SAINS TANAH – Journal of Soil Science and Agroclimatology

Journal homepage: http://jurnal.uns.ac.id/tanah

Biochar research advancement in Bangladesh: challenges and opportunities of biochar in improving soil health

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ARTICLE INFO

Keywords:
Agriculture
Greenhouse gas
Heavy metals
Soil acidification
Soil pH

Article history
Submitted: 2022-03-01
Accepted: 2022-04-18
Available online: 2022-08-01
Published regularly: December 2022

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ABSTRACT

Globally, biochar research and its application for soil improvement have attracted the interest of many researchers, primarily environmental and soil scientists, in the last decade. But a limited number of biochar research studies have been conducted in Bangladesh. Therefore, a comprehensive study on biochar research is necessary to find out the scope and opportunities of biochar application in the soils of Bangladesh. Generally, biochar can improve the physical, chemical, and biological properties of soils. It also has a significant role in greenhouse gas emissions. The contaminated soils can also be remediated through the judicious application of biochar. In Bangladesh, biochar application enhanced soil pH, organic matter, phosphorus availability, and agricultural production while decreasing soil acidification, microbial activity, and heavy metals mobility. Besides that, there were both positive and negative findings regarding nitrogen availability, greenhouse gas emissions, and heavy metal accumulation. However, this review includes the selection of feedstock, the advancement of pyrolysis technology, the characterization of biochar, and the agronomic and environmental benefits of biochar use. This paper also reviews biochar study and application activities in Bangladesh over the last decade. Further research directions have been suggested to ensure the beneficial and safe application of biochar to agricultural property.

How to Cite: Baquy, M.A.A., Mamun, M.A.A., Mia, S., Alam, M.M., Khan, M.S.H., Rahman, S.M. (2022). Biochar research advancement in Bangladesh: challenges and opportunities of biochar in improving soil health [Review]. Sains Tanah Journal of Soil Science and Agroclimatology, 19(2): 145-159. https://dx.doi.org/10.20961/stjssa.v19i2.59758

1. INTRODUCTION

The loss of soil fertility on almost 65% of agricultural land in Bangladesh is a significant concern for crop production. Besides, soil organic matter content is reportedly decreasing in the soils of Bangladesh, which is also viewed as an important issue in soil health (Ahmmed et al., 2018). The excessive use of chemical fertilizers coupled with intensive crop production with less organic fertilizer uses is the primary cause of soil fertility difficulties in Bangladesh. Traditional organic amendments like composts, manures, and crop residues have a limited longevity in the soil, and the practice of applying them in large amounts on a regular basis has distracted the focus of scientists away from this activity. Therefore, there is no way to improve the health of the soil in Bangladesh or increase its productivity until resource conservation strategies are used (Mia et al., 2014; Rahman et al., 2016). Biochar looks to be a magical answer for boosting carbon content, enhancing soil health, and assuring agricultural sustainability in such circumstances, and the scientific community has high expectations for it. In Bangladesh, the Bangladesh Biochar Initiative (BBI, www.biochar-bangladesh.org) has been promoted by the voluntary Non-Governmental Organization Christian Commission for Development in Bangladesh (CCDB) since 2013. The BBI is a two-pronged program that addresses the country's energy crisis by providing efficient gasifier cook stoves and producing biochar (BBI, 2021; Karim et al., 2020). Despite the increased study focus paid to biochar over the past 10 years throughout the world, only a few studies on biochar and the factors that influence its production have been undertaken and examined in Bangladesh.

Biochar, a carbon-rich plant-based biomass, also called "Black Gold", is produced by pyrolysis under high temperature and oxygen deprived conditions. There is diverse origin of waste biomasses such as rice husks, plant parts, branches, woods, sawdust, bones, sugarcane bi-products, fallen tree leaves, weeds, straw, and grasses which are commonly used in the production of biochar. The low heat conductivity, high porosity, large specific surface area, renewability, high stability, high carbon content, and high bulk density of biochar make it one of the most promising ingredients for a wide range of soil applications (Seow et al., 2022). Because of the numerous agricultural, environmental, and economic benefits associated with biochar application, it has been positioned as a vital alternative for sustainable development and carbon-trading system (Karim et al., 2020; Rasul et al., 2022). Recently, "biochar" has been praised for its capacity to ameliorate poor soil conditions such as leaching, acidity, and contamination while directly reducing carbon emissions in the atmosphere and promoting renewable energy. Biochar is capable of directly retaining plant macronutrients such as N, P, K, and Ca, depending on the type of precursor biomass of the biochar (Domingues et al., 2017; Khan et al., 2016a; Laghari et al., 2015). Soil amendments including biochar may recover approximately 46%, 54%, 54%, and 61% of total C, N, P, and K content, respectively. Thus, substantial amounts of nutrients might be returned to the soil while biochar is used to grow crops (Mia et al., 2018). The high nutritional value is attributed to the high nutritional value of the biochar it contains. Indirectly, the use of biochar leads to a number of additional benefits for plant nutrient cycling, including increased retention and utilization efficiency, as well as reduced leaching, hence boosting soil fertility (Domingues et al., 2017).

