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Title: Biochar for Agricultural Revolution and Environmental Sustainability in Bangladesh - A Review

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ABSTRACT

Recent research on biochar mainly heeds its use in climate-related studies, immobilizing contaminant, amending soil properties, restoring nutrient availability, and treating wastewater. The tangible attributes of biochar for improving plant growth and fertilizer use efficiency has become orthodox in enormous studies. Meager cost, excessive porosity, ample surface area and renewability hold promise for various engineering applications, some of which need further contemplation. This review successively quests the compatibility of biochar as a potential carrier material toal lot agrochemicals and microbes. It enlightens crucial specifications for evaluating biochar's potential as a delivery agent, including its physicochemical properties, adsorption and release mechanisms of agrochemicals and microbes, long-term effects as well as economic and environmental benefits. The review concludes with a brief discussion on how nano-interventions could enrich biochar properties for effective delivery applications.

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INTRODUCTION

Bangladesh, greatly reliant on agriculture as the driver of its economy, is passing a critical period of storming challenges regarding sustainable agricultural production and conserving ecosystem. Due to the increasing threats imposed by climate change and soil degradation, exploring novel soil amendment strategies has become indispensable.

Biochar, a product of biomass pyrolysis, attracts resolver's attention for its unparalleled physicochemical properties. Inclusion of charred bio-waste as a carbon source can improve soil quality and enhance productivity (Biederman and Harpole, 2013). The novel structures and surface properties denote the remediation efficacy of biochar. It is a versatile carbon-rich product with high surface area and cation exchange capacity, influenced by feedstock choice (Verma et al., 2024; Maniraj et al., 2023; Agyekum and

Nutakor, 2023). It has proven effective in environmental remediation, particularly in water and wastewater treatment by removing contaminants (Wang et al., 2020), and in agriculture by improving soil fertility and reducing water needs (Maniraj et al., 2023). Additionally, biochar is gaining attention in material science as a sustainable filler in polymer composites, enhancing their mechanical and electrical properties while supporting circular bioeconomy goals (Bartoli et al., 2022). It significantly enhances soil physicochemical properties including organic carbon, moisture retention, and nutrient holding capacity. Crop yield benefits are more pronounced in highly weathered soil areas, increasing over time post-initial application (Crane-Droesch et al., 2013). It lessens heavy mineral fertilizer and pesticides use, creating a positive plant-soil-microorganism interactions which tends to a sustainable approach in agriculture (Sashidhar et al., 2020). Combining with mycorrhizal fungi it enhances root characteristics, and consequently elevates crop productivity (Ning et al., 2019). The high carbon content of biochar (60% - 90%) favors efficient atmospheric CO_2 sequestration in terrestrial ecosystems (Santos et al., 2019). It is also capable of diminishing agricultural emissions stemming from frugal fertilizer requirement. Moreover, biochar has been utilized for precise, gradual, and controlled dispensing of agrochemicals and microbial inoculants, requiring reduced quantities of input materials (Kookana et al., 2011; Mukherjee et al., 2011).

The incorporation of biochar into soil improves structure by increasing porosity and reducing compaction, which facilitates better water retention and nutrient availability (Soliman et al., 2022). Additionally, biochar adjusts soil pH to more favorable levels, enhances cation exchange capacity, and increases organic carbon content, all of which support more efficient nutrient cycling (Soliman et al., 2022). These soil improvements contribute to better plant growth and stress tolerance. Biochar also enhances key physiological and biochemical processes in plants, such as photosynthetic efficiency and antioxidant activity, which are crucial for coping with stress conditions (Shao et al., 2024; Imran et al., 2022). Furthermore, it supports ionic homeostasis and mitigates oxidative damage, improving tolerance to drought, salinity, and heavy metals (Imran et al., 2022). In specific crops like brassica, biochar has been shown to enhance yield and oil content under flooding conditions through improved osmolyte accumulation and nutrient uptake (Shao et al., 2024).

