



Exploring the Role of Rice Straw Biochar in Sustainable Agriculture and Environmental Health

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ABSTRACT

Burning rice straw in open fields has led to a plethora of concerns, ranging from air pollution to soil carbon losses, posing a risk to human health and disturbing the soil ecosystem. The problem of rice stubble burning has been addressed by adopting different in-situ and ex-situ conservation technologies supported by the government and private companies. Biochar production from rice straw is one such method. Biochar is a carbon-rich porous material produced by the thermochemical conversion of various biomass feedstocks and is used globally to improve soil properties. It plays a crucial role in sustainable agriculture and in environmental health. It has the potential to enhance soil fertility, water retention, and nutrient cycling, while also offering carbon sequestration benefits. However, the adoption of biochar as a soil amendment practice is still challenging owing to the limited understanding of the long-term effects on soil health, the establishment of onsite production facilities, high energy consumption in the production process, and inconsistent results depending on the variable soil types. For biochar to be applied practically for soil improvement in different climatic regions and crop production, it is important to understand the potential effects of biochar on soil properties, the factors that cause soil to change when biochar is added, and the mechanisms of biochar–soil interaction. This review provides an overview of the current research on rice straw biochar and identifies key limitations that will direct future research and policy decisions for its integration into sustainable farming practices. It underscores the potential of biochar to combat global warming, mitigate environmental damage, and its role in reversing the impacts of climate change in line with sustainable development goals.

1. INTRODUCTION

India is the second-largest producer of rice, after China. It is grown widely in Punjab, Haryana, Uttar Pradesh, West Bengal, Tamil Nadu, Andhra Pradesh, and Odisha. A total of 1357.55 Lakh tonnes of rice is produced annually (2022–23). Approximately 500 pounds of rice husks and straw are generated for every ton of rice produced. Unfortunately, approximately 80% of this rice straw is disposed of through open burning, which significantly contributes to air pollution and greenhouse gas emissions, posing serious risks to human health and water quality. Furthermore, this practice leads to the loss of a significant amount of organic matter and affects soil microflora. The burning of paddy straw has immediate and notable impacts on soil microbiota, drastically reducing the populations of key microorganisms, including bacteria, fungi, actinomycetes, mineral phosphate-solubilizing microorganisms, potassium-solubilizing bacteria, and cellulose-degrading bacteria. Although these populations often recover within 30 to 60 days post-burning, indicating a temporary resilience of soil microbiomes, the levels of microbial enzymes remain low (Kumar et al. 2019, Ravali et al. 2022, Arunrat et al. 2023). To circumvent this problem, alternative strategies for rice waste management are required. Using rice straw biochar as a soil amendment is a promising strategy for enhancing soil health and addressing the challenges of rice straw management.

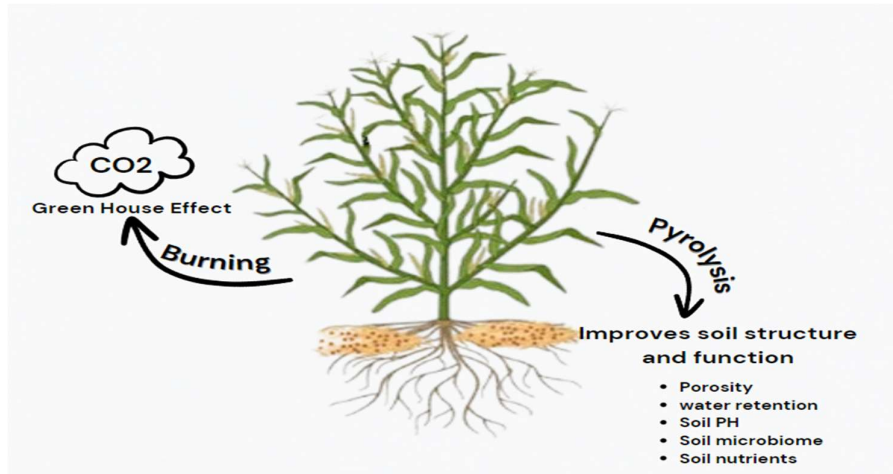


Fig. 1: Biochar: A sustainable approach to biomass utilization.

Table 1: Biomass to biochar: Aligning with sustainable development goals.

