Policies and Strategies for Sustainable Use of Biochar in Indian Agriculture

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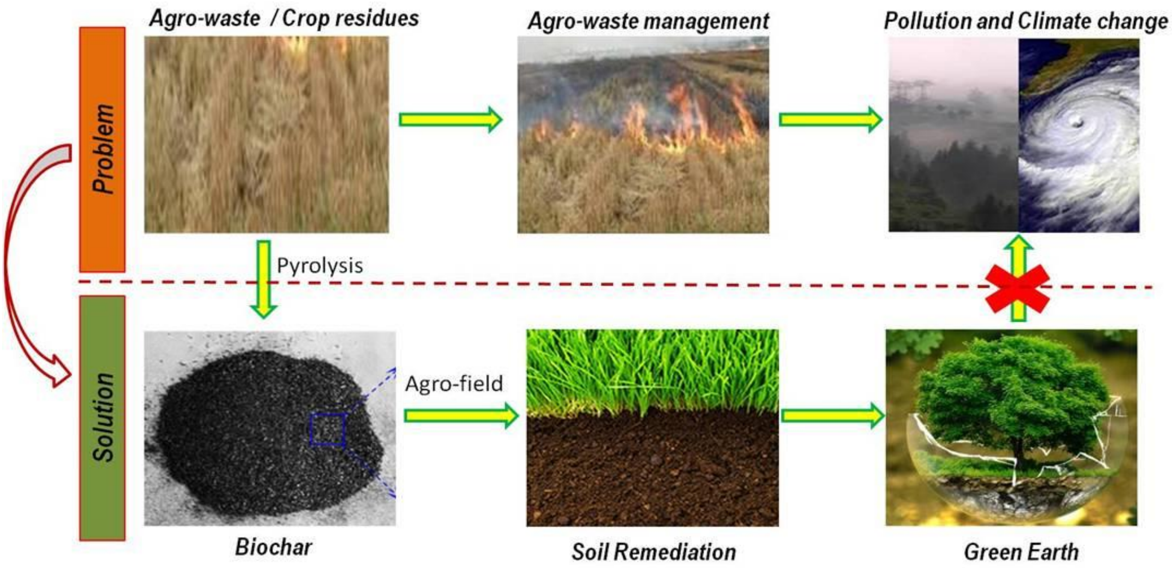
GRAPHICAL ABSTRACT



Policies and Strategies for Sustainable Use of Biochar in Indian Agriculture

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Agriculture plays a fundamental role in India's economy, supporting 70% of rural households. While often perceived as non-productive, agricultural waste harbors materials potentially beneficial to humans through the creation and utilization of biochar in the production and processing of agricultural goods. This study conducts a comprehensive exploration into the advantages and risks associated with biochar application, considering its role as a soil amendment, bioremediation agent, and its broader implications for human health and the environment. Biochar, primarily composed of stable carbon, was initially proposed as a soil amendment to sequester carbon. Efficient resource utilization has emerged as a viable means to address global environmental challenges associated with waste disposal. This review delineates diverse agricultural waste types and sources, identifies related environmental risks, and advocates for government-led measures aligned with circular economy principles to manage such waste. Furthermore, it offers insights into potential management strategies, policy considerations, and practical approaches, fostering sustainable agriculture practices and environmental conservation in India.

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Keywords: Biochar; Environment pollution: Policy challenge; Soil properties; Waste management

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INTRODUCTION

India generates a substantial volume of agricultural wastes, which has been estimated to be between 350 and 990 million tons per year; this waste encompasses crop residues such as leaf litter, seed pods, stalks, aquaculture waste, agro-industrial waste, and livestock waste (Sadh *et al*. 2018; Premalatha *et al*. 2023). In the prevalent rice-wheat cropping system in India, farmers commonly burn residues to clear fields for the next crop due to their low nutritive value and as a cost-saving measure.

The management of agricultural waste has become a crucial issue, demanding a shift towards sustainable practices. Utilizing these wastes as raw materials presents an opportunity to cut production costs and reduce environmental pollution. These residues, often rich in bioactive chemicals, hold potential for beneficial use.

