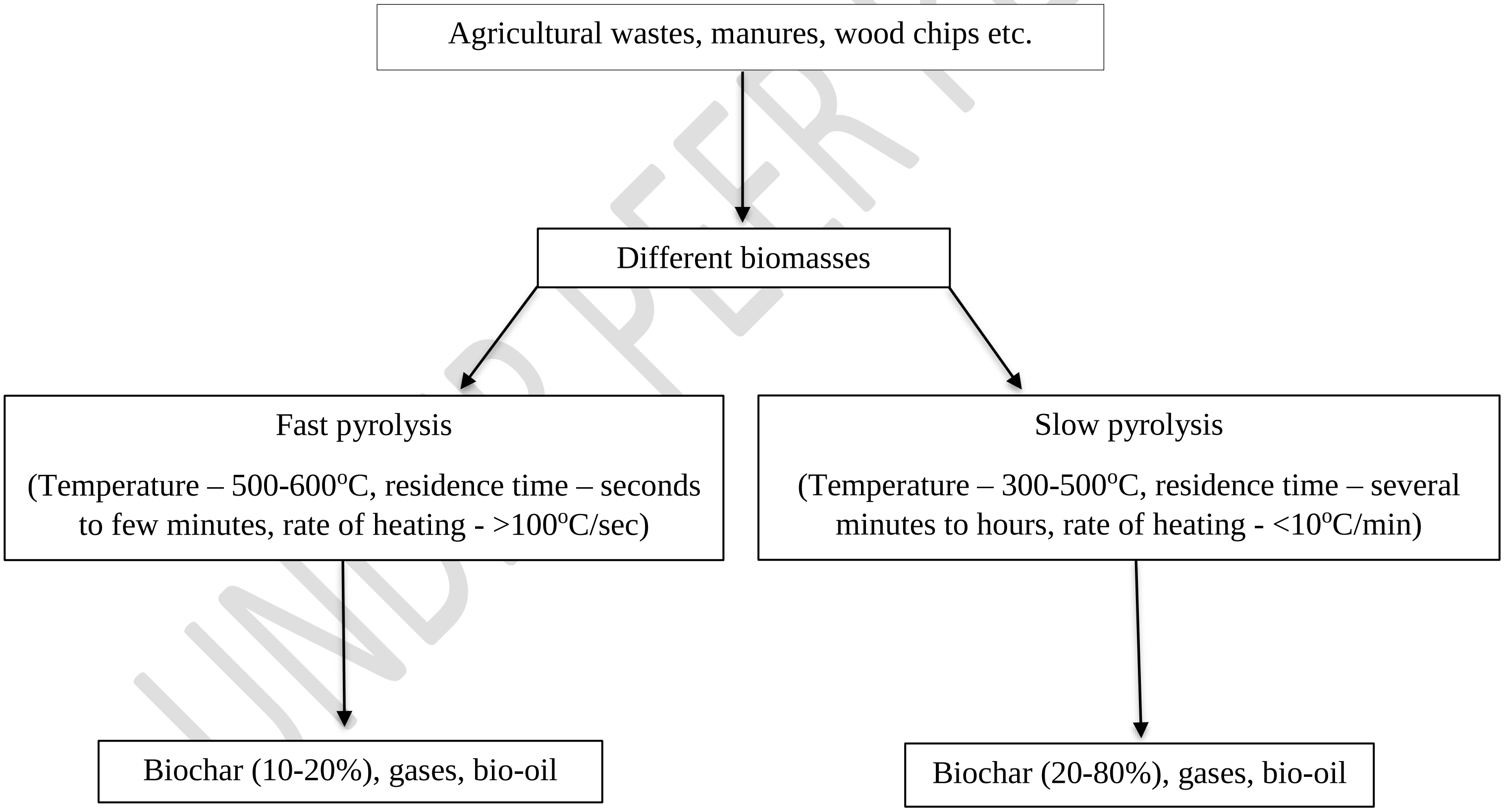

Fig. 2. *Biochar production from different biomasses* (Rawat *et al.*, 2019).