Ultimately, this review provides valuable insights and a comprehensive understanding about the role of biochar in catalyzing agricultural revolution while fostering environmental sustainability in Bangladesh. It also endeavors to explore the potential of biochar nano-interventions. This systematic review evaluates biochar's role in enhancing agricultural productivity and environmental stability. It explores its effective use, and impact on crop production, suggesting potential nano-interventions with biochar for future agricultural advancements.

METODOLOGY

Literature search and selection criteria

The review sourced data from only peer-reviewed papers and annual reports of various agricultural institutes of Bangladesh published within 2010-2022. Scientific papers prioritizing primary research were accessed by Google Scholar using specific keywords and criteria. High-caliber papers including content, credible insights, and resonant conclusions were preferred.

Data collection, synthesis, and presentation

Secondary data from selected studies, encompassing study design, sample size, examined variables, methodologies, and key findings, were extracted. The collected data were synthesized to align with the review's objectives and presented in Table 1. Thematic information was visualized through graphical figures including narrative descriptions.

Limitations

Variability in study designs, heterogeneity of samples, and challenges related to the synthesis of diverse studies are major limitations of this review.

Contribution to Knowledge

The review projects a complete scenario of biochar's potential as a carrier material for agrochemicals and microbes. It focuses on key parameters including biochar's physicochemical properties, mechanisms of adsorption and release, and environmental convenience. Additionally, it discusses the potential of nano-interventions to enhance biochar properties for delivery applications.

DISCUSSION

Implication of biochar on soil's physicochemical attributes

Biochar offers several benefits for soil health and plant growth. It has the potential to enhance soil's physical attributes (Figure 1.), such as porosity, water retention, and aggregate stability. Typically, greater biochar application rates decrease bulk density (Głąb et al., 2016; Rogovska et al., 2016) while increase soil porosityand water retention. However, the impact varies with soil texture (Blanco-Canqui, 2017). The organic components of biochar improve particle bonding, particularly in coarse soils, increases wet stability in sandy soils but has varying effects on dry stability, being more significant in sandy loams or silt loams compared to sandy soils (Burrell et al., 2016). The addition of corncob biochar decreased soil thermal conductivity, influencing heat transfer and the overall energy balance in the soil (Zhang et al., 2013).

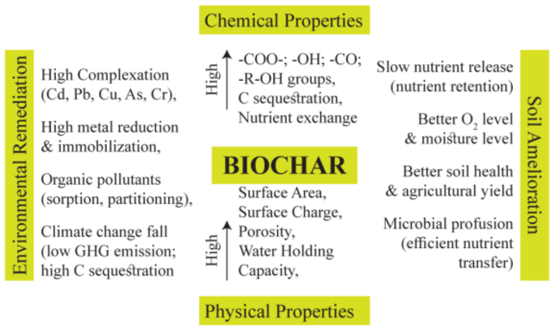

Figure 1. Implication of biochar on soil's attributes (Modified from Das et al., 2021).

Biochar improves soil pH (Karim et al., 2020; Raboin et al., 2016). It undergoes abiotic reactions after field application, changing its surface groups to negative functionalities e.g. carboxylic, phenolic, and hydroxyl, resulting in an increase in the soil's cation exchange capacity (CEC) as reported by (Bakar et al., 2015; Gamage et al., 2016). Biochar's surface chemistry, developed from oxidation, enhances nutrient retention through cation exchange (e.g., K^{+}, Na^{+}, Ca^{2+}, Mg^{2+}) and minimizes leaching of anions (e.g., NO^{3-}, PO_4^{3-}). It alters soil properties, improving nutrient retention (Haque et al., 2021; Streubel et al., 2011).

Manipulating soil conditions through biochar application can have positive or negative effects on soil microbes by altering their environment, directly influencing their growth. It enhances organic carbon breakdown in soils, carbon sequestration (Sohaimi et al., 2017). Prolonged biochar use can increase carbon storage (Novak and Busscher, 2013). However, Xu et al. (2018) found contradictory effects in some cases. Biochar amendments rejuvenate soil by enhancing biological properties, including enzyme activity (Gascó et al., 2016). Biochar's liming effect alleviates aluminum toxicity in acidic soil (Teutscherova et al., 2018).