Sustainable Development Goal (SDG)	Relevance to Biochar Technology	Reference
SDG 2: Zero Hunger	Improve soil fertility and enhance agricultural productivity.	Farhangi-Abriz et al. (2021)
SDG 3: Good Health and Well-being	Improve food quality and reduce air pollution	Dong et al. (2025)
SDG 6: Clean Water and Sanitation	Improve water retention and reduce water pollution	Gwenzi et al. (2017)
SDG 7: Affordable and Clean Energy	Support sustainable energy production	Ahuja et al. (2024)
SDG 9: Industry, Innovation, and Infrastructure	Promote innovative technologies for sustainable agriculture	Amalina et al. (2023)
SDG 12: Responsible Consumption and Production	Promote sustainable resource use and reduce waste	Afshar and Mofatteh (2024)
SDG 13: Climate Action	Reduce greenhouse gas emissions, enhance carbon sequestration	Kalu et al. (2024)
SDG 15: Life on Land	Combat land degradation, enhance soil health	Shoudho et al. (2024)

Biochar is a carbon-rich material that, when added to soil, enhances soil quality, boosts crop yields, and stores carbon, benefiting agriculture and the environment. Rice straw biochar has demonstrated effectiveness in improving soil structure, retaining water, increasing nutrient availability, and stimulating microbial activity. Thus, production of biochar from agricultural waste is a sustainable approach that improves soil fertility and minimizes air pollution (Fig.1).

Additionally, the use of rice straw biochar supports various global sustainability objectives, such as mitigating climate change, reducing waste, etc (Table 1).

However, challenges such as inconsistent biochar quality, costly production, limited farmer awareness, and regulatory gaps hinder its widespread adoption. This review explores the significance of rice straw biochar in promoting sustainable agriculture and environmental health, emphasizing its advantages, operational mechanisms, and practical applications. It also addresses current challenges and suggests future research paths to enhance its efficacy and encourage its incorporation into

conventional agricultural methods. To synthesize this review article, a systematic literature search was conducted on Scopus, Web of Science, ScienceDirect, and Google Scholar for studies published between 2000 and 2024 using keywords like “rice straw biochar,” “pyrolysis,” “biochar modification,” “soil amendment,” and “environmental impacts.” The inclusion criteria were studies focusing on rice straw biochar, providing experimental or field data, and published in peer-reviewed journals. The exclusion criteria involved non-rice biomass studies, non-peer-reviewed sources, and articles lacking clarity in methodology or agricultural/environmental context. The selected studies were assessed for pyrolysis conditions, characterization methods, soil type, experimental scale, and reported outcomes. Conflicting results were compared based on methodological differences and contextual factors to ensure the reliability and relevance of the review.

2. BIOCHAR

Biochar is a form of carbon with very high stability, produced

via the pyrolytic treatment of organic resources, such as agricultural waste, forest residues, or any other biomass. This process involves heating biomass in the absence of oxygen, which helps protect the biomass from burning and instead turns it into a charcoal-like material. Pyrolysis can be performed as slow pyrolysis, Fast Pyrolysis, and Flash pyrolysis (Fig. 2). Slow Pyrolysis runs at low heating rates, $0.1-1^{\circ}\text{C}\cdot\text{s}^{-1}$, with temperatures between 350°C and 450°C . The residence times are long, ranging from 5 min to days, and the process produces large quantities of biochar and bio-oil; thus, it can be directly applied as a solid fuel. Fast pyrolysis is carried out over a relatively moderate temperature range of $450-600^{\circ}\text{C}$, while heating rates range between 10 and $200^{\circ}\text{C}\cdot\text{s}^{-1}$ with residence times of 0.5-2 seconds. The bio-oil yield was the highest, whereas low yields of char and gas were obtained. Flash pyrolysis employs very high heating rates of up to $1000^{\circ}\text{C}\cdot\text{s}^{-1}$ and temperatures between 800 and 1000°C . Hence, the residence time is very short, less than 0.5 s. It maximizes liquid product yield, leaving mainly bio-oil, with minimum char content (Kavan & Panwar 2024).

3. RICE STRAW BIOCHAR (RSB): PRODUCTION AND PROPERTIES

Rice straw contains approximately 40% carbon, 30% oxygen, 5-6% hydrogen, 1% nitrogen, and less than 0.2% sulfur. Rice straw typically has a high ash content (8.5–20.4%) (El-Hassanin et al. 2020). The ash in rice straw is primarily composed of silica oxide, along with other oxides such as aluminum oxide and calcium oxide. Due to its low moisture content (<10%), rice husks are suitable for pyrolysis and biochar production. Rice straw biochar can be obtained by heating rice straw at high temperature under anaerobic conditions. Rice straw, during pyrolysis, is deconstructed in several steps with respective differentiation through a range of temperatures and chemical changes (Park et al. 2014). It includes the initial drying stage ($100-250^{\circ}\text{C}$), where the amount of moisture in the biomass is lowered and it is prepared for subsequent heat processing. This is followed by pre-pyrolysis ($280-350^{\circ}\text{C}$), wherein the straw undergoes decomposition, leading to the initiation of the breaking of hemicelluloses and amorphous cellulose, thereby releasing volatile chemicals (Chaijak et al. 2023). Finally, the pyrolysis activation stage is achieved (above 350°C), which is critical for transforming biomass into valuable products, particularly bio-oil, char, and gases. Careful control of the temperature and reaction conditions is essential to optimize the yield of these products, making this stage a focal point in biomass conversion technologies.