Biochar is a recalcitrant compound that is produced after various thermochemical conversions under low oxygen supply (pyrolysis) conditions. It has been getting attention due to its porous nature and large surface area. Its multipurpose qualities cover a wide range of applications, including improving soil health, acting as a carrier of microbes and nutrients, immobilizing organic contaminants and toxic metals in soil and water, acting as a catalyst in industrial settings, and acting as a porous material to reduce odorous compounds and greenhouse gas emissions and nutrient absorption. However, the kind of feedstock and the pyrolytic circumstances affect the unique characteristics of biochar (Oni *et al*. 2019).

A new opportunity has developed with the potential to address several of the shortcomings of traditional agriculture, such as excessive fertilizer use, poor yield, and organic agriculture (Jones *et al*. 1997). Biochar, sometimes known as “black gold” in the agricultural industry, is a carbon-rich substance. Biochar has high concentrations of C, H, and O and low concentrations of N, S, P, K, Na, Mg, Al, Fe, Ca, and Si. Biochar doesn't represent a single product with fixed chemical or physical properties. It encompasses diverse forms of black carbon, varying in properties based on the feedstock, pyrolysis unit, and processing conditions (Spokas 2010).

Moreover, biochar production using all types of agricultural waste, animal manure, and municipal waste is a smart way of recycling agro-waste. According to Abrol and Sharma (2019), among its many advantageous qualities are the improvement of soil fertility, crop output, and food security. However, the exact mechanism of biochar induced increase in crop productivity is still not well known. This review emphasizes the importance of environmental awareness in handling agricultural biomass wastes. Additionally, it offers strategic suggestions for policymakers to establish and execute agriculture waste management programs in line with circular economy principles. Thus the study concludes with a comprehensive review covering the biochar advantages, limitations, technological readiness, operational obstacles, and prospects.

RESIDUE BURNING AND AIR POLLUTION

The cultivation of rice, paddy, and wheat is a major industry in the states of Haryana, Punjab, Rajasthan, and western Uttar Pradesh. According to data from NPMCR, the states of Uttar Pradesh and Punjab generate the most agricultural leftovers, respectively, at 60 and 46 MT yearly, with 92 MT being burnt. Almost 70% of these wastes come from rice and wheat activities. Unfortunately, these regions are notorious for the common practice of burning straw and stubble after harvest, resulting in significant nutrient and resource loss.

Rice contributes the most significant portion at 43%, followed by wheat at approximately 21%, sugarcane at 19%, and oilseed crops at around 5% (Jain *et al*. 2014). This burning process results in significant soil nutrient loss, including the loss of organic carbon (3850 million kg), nitrogen (59 million kg), phosphorus (20 million kg), and potassium (34 million kg), in addition to deteriorating the quality of the air. Moreover, it emits significant amounts of COX, CH_4, NOX, and SOX into the atmosphere (Kumar *et al*. 2015).

Consequently, soil fertility is adversely affected by this open-field burning, leading to a decline in overall soil nutrients. Severe health concerns are associated with the poisonous gases released during this procedure, which can lead to respiratory conditions such asthma, emphysema, bronchitis, eye irritation, corneal opacity, and skin problems. Breathing in the released particulate matter might worsen pre-existing lung and heart conditions, which may cause early mortality in those who are impacted. Figure 1 shows the crop residue generation in India (Sahu *et al*. 2021).

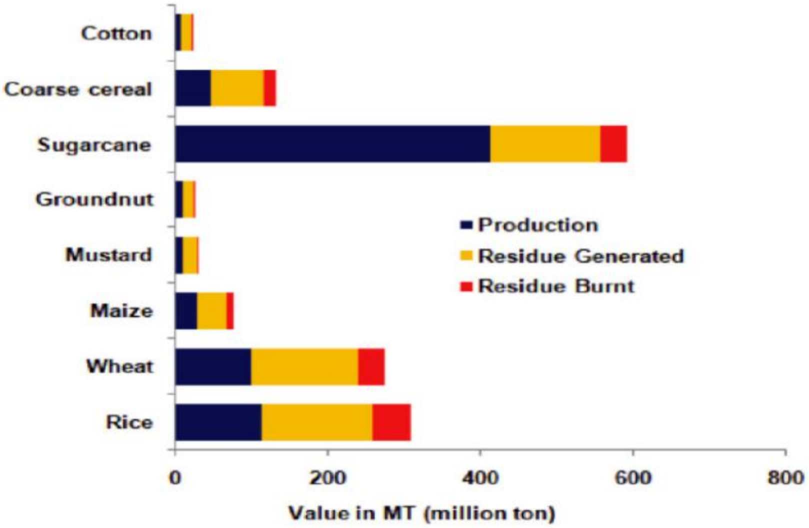

Fig. 1. Crop-wise distributions of crop production, residue generated, and residue burnt in India for the year 2018 (Porichha *et al*. 2021; Re-used under CC BY 4.0)