Microbial Response to Biochar Amendment

Biochar incorporation into soil has been shown to reduce the availability of contaminants in the rhizosphere, thereby enhancing soil health and microbial activity. Its surface is rich in oxygen-containing functional groups that can immobilize heavy metals, reducing their bioavailability (Abdelhafez et al., 2014). This immobilization contributes to a less toxic environment for soil microbes. For instance, Prayogo et al. (2014) reported an increase in Gram-negative bacterial populations following biochar application. Additionally, wheat straw biochar has been found to alter fungal gene expression (Cheng et al., 2013), an effect influenced by changes in soil mineral elements, organic compounds (Lehmann et al., 2011), and elevated pH levels (Chen et al., 2013).

Heavy metal contamination, such as with cadmium (Cd) and lead (Pb), often reduces phospholipid fatty acid concentrations, a sign of microbial toxicity (Xu et al., 2018). By mitigating these toxic effects, biochar promotes beneficial microbial communities, which in turn support broader ecosystem functions. Moreover, biochar reduces the toxicity of organic contaminants like polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) through enhanced microbial activity (Beesley et al., 2011).

Modified biochar further amplifies these benefits. Improvements such as increased specific surface area, greater oxygen-containing functional groups, and enhanced electronic shuttling capacity contribute to more effective contaminant adsorption and microbial immobilization (Jiang et al., 2022). Advanced modification techniques, including the use of layered double hydroxides (Zheng et al., 2021), hydrogen peroxide (H_2O_2) treatments (Youngwilai et al., 2020), and Fe_3O_4 (magnetite) functionalization (Wang et al., 2021), have been employed to tailor biochar for optimized microbial support and contaminant remediation.

Figure 2. Microbial responses to biochar application (Bolan et al., 2023)

Studies affirm that biochar-immobilized microorganisms readily colonize plant roots without impediment (Hale et al., 2014) where, biochar does not obstruct root colonization by native soil microorganisms or when used with inoculum (Hashem et al., 2019; Liu et al., 2018). Plant-growth-promoting microbes offer varied benefits for plant health (Figure 2.), such as nutrient acquisition and bolstering growth, extensively studied in agricultural contexts (Ramakrishna et al., 2019). Immobilized microbes on biochar effectively remove contaminants from various sources like industrial wastewater, domestic waste, soil, and air (Li et al., 2022). These investigations focus on organic contaminants like phenols, pesticides, dyes, pharmaceuticals, antibiotics, and polycyclic aromatic hydrocarbons (PAHs) (Sun et al., 2020; Zhang and Wang, 2021) as well as potentially toxic elements (PTEs) such as Cu(II), Cd(II), Pb(II), As(V), Mn(II), and others ((Huang et al., 2020; Shen et al., 2019; Zhang et al., 2022).

Effect of biochar on plant-microbe interaction and soil health

The application of biochar plays a crucial role in enhancing plant–microbe interactions and improving overall soil health through its multifaceted influence on soil properties, microbial communities, and disease dynamics. As a stable organic amendment, biochar improves key soil physical and chemical characteristics, including pH balance, nutrient availability, and water-holding capacity, thereby creating a more favorable environment for plant growth (Saleem et al., 2022). Furthermore, it contributes to increased soil organic carbon and microbial biomass—two essential components for efficient nutrient cycling and long-term soil fertility (Bai et al., 2025).

Biochar also supports the proliferation of beneficial microbial communities. For example, it increases the abundance of plant-friendly microbes such as *Bacillus* and *Pseudomonas*, which are known for their roles in suppressing soilborne pathogens and enhancing plant resilience (Yan et al., 2024). Additionally, biochar stabilizes the microbial network in the rhizosphere, increasing its structural complexity and resilience to environmental disturbances (Wang et al., 2024).