Table 1. *Pyrolysis products under different conditions* (Tomczyk, 2020)

Method	Pressure	Time of residence	Pyrolysis temp. (ºC)	Proportions of products created through pyrolysis (%)		
				Biochar	Bio oil	Synthetic gas
Gasification	Atmospheric-elevated	Second-minutes	700-1500	10	5	85
Fast pyrolysis	Vacuum-atmospheric	Seconds	400-600	12	75	13
Slow pyrolysis (Biocarbonization)	Atmospheric	Seconds-hours	350-800	35	30	35

EFFECT OF PYROLYSIS ON BIOCHAR

Biochar is made in three steps: pre-pyrolysis, pyrolysis, and the production of soil carbon compounds (Ding *et al.*, 2014). Biochar production begins with drying and releasing volatile components at low temperatures (up to 200°C). The next stage, between 200°C and 500°C, witnesses a rapid breakdown and volatilization of hemicelluloses and cellulose (Asadullah *et al.*, 2007). High temperatures (over 500°C) mark the final stage, breaking down tougher organic compounds like lignin (Askeland *et al.*, 2019). Biochar's properties and structure directly depend on the temperature used during its production through pyrolysis (Agarwal *et al.*, 2022). The physical and chemical properties of biochar are affected by the pyrolysis temperature (Ajema, 2018).

Pyrolysis is differentiated based on heating parameters, with fast pyrolysis employing temperatures surpassing 500°C and exceedingly rapid heating rates exceeding 1000°C per minute. This specific condition is favorable for maximizing the production of bio-oil. Conversely, Slow pyrolysis produces more biochar but takes longer to finish, ranging from several hours to minutes (heating rates is less than 100°C/min). The range of temperatures remains between 250°C and 500°C (Stoyle, 2011). Higher pyrolysis temperatures result in decreased cation exchange capacity (CEC) and surface functional group content despite increased carbonized fractions, surface area, pH, etc. Pyrolysis has substantial influence on biochar quality and potential agricultural benefits including carbon sequestration and agronomic performance.

Table 2. *The physical and chemical properties of biochar* (Kumari *et al.*, 2023)

Biochar	
Physical Properties	Chemical Properties
1) Surface area 2) Density 3) Porosity 4) Pore volume 5) Water holding capacity 6) Pore size distribution	1) Energy content 2) Elemental composition 3) Fixed carbon and volatile matter 4) Structural composition 5) pH 6) Cation exchange capacity (CEC)

BIOCHAR ANALYSIS

Produced through pyrolysis, biochar offers long-lasting benefits for soil health and carbon capture. However, biochar properties are highly dependent on the specific process and feedstock used (Song *et al.*, 2016). Pyrolysis temperature heavily impacts biochar yield, with higher temperatures resulting in lower production. This effect is most pronounced for both woody and herbaceous feedstocks (Askeland *et al.*, 2019). The biopolymers in each feedstock differ in their composition of hemicellulose, cellulose, and lignin, each breaking down at distinct temperature ranges. Softwoods have a higher proportion of lignin compared to grasses (more cellulosic), due to the stiff structure that trees require. Hemicellulose is most easily broken down and breaks down completely at 330°C. At lower temperatures, cellulose can decompose by breaking carbon-hydrogen bonds and carbon-oxygen, although the majority of cellulose breakdown occurs at 427°C. This breakdown releases many volatile substances (Buss *et al.*, 2015). Lignin's complex structure makes it highly resistant to breakdown in pyrolysis, requiring temperatures above 607°C (Shenbagavalli and Mahimairaja, 2012).