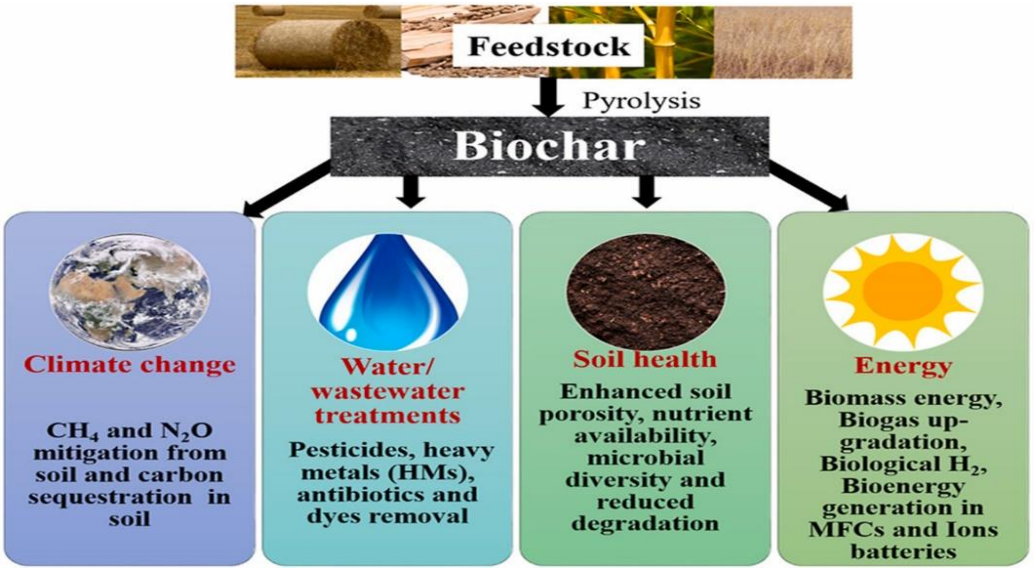

Fig. 2. Advantages of biochar

BIOCHAR AS SOIL AMENDMENT

Soil Physical Properties

The porous nature and extensive surface area of biochar significantly enhance various soil physical properties such as total porosity, moisture content, water retention capacity, soil aggregation, and hydraulic conductivity (Zhang *et al*. 2021). The increased soil porosity facilitates microbial growth and elongation of roots, while its elevated cation exchange capacity (CEC) enhances nutrient retention and availability (Glaser *et al*. 2002). Notably, biochar helps prevent nutrient leaching, thereby fostering soil fertility (Jeffery *et al*. 2011). Soil bulk density is an important characteristic to control aeration and nutrient transformation in soil (Sharma *et al*. 2021). By preventing nutrient losses through leaching or gaseous emissions, biochar helps maintain soil fertility. Its aromatic nature results in biochemical resistance, generating negatively charged surface groups like carboxyl and phenolic groups (Liang *et al*. 2006; Cheng *et al*. 2008). Biochar incorporation can enhance soil structure, promoting better water retention and drainage, which is conducive to root growth and overall soil health (Graber *et al*. 2010). Figure 2 shows the various advantages of biochar on soil health.

Furthermore, biochar improves water sorption, decreases soil density, changes aggregate properties, and increases pore volume—all of which support the growth of soil microorganisms and plants (Abrol *et al*. 2016; Sharma *et al*. 2019). According to Razzaghi *et al*. (2020) and Edeh *et al*. (2020), biochar having large specific surface area and hydrophilic domains enhances its ability to retain water, which boosts agricultural yield (Bonanomi *et al*. 2017; Rawat *et al*. 2019).