Biochar's long-term sustainability and stability for soil amendments and environmental protection have been backed up by plenty of research findings from throughout the world. In recent years, Bangladesh has seen the acceptance and application of several sustainable farming technologies to improve the state of its soil. Modern and sound technology is the application of biochar in crop fields with the purpose of promoting long-term agriculture (BBI, 2021). Biochar is widely regarded as a very effective solution for cleanup of heavy metals from contaminated soils and water bodies. A few investigations have examined the use of biochar in soils contaminated with heavy metals in Bangladesh (Alam et al., 2020; Ferdousi & Imamul Huq, 2020; Noor et al., 2015). Biochar assisted detoxification of heavy metals in soils primarily involves their immobilization via electrostatic interactions, cation exchange, and adsorption, resulting in their reduction to less toxic species (Li et al., 2017). The organic matter content of biochar may help immobilize heavy metals in polluted soils through electrostatic and non-electrostatic forces (Yuan et al., 2019). The use of biochar for soil conditioning has been proven to be generally beneficial, as evidenced by improvements in an ecosystem quality, climate change mitigation, and lower resource use. On the other hand, the heterogeneity in biochar qualities, makes it challenging to upgrade technology, implementation, and commercialization, and the lack of regulations and standardization makes biochar adoption challenging (James et al., 2022).

Biochar has unique physicochemical qualities those enable it to be utilized for an extended period of time, to safely store carbon in the environment, and to promote soil health. In the field of biochar testing, there is a significant amount of literature devoted to the findings obtained on almost all kinds of soils. The majority of these studies concluded that biochar might be a good soil amendment (Mia et al., 2014; Zhang et al., 2021). Biochar treatment has been shown to boost crop production in nutrient-depleted and degraded soils, although its impact is not necessarily substantial in fertile or healthy soils (Hussain et al., 2017; Yuan et al., 2019). The effect of biochar amendment on crop yield is mainly reliant on the wide variation in experimental setup and circumstances, including soil and biochar types, crop species, time, and rate of biochar application (Liu et al., 2013; Solaiman & Anawar, 2015). Therefore, an emerging effort is underway to understand the processes and roles of biochar in enhancing agricultural crop productivity through long-term field research utilizing a variety of biochar types in a variety of soils. A more extensive meta-analysis of the existing literature is also required to make suggestions to researchers and consumers regarding the best suitable feedstock, production conditions, and soil type. The prospective characteristics of biochar make it very clear that this technology has the potential to become an essential technology for Bangladesh, and this review has been undertaken in order to fulfill the following objectives:

a) to present an in-depth analysis of recent research findings and theoretical advancements on biochar usage in Bangladesh.
b) to evaluate the application of beneficial biochar and biochar-based products in agriculture, with a goal to increase the use of these products, particularly for soil improvement.
c) to identify future research directions and recommendations for biochar in agriculture of Bangladesh.

2. Data collection and analysis

To understand the relationship between biochar and other parameters related to soil health, scientometric analysis was performed through searching the keywords used in published biochar research in Bangladesh (Fig. 1). The relationship between biochars procured from different feedstocks, and pH, electrical conductivity (EC), cation exchange capacity (CEC) and total carbon content were studied to know the feedstock type's impact on the properties as mentioned earlier. Afterwards, to investigate the consequence of biochar application rate on organic carbon (OC) content, a correlation between biochar application rate (ton ha^{-1}) and soil OC content (%) was carried out from the previously accumulated data used in the listed references of this manuscript. Contrastingly, other valuable attributes of biochar might have an immense relationship with crop yields, greenhouse gas emissions, and heavy metals remediation, but were not analyzed due to the scarcity of related data on Bangladesh soil.