In terms of disease mitigation, biochar has been shown to reduce the incidence of soilborne pathogens like *Ralstonia solanacearum*, thus lowering the risk of crop diseases (Wang et al., 2024). When applied in combination with plant growth-promoting bacteria (PGPBs), its suppressive effect on pathogens is further enhanced, contributing to both improved plant health and productivity (Yan et al., 2024).

Despite these benefits, caution is warranted as some studies suggest that biochar could potentially introduce harmful substances or cause undesirable shifts in microbial communities. Such concerns highlight the importance of context-specific application strategies and ongoing evaluation to ensure its safe and sustainable use (Lytand et al., 2023).

Biochar as a carrier material

Biochar favors micro-environments through flocculation, adsorption, encapsulation, entrapment, and bonding (Lehmann et al., 2011) Microbial adhesion relies on mineral content and pore size of biochar surfaces (Figure 2). High porosity enhances water retention, and protects microbes against desiccation (Glodowska, 2014). Thus, it increases biomass yield (10–30%) and elevates microbial activity (Jeffery et al., 2011). Moreover, biochar can perform better than charcoal and peat as a carrier for microbial inoculants (Figure 3), and enhances compost quality, nitrogen conservation, and reduction of greenhouse gas emissions (Tu et al., 2019). Maintaining biochar sterility pre-inoculation and adjusting pH through controlled pyrolysis are strategies proposed to enhance biochar applicability (Vanek and Thies, 2016).

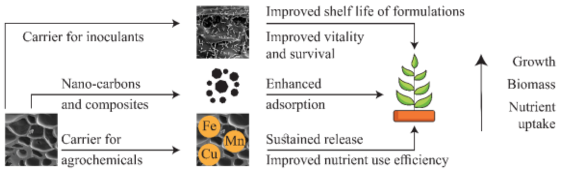

Figure 3. Application of biochar as a carrier material (Sashidhar et al. 2020)

Biochar as a carrier for chemical and bio-fertilizers, can sequester C, mitigate greenhouse gas emissions, consolidate the risk of eutrophication, rejuvenate degraded land (Calabi-Floody et al., 2018). It exhibits strong capabilities in adsorbing pesticides due to its diverse physicochemical characteristics (Figure 1.), including its carbon content, surface area, porosity, and mineral composition (Liu et al., 2018).

Adsorption mechanism of biochar

Multiplex surface chemistry of biochar abates nutrient leaching and accelerates soil fertility. Biochar having higher buffering capacity monitors control release, and movement of nutrients e.g. nitrogen and phosphorus into soil (Mukherjee et al., 2011). It has negative charges distributed on the surface which attract cations. While forming complex with soil clay, organic matter, and nutrients, it can grip anions. With ageing, surface oxidation of biochar generates huge oxygenated functional groups consequently bumping the kinetics of sorption and exchange of nutrients and agrochemicals (Qian and Chen, 2014). Sumaraj and Padhye, (2017) showed that the oxygenated functional groups *viz.* phenols, lactones, and carboxyl groups interact with the positively charged ions like NH_4^+ by forming a H-bond which amplifies cation exchange capacity (CEC) of the biochar. Again, acidic functional groups pull the negatively charged ions like NO_3^-. However, alkaline soil pH (7.7-8.7) favors the adsorption of cationic agrochemicals (Figure 4) making them unavailable for further leaching and uptake by plants (Ahmad et al., 2014). Elemental composition of biochar also promotes the chemisorption of nutrients such as C, H, N, O, and S (Kookana et al., 2011).