The application of biochar, especially at higher levels, significantly increases soil field capacity (Singh *et al*. 2017). These effects are particularly advantageous in non-irrigated regions, augmenting available water for crop growth and reducing water stress between rainfall events (Sharma *et al*. 2021). According to Adekiya *et al*. (2020), biochar was applied at four levels 0, 10, 20, and 30 t ha^{-1} for the experiment in 2017 and 2018 and the study showed reduction in the soil's bulk density by 74.7% and an increase in porosity by 65.0% in the second year. Application of biochar at 10, 20, and 30 t ha^{-1} reduced bulk density and increased porosity by 4.3, 8.3, and 18.7%, respectively, in the second year compared with the first year.

With regard to the soil physical properties, Table 2 shows that the application of biochar increased the cation exchange capacity up to 45% (Singh *et al.* 2022). Rice husk biochar reduced soil bulk density up to 1.5% (Sharma *et al.* 2021) and increased water use efficiency (Abrol *et al*. 2024). Mixed wood biochar reduced soil bulk density, increased infiltration, and decreased runoff (Abrol *et al.* 2016). Corn stover biochar increased macro aggregates (Hearth *et al.* 2013). Miscanthus biochar helped to decrease bulk density by 31% and increased porosity by 12% to 41% (Liu *et al.* 2016).

Soil Chemical and Biological Properties

The alkaline properties of biochar aid in neutralizing acidic soils, thereby enhancing pH levels and fertility (Lehmann 2019). Studies have consistently showcased biochar's efficacy in elevating soil pH (Chu *et al*. 2011), leading to enhanced nutrient assimilation (Zwieten *et al*. 2010). Over the long term, tropical soil treated with biochar exhibits increased nutrient availability (Lehmann *et al*. 2003; Rondon *et al*. 2007). Incorporating biochar reduces the need for nitrogen fertilizers and enriches soil carbon content (Widowati *et al*. (2012), functioning as a stable soil conditioner and fertilizer that mitigates nitrogen leaching (Steiner *et al*. 2008). The augmentation of aromatic carbon content from biochar positively influences soil properties (Knicker *et al*. 2013). According to Sukartono *et al*. (2011), biochar, due to its porous structure, has significant impact on nutrient retention through high CEC levels.

In reference to Table 2, oil palm empty fruit bunch biochar helps improve soil chemical properties *via* increasing the soil available potassium up to 37% over RDF (Bindu *et al.* 2020); tobacco stalk biochar helps increase the soil pH (Bindu *et al.* 2016); biochar from eucalyptus wood, bamboo, and rice husk helped decrease exchangeable AI by 34.4 to 95.7% (Geng *et al.* 2022); rice straw biochar helped increase soil pH by 8.5% to 79.2%. Cacao shell biochar increased soil pH by 0.5 units (Martinsen *et al.* 2015).

Soil hosts a variety of organisms influenced by soil conditions, climate, and land management. Biochar has the potential to impact soil microbial communities by supporting beneficial populations and mitigating certain pathogens, positively affecting nutrient cycling, and soil health (Lehmann *et al*. 2011). The exact influence of biochar on soil biota is an ongoing area of study. Some research emphasizes bacteria, mycorrhiza, and earthworms. Additionally, Graber *et al*. (2010) found increased colonies of specific bacteria and yeasts with higher biochar rates but reduced culturable filamentous fungi. The porous structure of biochar likely facilitates microbial colonization and growth.

CROP PRODUCTIVITY

Applying biochar has proven to have the ability to increase soil productivity in terms of its physical, chemical, and biological properties (Lehmann *et al*. 2003; Chan *et al*. 2007). In particular, Chan *et al*. (2007) found that biochar application enhanced soil structure, increased soil water retention capacity, and decreased soil compaction. Moreover, studies by Liang *et al*. (2006) and Yamato *et al*. (2006) indicated that biochar application elevates soil pH and enhances cation exchange capacity (CEC). For instance, Zwieten *et al*. (2010) demonstrated that combining paper mill waste biochar with inorganic fertilizer led to greater biomass production in soybean and radish compared to the exclusive use of inorganic fertilizer. Similarly, Widowati *et al*. (2012) found that the use of biochar made from municipal trash and chicken dung boosted the biomass of maize. Biochar’s capacity to raise soil pH and CEC is linked to increased crop production (Liang *et al*. 2006; Yamato *et al*. 2006). Figure 2 depicts the use of biochar in wastewater treatment.