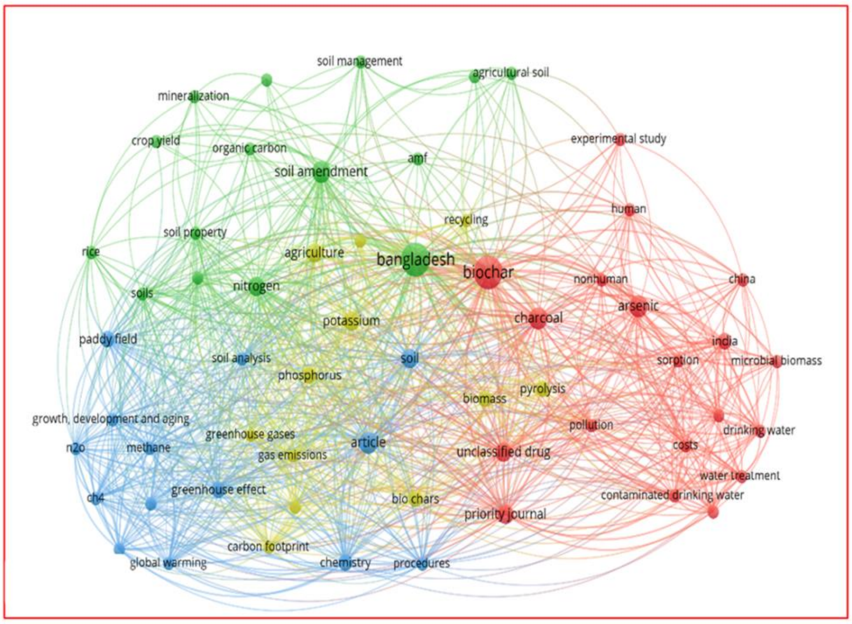

Figure 1. Scientometric analysis showing research of biochar in relation to soil health in Bangladesh

3. Production technology of biochar in Bangladesh

Organic wastes can be employed in Bangladesh as a possible soil amendment to improve soil quality. The wastes include domestic, agricultural, animal, agro-industrial, forest residues, and city wastes (Halder et al., 2014). Total biomass resource accessible for energy is 94.16 million tons in Bangladesh (Himel et al., 2019). Every year, large amounts of crop residues are produced in Bangladesh. Livestock and poultry waste (e.g., cow dung, poultry litter) is an excellent feedstock for biochar. Furthermore, biomass from the forest and forestry industries is also source of feedstock which accounts for approximately 9.0 million tons (Alam, 2017). Unfortunately, it is used with scant regard to soil improvement. Crop residues are typically burned or taken to clean the land, resulting in this potentially valuable resource loss. In general, crop residues can be recycled in various ways, including composting, mulching, and direct incorporation into the soil. Crop residues can be considered one of the principal feedstocks for biochar production. Because of the shortage of woody resources, it has been noticed that the utilization of tree leaves and jute sticks might be an alternate source of biochar feedstock (Rahman et al., 2020).