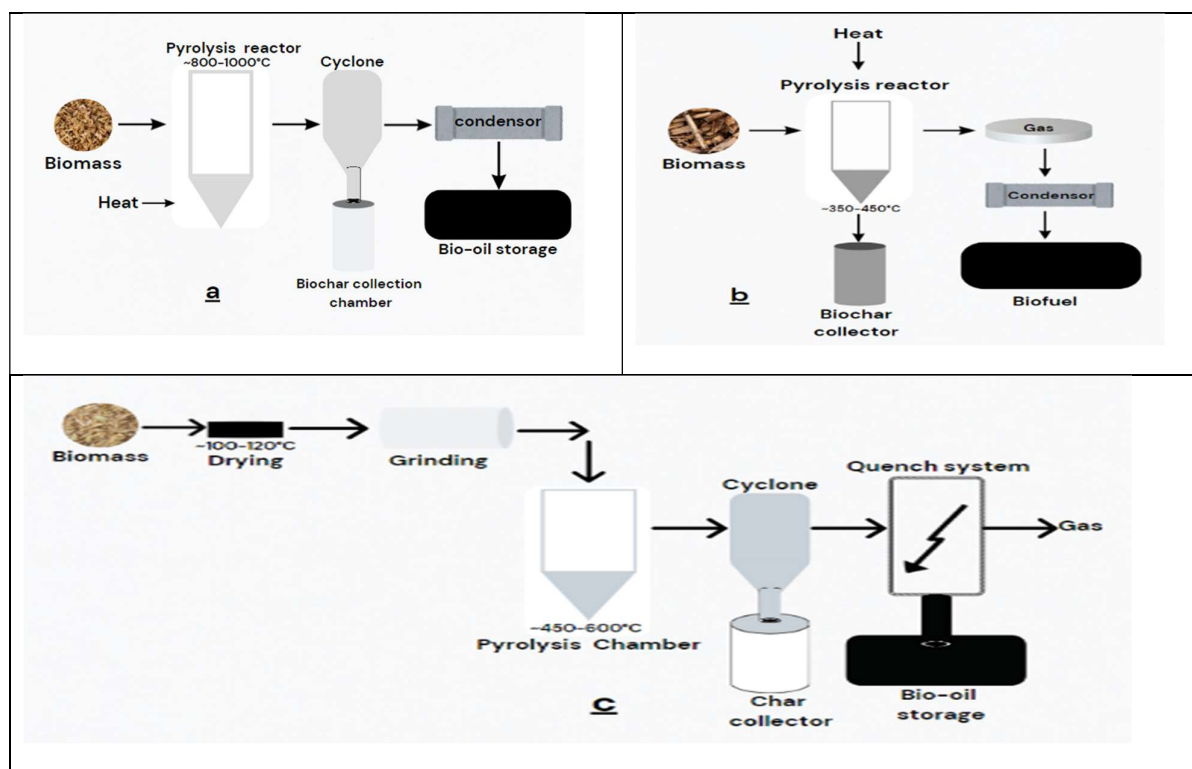


Fig. 2: Different types of pyrolysis: a) flash pyrolysis, b) slow pyrolysis, c) fast pyrolysis.

3.1. Physicochemical Properties of Rice Straw Biochar

Rice straw biochar is characterized by various physical, chemical and structural properties (Table 2).

A thorough understanding of these characteristics helps in the optimization process of biochar development and its applications for various purposes. To achieve this, several analytical techniques and instrumentation are employed. Fig. 3 summarizes the key characterization methods for analyzing biochar, including surface area, porosity, elemental composition, surface functional groups, thermal stability, and crystalline structure.