The bulk density of feedstocks employed might differ based on conditions like the nature of the material, moisture content, particle size, and pyrolysis temperature (Yeboah *et al.*, 2020). Biochar's bulk density rises with increased pyrolysis temperatures, at least to a certain point. Furthermore, a change in bulk density will influence soil porosity, aeration, and perhaps microbial respiration (Tomczyk, 2020). It was found that temperature has a significant impact on volatile matter content, which decreases with higher temperatures. Besides temperature, feedstock has been discovered to have a major impact (Asai *et al.*, 2009). Temperature and feedstock are recognized as the primary factors in ash. Most of the inorganic components, heavy metals and carbonates, that cannot be volatilized or broken down by burning are represented by the ash fraction, which increases as temperature increases (Lewandowski *et al.*, 2010). Ash content in biochar can hinder the formation of aromatic structures, which are essential for high fixed carbon content (Yeboah *et al.*, 2020). The fixed carbon values are correlated with the index values of thermal stability, where higher values typically suggest a longer duration of the soil biochar. An increase in carbon concentration is often associated with a decrease in hydrogen concentration due to processes like polymerization, dehydration, and volatilization. Therefore, biochar's H:C ratio reflects its aromaticity, which impacts carbon storage (Das and Sarmah, 2015).

Dehydration causes hydrogen loss; however, condensation and graphitization increase carbon content and influence the H:C ratio. Denser, graphite-like structures in biochar lead to higher bulk density. However, this densification comes at the cost of lower yield and a decreased H:C ratio due to mass loss (Das and Sarmah, 2015). Though their resistance to thermal degradation is mostly determined by the original feedstock, these correlations are temperature-dependent. Increasing the pyrolysis temperature leads to a rise in both electrical conductivity and pH of the resulting product**.** The interactions between temperature, feedstock, and electrical conductivity were determined to be crucial in influencing pH and EC values (Nandini *et al.*, 2022; Yeboah *et al.*, 2020). When the ash fraction increases, more ions are present, resulting in a higher EC. Biochar alkalinity is also known to increase at higher pyrolysis temperatures (Asai *et al.*, 2009). Biochar from higher temperatures has stronger cation attraction (higher cation exchange capacity (CEC)) (Ohtsuka *et al.*, 2021).

INFLUENCE OF BIOCHAR ON SOIL AND SOIL HEALTH

According to reports, incorporating biochar into soil raises its pH level and improves moisture retention, attracting beneficial fungi and microbes while also boosting cation exchange capacity. These actions contribute to the enhancement fertility of soil and quality, aiding in the preservation of essential soil nutrients (Ajema, 2018; Liang *et al.*, 2006). Biochar modifies soil physicochemical characteristics, soil aeration, and cation-exchange capacity, however, it alters consistency and structure and decreases soil density and hardness (Nartey and Zhao, 2014; Yeboah *et al.*, 2020). Biochar has high carbon content, which enhances soil health by improving nutrient retention and increases water-holding capacity (Lehmann and Joseph, 2015). Biochar's ability to improve crop yields and store carbon in the soil makes it a popular tool in agriculture (Agarwal *et al.*, 2022; Liu *et al.*, 2013). Biochar attracts and holds onto clay, silt, and soil organic matter through weak chemical bonds (hydrophobic and van der Waals forces) (Hernandez-Mena *et al.*, 2014). This unique interaction of biochar determines how it alters soil physicochemical qualities and interacts with cations, anions, and different organic substances (Lewandowski *et al.*, 2010). Biochar's effects on key soil properties like surface area, CEC, density, and water retention can be positive or negative, depending on various factors (Ohtsuka *et al.*, 2021).