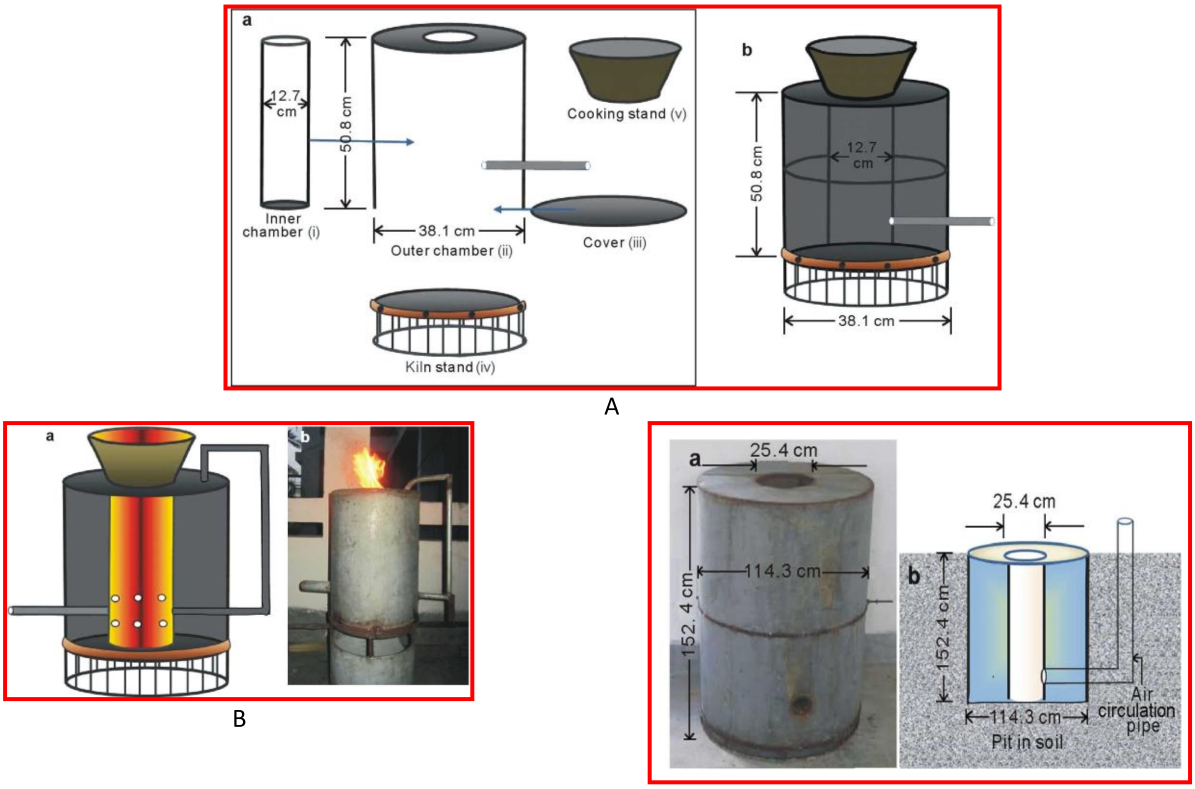

Figure 2. A different model of biochar production kilns: A) Model I, B) Model II and C) Model III. (Adapted from Mia et al. (2015)).

It is estimated that approximately 47 thousand tons of waste will be generated per day in 2025. The six biggest cities in the country, Dhaka, Chittagong, Khulna, Rajshahi, Barisal, and Sylhet produce approximately 8 thousand tons of solid trash every day (Abedin & Jahiruddin, 2015). City wastes are also valuable feedstock for making biochar.

In 2016, urban waste production in Bangladesh was projected to be between 15,507 and 15,888 tons per day, with organic waste accounting for 75 percent of total waste (Mia et al., 2018). Bangladesh produces 78 million tons of agricultural waste, 83 million tons of animal and poultry waste, and 15 million tons of processed residues (Alam, 2017). In addition, Bangladesh generates 17 million tons of forest waste (Halder et al., 2014).

Biochar-making technology is not widely available at the farmer and industrial scale in Bangladesh. Rural households rely almost entirely on biomass for cooking. Thus, biochar technology should be used so that heat energy for cooking and biochar production for agricultural use occur simultaneously (Mia et al., 2014). Recently, three different models of biochar production techniques depending on the syngas circulation for farmer's use were proposed by Mia et al. (2015). The models are: (1) airtight with no syngas circulation (Model I), (2) semi-airtight with external syngas circulation (Model II), and (3) semi-airtight with internal syngas circulation (Model III). Model I was recommended for quality biochar production, whereas Model III was recommended for cooking and biochar generation in rural regions (Fig. 2).

Among the improved design stoves, the most popular charcoal-generating cooking stove is the top-tilt updraft gasifier (TLUD) (BBI, 2021). TLUD gasifiers produce char as part of the cooking process. The operation of TLUDs is relatively straightforward manner. Briefly, the TLUD is a canister that contains a fuel bed made of small pieces of biomass. A grating at the bottom and top of the cylinder, above the fuel bed, has openings through which air can enter the canister. The top of the fuel bed is kerosene-soaked and ignited. White smoke is produced as an ignition front goes through the fuel, leaving unburned char above. The oxygen (primary air) entering the cylinder's base helps sustain the ignition front. The white smoke is combustible and is used for cooking at the upper end of the TLUD. The oxygen (secondary air) enters the cylinder via side holes or a gap at the top to maintain the gas flame. The smoke-producing process occurs when the igniting front reaches the bottom of the cylinder, and the gas fire extinguishes. Finally, the char is taken out of the cylinder and used to make biochar (Fig. 3).

With the assistance of the Bangladesh Biochar Initiative (BBI, 2021), a low-cost and environmentally friendly TLUD gasifier stove named Akha has been developed. The pyrolysis temperature of Akha ranges from 650 to 800 °C. In this pyrolysis technique, char makes up around 15-25 % of the original dry weight of the wood fuel with 30-35% energy efficiency.