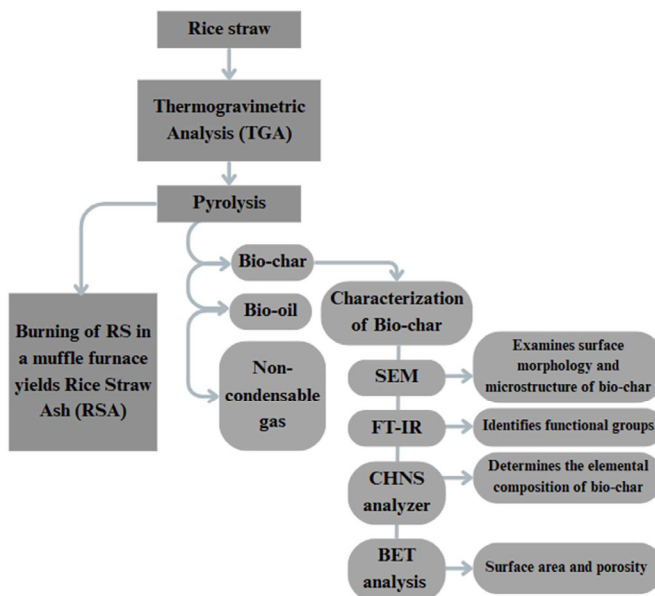
The physicochemical properties of rice straw biochar are significantly influenced by the pyrolysis temperature used during its production (Kanboj et al. 2025). Generally, higher pyrolysis temperatures (typically ranging from 300 to 700°C) lead to a decrease in the biochar yield, as higher temperatures lead to the release of more volatile

matter, resulting in a lower solid biochar yield. Higher temperatures resulted in a more porous structure with a larger specific surface area. The pyrolysis of rice straw biochar at high temperatures also leads to an increased ash content. Organic matter decomposition leads to higher ash content in biochar at higher temperatures. Changes in the pore size distribution were also accompanied by an increase in the pyrolytic temperature. Biochar produced at higher temperatures tends to have a higher pH. This can be attributed to the increased concentration of alkali metals and the loss of acidic functional groups. The increased carbon content and graphitic structures at higher temperatures can slightly increase the electrical conductivity of biochar.

The pyrolysis temperature has a profound effect on the elemental composition of rice straw biochar (Gezahegn et al. 2024), which ultimately affects its functions. The effects of temperature on the elemental composition of rice straw biochar are summarized in Table 3.

Table 2: Key functional properties of rice straw biochar.

Property Category	Specific Property	Significance	References
Textural	Specific surface area (SSA)	Governs adsorption capacity—higher SSA means more active sites for pollutants or nutrients.	Kalina et al. (2022)
	Total pore volume	This relates to how much material (water, nutrients, gases) the biochar can hold.	El-Hassanin et al. (2020)
	Pore size distribution	Determines accessibility: micropores (<2 nm) vs. meso (2–50 nm) and macropores (>50 nm).	Kameyama et al. (2019)
Morphological	Particle size & shape	Influences packing, flowability, and mixing with soils or composites.	Wangdi et al. (2023)
	Surface roughness & structure	Affects water retention, microbial colonization, and interfacial interactions.	Phuong et al. (2015)
Chemical Composition	Elemental makeup (C, H, N, O, S)	Defines basic carbon content, energy potential, and possible nutrient contributions.	Wijitkosum and Jiwnok (2019).
	Ash content & mineral phases	High ash can buffer soil pH; mineralogy (silica, oxides) influences soil amendment value.	Shah et al. (2024)
	Inorganic/metals content (e.g., K, Ca, Si)	Determines potential nutrient release or contaminant risks.	Tsai et al. (2023)
Surface Chemistry	Functional groups (–OH, –COOH, C=O, etc.)	Key for pollutant binding, nutrient exchange, and redox reactions.	Malik et al. (2023)
	Point of zero charge (pHpzc)	pH at which the surface has a neutral charge, critical for the adsorption of ions.	Neusatz Guilhen et al. (2022)
	Cation Exchange Capacity (CEC)	Measure of nutrient-holding ability, relevant to soil fertility.	Li et al. 2013
Physical & Bulk	Bulk density	Affects transport, handling, and soil incorporation rates.	Kamara et al. (2015)
	Water holding capacity	Impacts soil moisture retention and plant-available water.	Kamara et al. (2015)
Thermal	Thermal stability/decomposition profile	Indicates resistance to further thermal breakdown, important for high-temperature applications.	Sakhiya et al. (2021)
	Heat of combustion (calorific value)	Relevant if biochar is considered as a solid fuel or for energy recapture.	Satlewal et al. (2018)
Electrical	Electrical conductivity (EC)	Reflects soluble salt levels, important for assessing salinity risks in soils.	Biswas et al. (2024)



SEM: Scanning electron microscopy, FT-IR: Fourier Transform Infrared (FTIR) spectroscopy, BET: Brunauer-Emmett-Teller

Fig. 3: Commonly used techniques for the characterization of rice straw biochar.

The elemental analysis of the biochar produced at different temperatures revealed that the biochar produced at higher temperatures showed a significant increase in carbon content, which was attributed to the enhanced carbonization processes occurring at elevated temperatures. As the pyrolysis temperature increases, there is a marked reduction in the hydrogen and oxygen content, driven by reactions such as dehydration and decarbonization. These reactions lead to the formation of non-condensable gases and hydrogen, contributing to the overall increase in carbon content and the transformation of biochar into a more aromatic and carbon-rich material (Brassard et al. 2017). An increase in the aromatic components and recalcitrance of the rice straw biochars was observed with an increase in temperature owing to the presence of a high concentration of silicon, which forms Si-C bonds (Jindo et al. 2014).