Applying biochar to soil is an effective strategy for reducing atmospheric CO_2 levels through carbon sequestration, with the long-term stability of biochar being key to sustaining lower CO_2 emissions (Tomczyk, 2020). Recent studies have shown that biochar could lessen harmful gas emissions from soil, like nitrous oxide (N_2O) and methane (CH_4) by influencing both biotic and abiotic processes (Hernandez-Soriano *et al.*, 2016). Biochar has longitudinal pores ranging in size from micro- to macropores making it highly porous. Large pores serve as homes for symbiotic microbes, enhancing soil quality (Lehmann and Joseph, 2015). In general, biochar increases soil's capacity to sequester carbon, lowers compactness, maximizes compost, enhances water retention and heavy metal sorption, raises soil pH, increases plant availability of micronutrients, and minimizes emissions of ammonia and carbon dioxide. Additionally, the growth of mycorrhizal fungi and rhizosphere microorganisms is promoted by biochar (Compant *et al.*, 2010; Saito, 1990). Microbial shifts impact soil processes (decomposition, carbon cycling, nutrient cycling) influencing plant growth. Biochar can influence the chemical, physical and agricultural growth, as well as the ecological features of soil (Cong *et al.*, 2023). As biochar matures, its elemental composition, physical structure, and surface functional groups change (Ohtsuka *et al.*, 2021). Additionally, when the microstructure of the biochar is destroyed, the soil's ability to adsorb trace elements also reduces. As the effects of biochar gradually wear off due to soil leaching, it must be used regularly to maintain its therapeutic impact. It is necessary to ascertain how long biochar ages in various types of soil. Initially, biochar can serve as a fertilizer for early-stage plant nourishment. Though biochar's effectiveness lessens over time, its long-lasting presence in soil benefits plants. As biochar ages, it improves nutrient uptake and retention, ultimately enhancing agricultural yields (Cong *et al.*, 2023).

IMPACT OF BIOCHAR ON PLANT GROWTH

Water intake triggers seed germination, ending when the root emerges. Biochar's impact on this process depends on several factors: (i) Salt release from biochar into the soil, (ii) Emission of toxins that harm plant growth (phytotoxins), (iii) Release of hormones that promote germination, (iv) Changes in soil's air and water holding capacity (porosity). These factors are influenced by the type of material used to make biochar (feedstock), the amount applied, and other biochar properties. This explains the varied effects of biochar on seed germination speed and success rates (Spokas *et al.*, 2012). It has been seen that aqueous extracts of some biochar promote seedling development along with germination (Prendergast-Miller *et al.*, 2014). The biochar impact is dependent upon several experimental variables, including soil types and habitats apart from crop species, biochar characteristics, rates, techniques, and frequency of biochar application. Regular application of biochar increases crop biomass by 10% to 30% on average (Song *et al.*, 2016).

Biochar application may prevent the growth of root hairs because the biochar-treated soil will have a greater phosphorus (P) content (Spokas *et al.*, 2012). When applied to plants growing in nutrient-rich soils in contrast to deficient soils, biochar has a bigger effect. Applying biochar tends to provide more favorable growth responses, especially in soils with coarse textures or high acidity (Semida *et al.*, 2019). In acidic, infertile tropical soils, biochar has been associated to strong beneficial plant responses through salt sorption, soil liming effects, P retention and soluble P from biochar (Spokas *et al.*, 2012). Biochar application significantly increases crop yields in sandy, depleted, and moderately acidic soils by improving soil properties and nutrient content.

BIOCHAR IMPACT ON SOIL MICROBIAL COMMUNITIES

Research shows that biochar boosts soil microbes, enhancing soil carbon storage. In addition to absorbing gases, nutrients, and organic materials, biochar provides a home for bacteria, fungi, and actinomycetes (Yeboah *et al.*, 2020). Pore spaces of biochar provide the right conditions for the growth of microbial and fungal populations. The addition of biochar to soil is recognized for its ability to enhance water retention, potentially affecting the soil's microbial communities. It is believed that the soil's capacity to hold water, the composition of microbial populations, and its capability to absorb heavy metals and other pollutants are notably influenced by the specific surface area of biochar (Poveda *et al.*, 2021; Rajapaksha *et al.*, 2016). Biochar enhances microbial activity which in turn boosts soil nitrogen absorption (Brown *et al.*, 2011). Biochar surpasses organics in long-term soil improvement due to exceptional microbiological and chemical stability. Higher pyrolysis temperatures and increased aromaticity further enhance its resistance to microbial degradation. Biochar is more resistant to microbial destruction with increased aromatic structures. The high bonding between the carbon atoms in biochar makes it resilient to microbial degradation and predation (Ohtsuka *et al.*, 2021). It being rich in carbon can withstand microbial and chemical degradation, allowing carbon to be stored for long (Brown *et al.*, 2011).