REMEDIATION OF SOIL AND WATER

Heavy metal and persistent organic pollutant (POP) contamination in soil, such as polycyclic aromatic hydrocarbons and polychlorinated biphenyls, poses severe threats to environmental sustainability, food safety, and human health. Biochar exhibits a remarkable capability to immobilize metals, including Cd, Cu, Ni, Pb, and Zn, thus reducing their availability in soil and water. This immobilization occurs through several mechanisms such as electrostatic attraction, ion exchange, and changes in soil pH induced by the addition of carbonates and phosphates. Various processes such as partitioning, pore filling, electrostatic attraction, π–π electron interactions, and the hydrophobic effect contribute to this effectiveness. Biochar's high porosity, surface area, buffering capacity, ash content, alkalinity, and aromatic qualities are associated with its effectiveness. However, the materials used and the pyrolysis process’s circumstances have an impact on biochar’s effectiveness (Wiedner *et al*. 2013). Table 1 shows the effect of biochar on different soil pollutants.

SYNGAS AND BIODIESEL FORMATION

Biochar serves as a versatile component in both syngas production and soil enhancement. Its role as a feedstock for syngas provides a renewable energy source, while its application in soils boosts agricultural productivity and environmental health (Huber *et al*. 2006; Kang *et al*. 2020). The two main processes for producing syngas are biomass gasification and pyrolysis, which allow for the large-scale, quick conversion of solid organic resources. As an alternative fuel to petro-diesel that is carbon neutral, biodiesel is made by esterifying and transesterifying vegetable or animal oils using homogeneous (*e.g.*, KOH, NaOH, HCl, H_2SO_4) and heterogeneous catalysts (*e.g.*, CaO, zeolite, amberlyst resins, SiO_2, TiO_2, Al_2O_3).

MITIGATING GREENHOUSE GASES

Adding biochar to soil helps reduce N_2O emissions and aids in the storage of carbon (Sapkota *et al*. 2024). According to a meta-analysis by Verhoeven *et al*. (2017), there were average decreases in N_2O emissions of between 9% and 12%.

But according to a different study, soil amended with biochar emitted around 50% less N_2O than unamended soil (Cayuela *et al*. 2014).

Additionally, soil amended with biochar alongside inorganic fertilizers enhanced soil organic carbon (SOC) storage and reduced C mineralization. Biochar can aid in reducing emissions of greenhouse gases including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from the soil, acting as a carbon sink (Sohi *et al*. 2010). Figure 2 shows the advantages of biochar application on CH_4 and N_2O mitigation.