3.2. Effects Of Biochar on Soil Structure and Properties

The application of biochar improves the physical, chemical, and biological properties of soil, enhancing aeration and water retention, especially under drought conditions (Singh et al. 2022). The properties of biochar are primarily influenced by its production conditions (Biswas et al. 2024). The water-holding capacity of biochar increases with pyrolysis temperature, from 12.9 to 22.5% as the temperature increases from 400 to 800°C (Khater et al. 2024). Higher temperatures also increase the surface area, which promotes water retention and microbial activity (Biswas et

al. 2024). Lower pyrolysis temperatures (<400°C) produce hydrophobic biochar, whereas higher temperatures reduce hydrophobicity and increase water retention (Li & Tan 2021). The surface area of rice straw biochar typically ranges from 100 to 500 m².g⁻¹, depending on the pyrolysis conditions (Tomczyk et al. 2020). Micrometer-range pores, which are critical for plant water uptake, are influenced by the initial pore structure of the raw material (Hyväluoma 2018). However, Adhikari (2023) concluded that the type of organic feedstock did not appear to directly affect water holding. Aging biochar and adjusting particle size can improve its water retention (Adhikari 2022). Biochar rich in nitrogen can enhance moisture retention (Zhang et al. 2024), while its high surface area and cation exchange capacity improve nutrient availability and pH, particularly in acidic soils (He et al. 2024). The high porosity, aromaticity, and surface functional groups of biochar facilitate its role in immobilizing heavy metals and organic contaminants (Foong et al. 2022). Numerous studies have quantified the adsorption efficiency of rice straw biochar for multiple pollutants (Table 4), demonstrating that the same structural attributes responsible for improved soil functionality also govern contaminant-binding mechanisms.

Biochar improves soil structure, water retention, nutrient dynamics, and contaminant immobilization, which collectively impact plant physiological performance. These mechanisms are crucial for assessing crop responses, as discussed in the following section.

Table 3: Elemental composition of rice straw biochar derived at different pyrolysis temperatures.

Temperature [°C]	C [%]	H [%]	O [%]	N [%]	H/C	O/C	C/N	Reference
300	72.1	5.03	21.3	1.55	0.84	0.22	54.27	Wu et al. (2012)
400	77.2	4.01	17	1.74	0.62	0.17	51.76	
500	82.8	3.25	12.1	1.77	0.47	0.11	54.58	
600	87.1	2.51	8.8	1.52	0.35	0.08	66.85	
400	49.92	2.8	12.2	1.22	0.67	0.18	47.74	Jindo et al. (2014)
500	37.48	0.93	8.64	0.61	0.3	0.17	71.68	
600	33.78	0.6	13.68	0.41	0.21	0.3	96.12	
700	36.26	0.51	17.38	0.34	0.17	0.36	124.42	
800	29.17	0.25	3.71	0.25	0.1	0.1	136.13	
300	68.72	5.22	22.78	3.28	0.91	0.25	24.44	Park et al. (2014)
400	75.47	4.62	16.93	2.98	0.73	0.17	29.55	
500	81.43	2.34	15.13	1.1	0.34	0.14	86.37	
600	87.52	2.11	7.48	2.89	0.29	0.06	35.33	
700	91.15	1.26	7.01	0.58	0.17	0.06	183.35	
400	45.5	4.4	49	1.1	1.16	0.81	48.26	Yakout (2017)
500	51.9	3.2	43.6	1.3	0.74	0.63	46.58	
600	65.3	2.9	30.1	1.7	0.53	0.35	44.81	
300	48.3	5.34	24.91	2.58	1.39	0.39	21.84	Liu et al. (2018)
400	54.28	3.65	15.64	2.15	0.81	0.22	29.45	
500	54.31	3.45	11.87	1.68	0.76	0.16	37.72	
600	56.85	2.27	7.89	0.87	0.48	0.1	76.24	
700	55.28	1.88	6.84	1.08	0.41	0.09	59.72	
300	41	3.67	52.7	1.71	1.07	0.96	27.91	Bhatia and Saroha (2024)
500	47.02	2.21	48.85	1.63	0.56	0.78	33.7	
700	47.1	1.26	50.05	1.39	0.32	0.8	39.5	
800	48.03	1.14	49.57	1.12	0.28	0.77	50.21	
400	54.92	3.6	17.19	1.3	0.79	0.23	49.29	Ma et al. (2022)
600	59.56	2.09	20.12	1	0.42	0.25	69.49	
400	38.3	ND	ND	0.9	ND	ND	49.65	Khater et al. (2024)
600	49.8	ND	ND	0.7	ND	ND	83	
800	52.5	ND	ND	0.4	ND	ND	153.13	

Table 4: Removal of heavy metals by rice straw biochar.