Biochar, through its ability to increase microbial activity and elevate soil pH, fosters a positive priming effect, accelerating the chemical hydrolysis and breakdown of native soil organic carbon. While biochar helps soil hold water and nutrients, it can also slow down the breakdown of organic matter in the soil. This needs further study to understand the full impact (Ahmad *et al.*, 2014). Biochar's porous structure harbors diverse microbes, but the intricate interactions are unclear. Biochar's influence on soil microbes is still a question mark. More research is needed to understand how its properties affect these communities. Notably, beneficial bacteria fighting soil-borne pathogens seem to benefit from biochar (Pietikäinen *et al.*, 2000). Utilizing both biochar and mycorrhizal fungus, alongside appropriate management techniques, presents a viable approach to harness potential synergies for enhancing soil quality (Saito, 1990; Song *et* *al.*, 2016). The bacterial and fungal hyphae that occupy the porous materials, such as biochar particles, could be shielded from soil predators including worms, bigger protozoans, etc. (Lehmann *et al.*, 2003). The enhancement of beneficial soil microbes, soil amelioration, modification of plant biochemical components, and morpho-physiological traits are all associated with plants' resistance to biotic and abiotic challenges because of biochar (Babu *et al.*, 2023). In addition to promoting microbial activity, adding biochar to the soil encourages fungal growth, which causes agglomeration of the soil and abundant root formation, which lowers bulk density (Brown *et al.*, 2011). The structure of the soil microbiome can be changed by biochar, which can reduce the plant pathogen. Biochar directly improves access to nutrients for plants, particularly potassium, phosphorus, and zinc. It also offers some benefits for calcium and copper availability, though to a lesser extent (Ding *et al.*, 2016).

BIOCHAR FOR IMPROVING GLOBAL WARMING

Contributing factors for the present of global warming trend are mostly anthropogenic activities and its management is exceptionally important (Arif *et al.*, 2017). The biggest cause of greenhouse gas emissions is agriculture. About 10%–12% of all anthropogenic emissions worldwide are attributed to three main greenhouse gases (GHGs): CH_4, N_2O and CO_2 (Biederman and Harpole, 2013). Establishing efficient sustainable farming methods that may reduce greenhouse gas emissions while increasing crop productivity is more important. Incorporating biochar into soil offers a double win for the environment: reducing greenhouse gas emissions and enhancing agricultural productivity, making it an eco-friendly strategy. Biochar's reaction to crop yield and soil GHG emissions suggests that the temperature at which pyrolysis occurs, and the properties of the feedstock may have an impact on how economically biochar is produced (He *et al.*, 2017; Jeffery *et al.*, 2011). Both soil properties and biochar characteristics play a crucial role in influencing crop production and soil GHG emissions (Joseph *et al.*, 2021; Lal, 2004). Adding biochar to soil can lead to diverse impacts on soil attributes, and the release of CH_4, N_2O and CO_2 gases (Lehmann, 2007; Lehmann and Joseph, 2024). The primary sources of carbon dioxide emissions include organic matter burning from the ground and agricultural trash, in addition to microbial decomposition. Turning plant waste into biochar traps carbon in the ground for a long time, helping fight climate change (Lehmann, 2007).