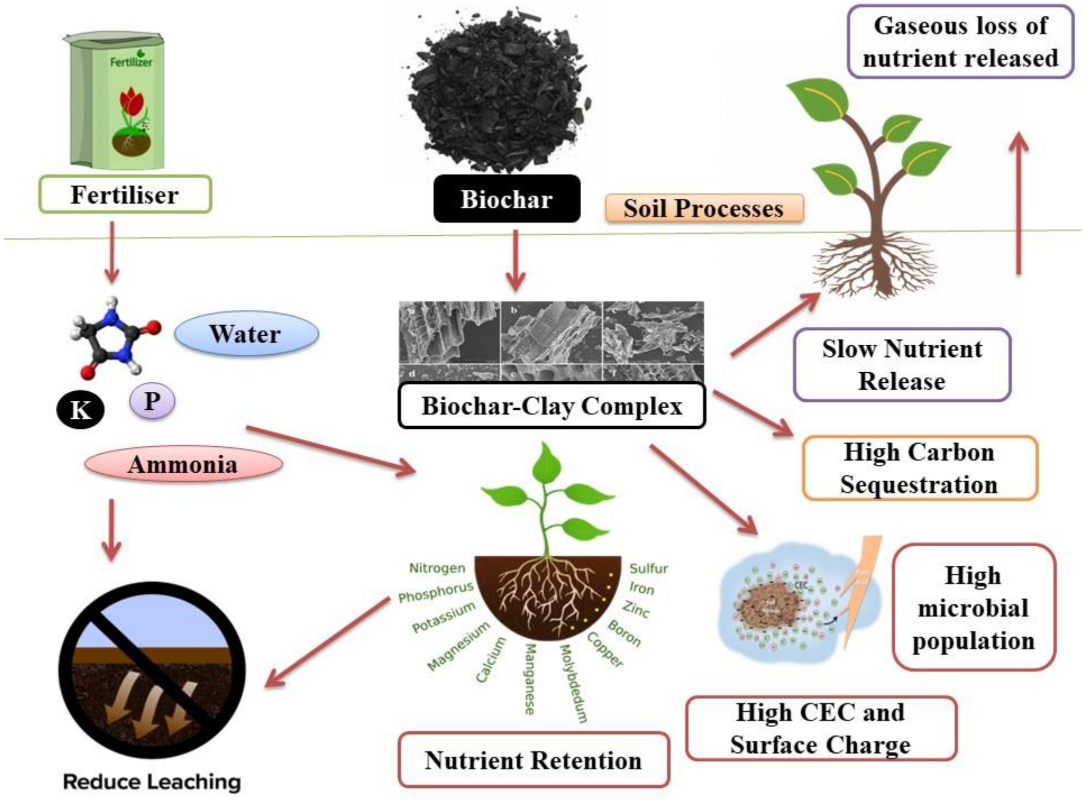

Fig. 3. Applications of biochar in soil (Redrawn with inspiration from Malyan *et al*. 2021)

Policies and Strategies for Biochar-related Activities

India has promoted biochar to increase soil fertility through programmes such as the National Mission on Sustainable Agriculture. To lessen reliance on fossil fuels, the National Policy on Biofuels promotes the production and application of biochar for sustainable agriculture.

The “National Biochar Initiative” was started by the Indian Ministry of Environment, Forests, and Climate Change as part of the government's efforts to support soil health enhancement, carbon sequestration, and sustainable agriculture.

Soil Health Cards scheme was implemented by the Govt. of India in the year 2015 with an aim to provide soil health cards to famers to apply appropriate recommended integrated nutrient management practices. Under this component, biochar can be used as soil amendment in acidic and saline soils where there is a scope to improve the water holding capacity.

India BioChar and Bioresources network is a platform that is committed to significantly reduce the greenhouse gases, increase carbon sequestration and improve various farm related problems in India. This organization helps aims to innovate across the value chain of biochar and bioresources in India.

Biochar integration can enhance soil water retention as part of the Pradhan Mantri Krishi Sinchayee Yojana, which focuses on water usage efficiency. The ICAR-established Krishi Vigyan Kendras are essential to the spread of biochar-related practices. The goal of this extensive programme, which is laid out in a five-year plan, is to include biochar into agricultural practices all throughout the nation. The main goals include improving soil fertility, lowering carbon emissions through sustainable practices, and lessening the negative environmental effects of agriculture. The programme is a critical step in resolving issues with burning agricultural waste and soil deterioration. Additional information on the execution, advancement, and consequences of this programme is available in the official records furnished by the Indian government.

CONCLUSIONS

1. Policy recommendations have been outlined in this work for a pragmatic framework for policymakers, fostering a circular economy in waste management. Investing in biochar research, technology, and policy in India is a key move towards promoting a sustainable future.
2. Utilizing biochar in biomass energy systems and as a renewable carbon source for fuel generation is a way to promote clean, green energy. Its carbon-neutral qualities make it a greener fuel compared to fossil fuels, crucially mitigating climate change by capturing carbon in soil.
3. Biochar’s role in alleviating water and soil contamination emerges as a cost-effective, environmentally friendly strategy. Enhancing soil quality, fertility, and microbial activity, biochar serves as a natural soil amendment and compost. Its potential in water treatment resonates with sustainable development goals, particularly those focusing on health, sanitation, and access to clean water.
4. Furthermore, the biochar industry and related sectors generate jobs, bolsters environmental sustainability and accelerates GDP growth.