Biochar Type	Contaminant Removed	Efficiency	References
RSB	Cr (VI) and Pb (II)	95.57% and 85.68%	Venkatraman et al. (2023)
CO ₂ activated RSB	As Mn	99.53% 96.23%	Sakhiya et al. (2023)
RSB	As and Mn	>85%	Sakhiya et al. (2023)
RSB	Pb ²⁺ Zn ²⁺	60% 70%	Sakhiya et al. (2022)
RSB	As (V)	>60%	Mukherjee et al. (2021)
RSB	PAHs	58.8%	Zhang et al. (2020)
RSB	Safranin O	31.06 mg.g ⁻¹	Phuong and Loc (2022)
RSB	Basic Red 46 dye	22.1 mg.g ⁻¹	Sackey et al. (2021)

4. APPLICATION OF RICE STRAW BIOCHAR IN IMPROVING PLANT GROWTH

The application of biochar to soil has been shown to improve plant growth and yield in various crops. Rice cultivated in rice straw biochar-amended soils exhibited increases in plant height by 18%, a 66% rise in tiller number, and an increase in dry biomass by 87% compared to non-amended soils (Kamara et al. 2015). Mohamed et al. (2024) investigated the effects of rice straw biochar and NPK mineral fertilizers on crop growth and soil health in the wheat-maize cropping system. Field trials were conducted using different treatments, including biochar, mineral fertilizers, and their combinations. The results showed that the combined mineral-organic treatments had the greatest impact on soil fertility and crop productivity. Hematimatin et al. (2024) evaluated the long-term effects of biochar aging over seven years on both soil pH and organic carbon. It was concluded that aging led to a significant pH decline post-application in 2015 and 2019. In contrast, the application of combined biochar with nitrogen fertilizer improved inorganic N content and increased the contents of soil organic matter between 2014 and 2018. The major practical use of rice straw biochar in rice fields is the reduction in nitrogen loss, as reported by Selvarajh et al. (2023). The mixing of biochar with urea at application rates of 5 and 10 tons ha⁻¹ reduced ammonia emissions compared to the application of urea alone. It also enhanced ammonium and nitrate retention by 65.37% and 50.9%, respectively. Additionally, enriched rice straw biochar improves nitrogen content while ensuring better growth of rice plants in pot experiments. Liu et al. (2019) reported that biochar treatments increased phosphorus and potassium availability for ryegrass, raising the nitrogen-to-phosphorus ratio when used in combination with phosphorus fertilization. The use of fertilizers in combination with biochar enhances nutrient efficiency and thus facilitates better growth by the plants

5. LIMITATIONS OF BIOCHAR

Although biochar has the potential to improve soil fertility and help mitigate climate change, it possesses important deficiencies at the technical, environmental, economic, and social levels. The agronomic or economic value of biochar greatly depends on the feedstock (some examples include wood, crop residues, and livestock manure) as well as the particular pyrolysis conditions (parameters of temperature, duration, and oxygen level) used for its production. The array of biochar types that exist leads to diverse outcomes with respect to plants and soil systems, which heavily disrupt the chance of standardization or anticipating results for particular uses (Sohi et al. 2010, Spokas et al. 2012, Joseph et al. 2021).

The varied methods of producing biochar result in changes in its physical and chemical characteristics, which affect its resiliency, nutrient concentration, and ability to adsorb pollutants (Al Masud et al. 2023). While some studies have reported increased crop yields and improved soil conditions after biochar application, others have shown little to no change or even perverse impacts, such as reduced crop yields or negative changes in soil chemistry. (Brtnicky et al. 2021).