Pyrolysis transforms a portion of the biomass into biochar, while simultaneously releasing bioenergy. Given that a greater amount of carbon is sequestered than released, combining the procedure of pyrolysis with the utilization of biochar in soil makes it possible to sequester atmospheric CO_2. This statement elucidates why the positive impact of utilizing biochar to counteract climate change relies on its resistance to microbial degradation, leading to a slower release of organic carbon as CO_2 into the atmosphere (Liu *et al.*, 2013; Major *et al.*, 2010). Biochar is good for the environment in two ways. First, it traps carbon in the soil for a long time, helping fight climate change. Second, it reduces harmful gas emissions from the soil, like methane and nitrous oxide. This can lead to higher crop yields, making biochar a win-win for both the environment and farmers. However, things like the type of soil and how much biochar is used can affect how well it works (Mukherjee and Zimmerman, 2013; Obia *et al.*, 2016; Park *et al.*, 2011).

DRAWBACKS OF USING BIOCHAR

While biochar shows promise, consider unintended impacts on various aspects like crop health, soil chemistry, and emissions. Biochar type and soil conditions can influence its impact on microbes, which can be positive, negative, or neutral. Additionally, potential harm from biochar-borne compounds like polyphenolics on soil microbes needs further study (Liesch *et al.*, 2010). It has been noted that applying biochar to agricultural areas can reduce mycorrhizae and overall microbial biomass and change the diversity of microflora in the soil. Discharge of contaminants like aromatic polycyclic hydrocarbons and bio-oil along with enhanced retention of hazardous materials (pesticides and heavy metals), some findings demonstrate a decline in microbial population and activity. It is illogical to assume that a unique type of biochar that benefits one soil biota will likewise benefit other soil biota (Gell *et al.,* 2011; Liesch *et al.*, 2010).

Biochar's potential negative effects on soil fauna are likely a complex interplay of various factors, including the presence of salts (e.g., chlorine, sodium), release of volatile compounds during production, and inherent properties of the biochar itself. Certain biochar may be directly harmful to the soil fauna and its functions, which might account for some of the agricultural production reductions found in research (Freddo *et al.,* 2012). Biochar's variable pH, influenced by its production process (feedstock, temperature, oxidation), affects the soil's ability to hold onto metals, potentially impacting its entire microbial community (Ding *et al.*, 2016). The presence of several phytotoxic compounds in biochar causes an unfavorable effect on plant development. In biochar, polycyclic aromatic hydrocarbons (PAHs) are the most often found hazardous substances (Hilber *et al.*, 2012). It is important to carefully assess any potential short-term consequences and determine whether they would be appropriate as a soil amendment.

FUTURE PROSPECTS

Biochar has significant potential for environmental applications and its use on soil is expanding quickly. It can improve the transportation of nutrients from soil to roots, if applied as a slow-released fertilizer (Agegnehu *et al.,* 2017). Investigating, refining, and establishing standardized pyrolysis conditions and feedstock types are essential for biochar production, aiming at diverse applications such as nutrient release, contaminant adsorption, and mineralization desorption. Multiple areas warrant exploration to facilitate the broader utilization of biochar in various settings (Agegnehu *et al.,* 2017; Kumari *et al.*, 2023).

Before large-scale applications of biochar, further *in-situ* or field tests should be carried out over an extended period to mimic the real environment and investigate the true impact. The threats of biochar created from various types of sludge or other polluted biomass, as well as the efficacy of other ways for consistently minimizing such risks, should be investigated further. Studies should be done to learn about the interaction of feedstock/pyrolysis and biochar physiochemical characteristics (for example, the importance of cellulose, hemicellulose, and lignin concentration, as well as the relationship between biochar structure and balance). Further study of microbial activity is necessary during the remediation of soil and mineralization. Additionally, a detailed investigation of the interactions, changes, and binding processes between biochar and soil is necessary. The significant rise in citations and publications highlights the expanding awareness of the possible uses for biochar. This increase in research interest emphasizes how urgently further studies on the long-term impacts of biochar are needed, especially in real-world field settings **(Figure 3)** (Kumari *et al.*, 2023).