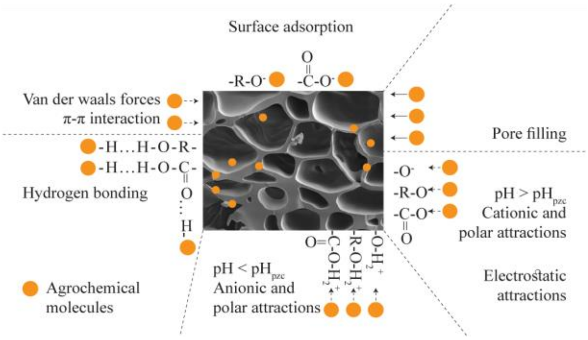

Figure 4. Adsorption and release of agrochemicals (Cara et al., 2022)

Biochar driving an agricultural revolution in Bangladesh

In Bangladesh, research indicates that biochar application significantly boosts up agricultural productivity (Baquy et al., 2022); increasingcrop yields by 116% (Table 1). Some cases show improved soybean yield but reduced water availability. During T. Aman, biochar leads to 30% reduced fertilizer dose maintaining optimal rice yield in charland soil. (BRRI Annual Report, 2022). Biochar boosts potato growth and yield. Incorporating 30% biochar and 70% soil is the optimal combination for sweet pepper production. It can suppress bacterial wilt of eggplant and tomato. Tricho-compost, composts, and biochar all enhance plant growth, crop productivity, and contribute to barley disease suppression. Additionally, biochar positively affects cabbage, maize, groundnut, and dragon fruit cultivation. (BARI Annual Report, 2022). The country's population growth and sustainable strategies are vital to counter chemical fertilizer-heavy farming. Biochar could be a sustainable solution (Karim et al., 2020) to enhance soil quality.

Depending on sorbate-sorbent interaction strength, biochar can adsorb synergistically by physisorption and chemisorption. Firstly, diffusion, hydrophobic interactions, π–π bonds, van der Waals forces, and H-bonding results in physisorption which is reversible weak intermolecular physical interaction. Secondly, covalent bonding or complex formation leads to irreversible monolayer chemical interaction i.e. chemisorption (Cara et al., 2022).

Table 1. Effect of biochar application on crop yields in Bangladesh

Feed Stock	Pyrolysis temperature	Biochar dose	Impact on the crop growth and yield	References
Sugarcane bagasse	600 °C	5 and 10 t/ha	10 t/ha, increased maize and groundnut yields by 40-60% in charland.	(Rahman et al., 2022)
Wood of Raintree, kadam, and chambul	300°C to 500°C	10 and 15 t/ha	15 t/ha, enhanced paddy growth.	(Shamim et al., 2018; Rambhatla et al., 2025)
Rice Straw	400 °C	16.60 g/kg	Biochar with chemical fertilizer boosted wheat production.	(Iqbal, 2017)
Mahogony Wood	450 °C	1, 3, and 5 t/ha	Biochar at 5 t/ha resulted in highest brinjal (67 t/ha) and cauliflower (42 t/ha) yields.	(Haque et al., 2019; Kadarwati et al., 2020)
Banana peel waste	400 °C for 2 h	1, 2, and 3%	Plant productivity decreased when 1% biochar was applied, but it improved when 2% and 3% biochar were used.	(Islam et al., 2019)
Rice husk	300 °C	0, 5, 10, and 20 t/ha	Maize yield was recorded as 89.75 g/plant at an application rate of 20 t/ha	(Shashi et al., 2018; Tsai et al., 2021)
Poultry litter biochar	300 °C, 10 min muffle furnace	1, 2, 3, and 4 t/ha	Higher biochar rates led to a significant increase ($p<0.001$) in the dry weight of Gima Kalmi	(Sikder and Joardar, 2019)

Environmental Sustainability

Remediating polluted soil

Influenced by source materials and pyrolysis temperatures, the substantial surface area of biochar and cation exchange capacities enhance the adsorption of organic and inorganic pollutants onto its surface (Beesley et al., 2011). This reduces the mobility of pollutants in treated contaminated soils. Sugar cane bagasse and orange peel and biochar exhibit effectiveness in remediating Pb contaminated soils (Abdelhafez et al., 2014). Biochar application raises soil pH and boosts soil organic matter, converting labile Pb into less available forms. However, attention is necessary before employing them in soils tainted with As contamination. Xu et al. (2018) reported that biochar enhances microbial carbon use efficiency to alleviate Cd and Pb metal toxicity and add carbon inputs. Alkali treated biochar possesses larger surface area than those of raw and acid treated bio-chars, and it serves as an adsorbent to remove tetracycline from aqueous solution of wastewater treatment plant (Liu et al., 2012).