Biochar production may contain or possibly include contaminants such as polycyclic aromatic hydrocarbons (PAHs) and heavy metals, particularly if its manufacture is carried out using contaminated feedstocks or under pyrolysis conditions, with adverse environmental effects on soil health, plant growth, and food safety (Bhandari et al. 2023). The current impetus on nanobiochar also comes with limitations. Nano-biochar is highly mobile, has a high surface area, and can adsorb and carry pesticides, antibiotics, and other toxicants, thus posing a risk of cross-contamination of ecosystems and toxicity to plants, soil microflora, and even humans (Freixa et al. 2018, Dong et al. 2019). The economic feasibility of biochar production, transportation, and application can be high, but the economic viability of biochar depends heavily on sustainability, and the effects of its economic benefit and economic benefits are marginal in most cases, especially when there is no policy support or carbon credits. The production processes and quality control do not have standardized configurations; hence, commercialization and regulation become very difficult because it is difficult to ensure the consistent quality and performance of products (Brtnicky et al. 2021, Bhandari et al. 2023). Technical and Measurement Issues also pose challenges to the widespread adoption of biochar. Measuring the rate and longevity of carbon from biochar in soils is technically challenging due to the chemical complexity of biochar and contamination by other black carbon and organic matter in the soil. This calls for an urgent need for accurate measurements of carbon accounting and climate policy, which remains a significant challenge (Al Masud et al. 2023). The opportunity cost of maximizing biochar production (for carbon storage) is the loss of energy (i.e., bioenergy) that can be produced from the same feedstock using different methods (Sohi et al. 2010). The large-scale use of biochar has potential unintended environmental consequences, as described for other geoeengineering methods. These include possible effects on nutrient cycling, soil biota, and indirect land-use change when biochar is produced from food crops or other natural ecosystems. Any global biochar strategy should also seriously consider the potential social consequences, such as competition for food crops and the displacement of local people.

Given these technical and environmental limitations, recent research has increasingly focused on engineering strategies to enhance the performance of rice husk biochars. Many of these drawbacks, such as low surface reactivity, variable nutrient content, inconsistent pollutant-sorption capacity, and the presence of undesirable compounds, are directly linked to the physicochemical constraints of pristine biochar. Consequently, modification approaches have been developed to systematically tailor the surface area, porosity, and functional chemistry to overcome these inherent limitations. The following sections delineate common modification and engineering paradigms applied to rice husk biochar for targeted applications in soil health, remediation, catalysis and energy systems:

6. ENGINEERING RICE STRAW BIOCHAR

6.1. Physical Modifications

Activation and particle size modification are two widely employed strategies for enhancing the functional properties of rice straw and rice husk biochars for environmental and agricultural applications. Activation, typically conducted at 873–1273 K using CO₂, steam, or air, induces controlled gasification, removes carbonaceous material, and generates a highly porous interconnected structure. Steam activation is particularly effective for developing hierarchical architectures rich in micropores (Bushra & Remya 2024). Co-pyrolysis and blending approaches, such as mixing rice straw with groundnut shells or wheat straw followed by washing, further improve biochar quality by reducing slagging and fouling potential, making it suitable for both soil and fuel applications (Bhatnagar et al. 2022).

Particle size reduction is another method for enhancing performance. Controlled grinding followed by sieving increases the external surface area and dispersibility, along with the selection of particle fractions of varying sizes for specific uses (Wangdi et al. 2023). Fine biochar fractions improve adsorption kinetics and have been shown to increase grain weight and filled spikelet numbers in rice (Kartika et al. 2018). However, particle size effects are context-dependent: larger particles improve tomato yield under salt stress by enhancing salt leaching and nutrient availability, whereas smaller particles may reduce yield in highly saline soils but enhance productivity in non-saline conditions (Wu et al. 2025).

In addition to mechanical modification, microwave and ultrasonic treatments further refine the biochar structure. Microwave irradiation accelerates devolatilization and pore development (Sahoo & Remya 2022, Zhang et al. 2015, Fodah et al. 2022, Potnuri et al. 2023), whereas ultrasonic

cavitation disrupts the carbon matrix, increasing the surface area and altering porosity (Chatterjee et al. 2018). Together, these engineering strategies substantially enhance the adsorption capacity, reactivity, and soil-improvement potential of rice-straw biochar.

6.2. Chemical Modifications

These modifications aim to alter the surface chemistry of biochar by introducing or altering surface functional groups to enhance interactions with target analytes or reaction substrates. The different chemical modifications include

6.2.1. Oxidative Modification

Treatment with oxidizing agents, such as atmospheric oxygen, ozone, hydrogen peroxide, or nitric acid, adds oxygen-containing functional groups (e.g., carboxylic, hydroxyl, carbonyl, and phenolic groups) to the biochar surface (Senapati et al. 2025, Yakout, 2015). These groups can improve the sorption of cationic species (Dey et al. 2023), nutrient retention in soil, removal of heavy metals (Bhadoria et al. 2022, Venkatraman et al. 2023), and serve as active sites for catalytic processes. The reaction with sulfuric acid adds sulfonic acid groups to the biochar surface, enhancing the adsorption capacity for basic organic dyes and heavy metal adsorption (Zhou et al. 2021, Ahmed et al. 2024).

6.2.2. Amination

Nitrogen-containing groups, such as primary amines and quaternary ammonium groups, can be incorporated through reactions with ammonia, urea, or amines (Leng et al. 2020). Aminated biochar has an increased affinity for anionic pollutants and heavy metal ions (Mian et al. 2018).