New techniques for statistical analysis like automated learning can be used to know the characteristics of biochar. To ensure long-term viability, further efforts should be undertaken to broaden the alterations and environmental uses of manufactured biochar. These efforts should focus on optimizing the modification process, cutting costs, and optimizing the suitability of a particular variety of engineered biochar. The processes behind the environmental uses of improved biochars should be the primary goal of future research. To create biochars that are more successful, additional efforts should be made to investigate the viability of integrating advanced techniques for modification with innovative pyrolysis procedures.

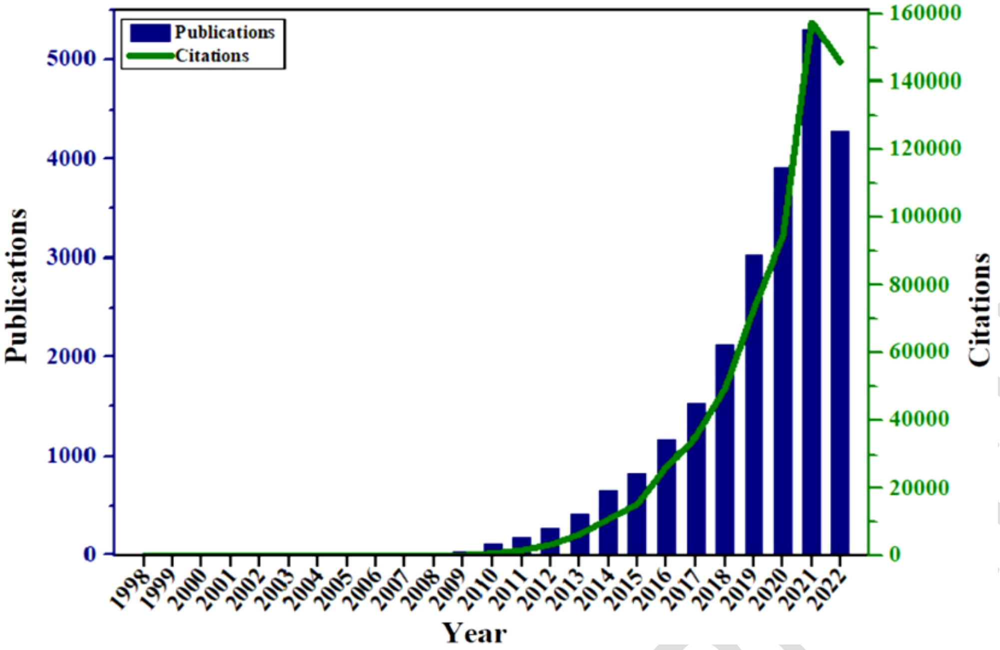

Fig. 3. *Biochar publications by year and citation count* (Kumar *et* al., 2023)

CONCLUSION

"Green Gold from Green Waste: Biochar Production from Plant Residues" emphasizes how biochar may transform plant leftovers into valuable resources while offering sustainable alternatives. This review study sought the biochar production from plant waste and emphasized key process components such as feedstock selection and pyrolysis temperatures. Biochar is a new way to manage trash while managing the challenges posed by agricultural waste. It can boost soil fertility, store carbon, and reduce negative environmental consequences, there is a strong justification for adopting it into current agricultural processes. Continued research will likely improve production procedures, improve biochar properties for specific uses, and discover novel applications in a variety of industries. Technological developments, sustainable development, and circular economy models are expected to expand biochar's potential as "green gold." A path from waste to wealth should be seen, considering the interdisciplinary partnerships, technological breakthroughs, and changing regulatory regimes that will impact biochar's future course and role in sustainability.

To summarize, converting plant remains into biochar is both an environmentally necessary and economically beneficial act. Biochar's potential as "green gold" is dependent on our collaborative research, sustainable practices, and smart integration of this resource into our waste and agriculture systems. To create a path for a more resilient as well as an ecologically improved future we will have to take such steps where plant residues are not just mere trash material but a powerful resource having sustainability.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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