Climate change mitigation

Ecosystem operation relies on the presence of soil carbon. Biochar, an engineered black carbon substance, acts as a soil conditioner. It counteracts the rise in atmospheric CO_2 by sequestering organic carbon in the soil. For effective carbon removal and storage in the soil compared to atmospheric CO_2, a continuous and lasting process spanning several centuries is necessary. Therefore, the relocation of biochar to subsoil layers is essential (Lorenz and Lal, 2014). Biocharplays a significant role in climate change mitigation by providing long-term carbon sequestration and improving soil health. One of its most impactful contributions lies in its ability to stabilize carbon in the soil for centuries, effectively removing carbon dioxide from the atmosphere (Keerthi, 2024). For instance, a study in British Columbia revealed that applying just 1 metric tonne of biochar per hectare could mitigate between 3 to 5 tonnes of CO_2 equivalent over 20 years. When scaled across 746,000 hectares, this could result in a total reduction of approximately 2.5 million metric tonnes of CO_2 (Lefebvre et al., 2023).

Beyond carbon sequestration, biochar enhances soil fertility, water retention, and microbial activity, all of which contribute to improved crop yields and reduced dependence on chemical fertilizers (Keerthi, 2024; Dadebo et al., 2023). This dual benefit underscores its value in promoting sustainable agricultural practices. For example, biochar produced from wastewater sludge has been shown to improve lettuce growth in pot experiments, highlighting its potential for economic and agricultural sustainability (Dadebo et al., 2023).

Furthermore, the climate mitigation potential of biochar can be significantly increased through optimized application strategies. Research suggests that carefully planned logistics such as targeting specific areas and optimizing transportation, can enhance the efficiency of biochar deployment. Spatial modeling has been found to potentially double the mitigation impact compared to random application strategies (Lefebvre et al., 2024).

Greenhouse gas emission

When pyrolysis gas is left unburned in the process of biochar production, the resulting pyrolysis emissions consist of CH_4, CO, and non-methane volatile organic carbon. Notably, N_2O and CH_4 are potent greenhouse gases. Utilizing fast pyrolysis to create a highly resilient biochar can enhance carbon sequestration and diminish greenhouse gas emissions. Stewart et al., (2013) reported that CO_2 comprised 20–35% of the CO_2 sequestered and the emissions like N_2O up to 89%. While biochar application can elevate global warming potential with extensive nitrogen fertilizer application, its integration effectively reduces N_2O emissions while simultaneously enhancing crop yields (Wang et al., 2012).

Biochar has emerged as a promising amendment for reducing greenhouse gas (GHG) emissions in agricultural systems, particularly targeting nitrous oxide (N_2O) and methane (CH_4), two potent GHGs. Its incorporation into soil has been shown to significantly decrease emissions under certain conditions. For example, Li et al. (2024) found that biochar application reduced N_2O emissions by up to 18.7% and CH_4 emissions by 16.9% under low nitrogen (N) input conditions, highlighting its effectiveness in low-input agricultural systems. However, the impact of biochar on carbon dioxide (CO_2) emissions is more variable. Schlesinger (2023) reported a wide range of CO_2 emission changes, from a 31% reduction to a 49% increase, suggesting that outcomes depend heavily on specific management practices and environmental conditions. Despite this variability, continuous application of biochar has shown potential for reducing CO_2 emissions over time, implying that long-term use may yield greater benefits (Park et al., 2023).

The effectiveness of biochar in mitigating GHG emissions also depends on application rates and interactions with nitrogen fertilization. Dong et al. (2024) observed that applying biochar at a rate of 1.5 tons per hectare effectively reduced emissions while maintaining crop productivity, particularly in rice cultivation. However, Li et al. (2024) cautioned that high nitrogen input levels might negate the emission-reducing benefits of biochar and could even exacerbate emissions in some cases. This underscores the importance of optimizing both biochar and fertilizer inputs to achieve climate mitigation goals.