6.2.3. Phosphorylation

Treatment with phosphoric acid introduces phosphate groups to the biochar surface, enhancing heavy metal cation sorption and improving soil phosphorus availability (Li et al. 2023).

6.2.4. Impregnation with Metal Oxides/Nanoparticles

Incorporating inorganic oxides into biochar enhances its properties, creating hybrid materials with unique advantages over pure biochar. The distribution of inorganic oxides within a carbon matrix enhances the surface characteristics and catalytic performance and aids in the retrieval of nanometer-scale materials (Weidner et al. 2022). The negative surface charge of biochar can be modified by adding positively charged metal oxides, increasing its affinity for anionic impurities. Metal oxides such as TiO₂ and ZnO enhance the photocatalytic activity of biochar (Liang et al. 2021). The addition of metallic species to biochars increases their weight, aiding in the separation process, especially when modified with magnetite (Fe₃O₄) to enhance their magnetic properties

(Kassim et al. 2023). Numerous studies have focused on enhancing the properties of rice husk and straw biochars by incorporating metal oxides. Yang et al. (2022) found that rice husk biochar loaded with zinc oxide was more effective in treating textile wastes compared to pristine biochar. Qin et al. (2020) demonstrated that magnesium oxide-modified biochar has improved porosity and showed promise for wastewater treatment. The preparation of magnetic biochar composites is becoming increasingly popular because they can be easily separated from water using a magnet (Thines et al. 2017). Magnetic rice straw biochar has been implicated in the efficient removal of Safranin O (Phuong and Loc, 2022), Rhodamine B (Ren et al. 2020), and organic dyes (Barzallo et al. 2025, Meng et al. 2024) from aqueous solutions.

7. IMPLEMENTING SUSTAINABLE POLICIES AND STRATEGIES FOR BIOCHAR USE IN INDIAN SOILS

In the past two decades, biochar has gained prominence in agriculture for enhancing soil fertility, sequestering carbon, and mitigating greenhouse gas emissions. In India, initiatives such as the National Mission on Sustainable Agriculture (NMSA) and the National Biofuels Policy promote the use of biochar to boost soil health and support sustainable farming. The Ministry of Environment, Forests, and Climate Change launched the “National Biochar Initiative” to improve soil and carbon sequestration. The India Biochar and Bioresources Network (IBBN) advocates circular agricultural practices, reducing emissions, and enhancing carbon storage while addressing agricultural challenges. The government has also revised the Crop Residue Management guidelines, focusing on the efficient handling of paddy straw in states such as Punjab, Haryana, and Delhi, with financial assistance for machinery and equipment. Private companies, such as PepsiCo India, have launched biochar initiatives using crop residues to combat stubble burning in Punjab through pyrolysis. Other players, such as Samunnati and Varaha, are promoting biochar technology for climate resilience and sustainable agriculture. Additionally, a government task force is exploring the use of biochar in steel production to reduce carbon emissions in India’s steel sector, a major contributor to greenhouse gas emissions. This multifaceted approach highlights the role of biochar in both agriculture and industry, advancing sustainability and environmental goals.

8. CONCLUSIONS AND FUTURE PERSPECTIVES

Open-field rice straw burning in India has been a long-standing environmental crisis, causing severe air pollution, greenhouse gas emissions, and health hazards. The slow

pyrolysis of rice straw into biochar presents a valuable opportunity to enhance soil health, increase agricultural productivity, and sequester carbon. By improving nutrient and water retention and supporting beneficial microorganisms, rice straw biochar offers a sustainable solution for modern agricultural practices that addresses environmental challenges.

The application of rice straw-derived biochar has shown promising effects on various crops and soil characteristics. Optimizing biochar synthesis can alter its chemical and structural properties, which may enhance its suitability for agricultural applications. However, there are significant knowledge gaps in understanding crop responses to biochar application, especially in relation to varying soil types, salinity levels, and pyrolysis conditions. This emphasizes the importance of gaining a more detailed understanding of the specific factors influencing outcomes. Additional research is required to scale up its production and application for practical large-scale use. This demands large-scale field experiments across varied agro-climatic zones to assess the long-term effects of biochar amendments on soil health and crop productivity. Future research focusing on understanding the interaction of biochar with soil microbiomes, including beneficial plant growth-promoting bacteria and crops, is required to understand the dynamics of nutrient recycling in soil. Its economic profile must be critically assessed for use by farmers. Cost-benefit analyses will be important for understanding the potential of this practice as a viable agricultural practice. Advocating for policies that allow collaboration between various stakeholders, from farmers to researchers and the government, will encourage the adoption of sustainable practices in the use of rice straw biochar.

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