Table 1. Effect of Biochar on Different Soil Pollutants

Feedstock; Pyrolysis Temperature (°C); Applied Dose (%)	**Pollutants**	**Initial Concentration (mg/kg)**	**Removal Efficiency (%)**	**Interaction Mechanism**	**References**
Wood, 450 °C, 1.5	Thiamethoxam	6.0	22.8	Oxygen - containing groups, reactive oxygen species, persistent free radicals	You *et al*. (2020)
Pig manure, 700 °C, 2.0	Clothianidin	4.95	90.5	Hydrophobic interaction, H – bonding, p/π- πinteractions	Zhang *et al.* (2020)
	Imidacloprid		81.4		
Sewage manure, 700 °C °C, 2.0	PAHS	0.04	74.0	Pore filling, hydrophobic interaction, π- πinteractions	Godlewska *et al.* (2022)
Rice husk, 700 °C, 4.0	PCB’s	0.08	91.0	Hydrophobic interaction	Silvani *et al.* (2019)
Pig carcass, 650 °C, 2.0	Zn	48.21	76.4	Inner complexation	Cao and Harris (2010)
Rice straw, 500 °C, 5.0	Zn	37.98	36.9	Hydroxide precipitation, cation - π interaction	Liu *et al.* (2022)
Rice husk, 500 °C, 5.0	Cd	6.10	25.0	Surface complexation	Karmaker *et al.* (2021)
Sheep bone, 800 °C, 10.0	Zn	265	57.0	Precipitation, ion exchange, surface complexation	Azeem *et al.* (2021)
	Cd	5.83	60.0		
Carrot pulp, 550 °C, 8.0	Cu	29.32	90.1	Electrostatic forces, covalent bonding	Gholami and Rahimi (2020)

Table 2. Quantitative Effect of Biochar on Different Soil Parameters and Crop Productivity

Biochar	**Impact**	**References**
Soil Physical Properties		
Biochar (Meta Analysis)	Increased Cation Exchange Capacity up to 45%	Singh *et al*. (2022)
Rice husk	Reduced Soil bulk density up to 1.5%	Sharma *et al.* (2021)
Rice husk	Reduced water use efficiency	Abrol *et al.* (2024)
Mixed wood, 620 °C	Reduced Soil bulk density, increased infiltration and decreased runoff	Abrol *et al.* (2016)
Corn stover, 350 °C	Increased macro aggregates	Hearth *et al.* 2013
Corn stover, 350 °C and 550 °C	Increased water content and hydraulic conductivity	Hearth *et al.* 2013
Miscanthus, 450 °C	Increased soil water content	Duarte *et al.* (2019)
Mesquite biochar @ 10 %	Decreased bulk density by 31 & and increased porosity by 12% to 41%	Liu *et al.* (2016)
Soil Chemical Properties		
Oil Palm Empty fruit bunch biochar	Increased the soil available potassium (37% over RDF)	Bindu *et al.* (2020)
Tobacco stalk biochar	Increased the soil pH	Bindu *et al.* (2016)
Biochar from Eucalyptus wood, bamboo and rice husk	Decreased soluble; decreased exchangeable Al by 34.38 to 95.66%	Shetty and Prakash (2020); Geng *et al.* (2022)
Rice straw, 250-450 °C	Increased soil pH by 8.48 to 79.25%	Peng *et al.* (2011); Geng *et al.* (2022)
Cacao shell, oil palm shell, rice husk; 250 to 350°C;	Soil pH increased by 0.5 units (Cacao shell biochar); 0.05 (oil palm shell biochar); 0.04 units (Rice husk biochar)	Martinsen *et al.* (2015)
Poultry litter; 450°C and 550°C	Increased soil total carbon	Chan *et al.* (2008)
Miscanthus giganteus; 450°C	Increased total carbon content	Duarte *et al.* (2019)
Soil Biological Properties		
Hardwood; 500°C; for 2 h	Increase in abundance of bacteria and archaea oxidizing ammonia to nitrates and nitrites	Prommer *et al.* (2014)
Lignin-rich wood; 350 to 500 °C;	Enhanced phosphorous solubilizing microbes' activity for P mobilization in phosphate rich soils, but significantly improved the crop yield in P deficient soils	Deb *et al.* (2016)
Eucalypt green waste; 650 to 750 °C	Improved microbial abundance	Abujabhah *et al*. (2016)

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