Although the potential of biochar is significant, researchers such as Park et al. (2023) emphasize the need for extended, long-term studies to better understand its mechanisms and sustainability in different agricultural settings. Furthermore, Schlesinger (2023) points out that indirect emissions associated with the biochar life cyclesuch as those from biomass harvesting and pyrolysis, must be considered, as they may offset some of the benefits.

Nano intervention of biochar

Biochar is used for soil amendment strategies and has been well-known over period. Recent investigations have shown the positive effects of nano carbons in biochar (Figure 5) to boost plant growth (Bhati et al., 2018). This sustainable strategy can mitigate the environmental pollution caused due to synthetic fertilizers. The surface functionalization strategies can allow the positive or negatively charged micronutrients to bind to the surface groups of biochar, as explained. This can increase plant uptake rate and prevent its localization and toxicity. The integrated approach of biochar technology with that of nanotechnology or biotechnology will further develop novel materials tailored for a specific environmental application. The size of the bulk Biochar resulting from the pyrolysis technology ranges from a few hundred micrometers to several centimeters. The biological effectiveness of the biochar particles can be increased further by reducing the particle size to less than 100 nm enabling the high surface area to volume ratios and higher surface energy. It can be expected that the nano-biochar might be superior in the adsorption of agrochemicals (Figure 4) or contaminants over the bulk biochar due to the large surface area and exposure of more functional groups for chemical attachment. The agglomeration of nanoparticles reduces the effective surface area and limits adsorption capacity. In addition to developing nano-biochar (Figure 5) to refine the adsorption properties of the bulk fraction, another approach to enhance the adsorption is adding functional nano materials on to the biochar surface. Several available materials like graphene, graphene oxide, metal nanocrystals, and carbon nanotubes (CNTs) have been impregnated onto the surface of the Biochar using various fabrication methods (Wei et al., 2018). (Xu et al., 2018) revealed that biochar improves soil conditions by raising pH, reducing metal availability, and immobilizing heavy metals. It enhances microbial activity and boosts Carbon Use Efficiency (CUE) in contaminated soils. However, further research is needed to understand long-term effects on microbial populations and potential nitrogen depletion due to nano-biochar's carbon sequestration in metal-contaminated soils.

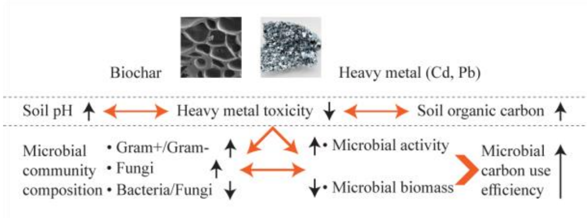

Figure 5. Nano-intervention of biochar and it's functions (Modified from Xu et al., 2018).

A few studies have evaluated the approach of combining other nanoparticles and biochar and tested its efficacy as a catalyst (Saxena et al., 2014). However, the synthesis of biochar-based nano composites is still in its infancy, and a wide knowledge gap exists between the laboratory testing of materials and its field application.

CONCLUSION

Considering the arrays of biochar benefits, it is a potentially untapped asset for sustainable soil health. The current review highlights the compatibility of biochar as a delivery agent for its engrossed traits e.g. physicochemical properties, mechanistic adsorption and release of agrochemicals and microorganisms. Additionally, the potent of biochar for controlled and gradual release of agrochemicals and microbial inoculants offers a pathway to minimize agricultural input materials while maximizing efficiency. This immobilization of agrochemicals facilitates improved soil health, plant growth in challenging conditions, and remediation of contaminated soils. Thus, biochar propels the agricultural revolution in Bangladesh and affirms environmental sustainability. Researchers must conduct thorough investigations into nano interventions to fully realize their potential applications. Current research has primarily focused on short-term effects, highlighting the urgency for long-term experiments to grasp biochar's enduring impact as its ages within soil. Addressing these gaps in knowledge could position biochar as a revolutionary scientific breakthrough beneficial to humanity.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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