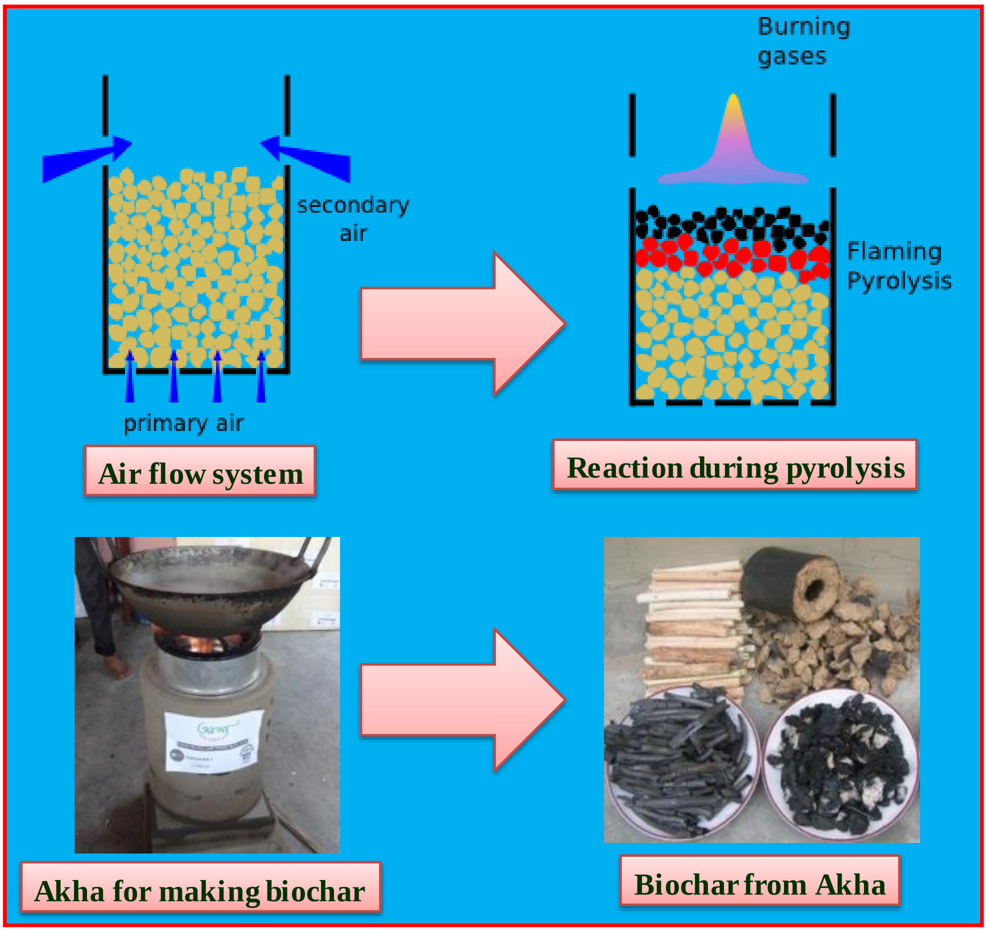

Figure 3. Pyrolysis mechanism and biochar production processes (Adapted with modification from BBI (2021))

Table 1. Impact of biochar applications on crop yields in Bangladesh

Feedstock	Pyrolysis condition	Biochar application rate	Impact on yield	References
Rice husk	Unknown	0, 5, 10, and 20 ton ha^{-1}	The higher maize yield was 89.75 g plant^{-1} at 20 ton ha^{-1}.	(Shashi et al., 2018)
Rice husk	Unknown	1 ton hectare^{-1} year^{-1}	The mulberry plant total leaf yield/hectare/year for the biochar amended treatment was 115.9% greater in the second year than the first.	(Ahmed et al., 2017)
Rice straw	Unknown	16.67 g kg^{-1}	Biochar improved wheat yield.	(Iqbal, 2017)
Sawdust	300-350 °C, 8 h	20 ton ha^{-1}	Soybean seed yield increased by 54% with biochar compared to control.	(Mete et al., 2015)
Banana peel waste	2 h, 400 °C	1, 2, and 3%	Plant productivity was lowered in treatments containing 1% biochar, but enhanced in treatments containing 2% and 3% biochar.	(Islam et al., 2019)
Cow urine, dry fallen leaves and rice straw	Unknown	2 ton ha^{-1}	Crop yield increased around 60%.	(Sutradhar et al., 2021)
Mahogany wood	Unknown	1, 3, and 5 ton ha^{-1}	Maximum yields of brinjal (67 ton ha^{-1}) and cauliflower (42 ton ha^{-1}) were obtained with biochar at a rate of 5 ton ha^{-1}.	(Haque et al., 2019)
Poultry litter	600-700 °C, 4 h	5, 10, and 15 g kg^{-1}	Biochar is effective for maize growth at a rate of 15 g kg^{-1}	(Masud et al., 2020)
Rice straw	400 °C,	16.60 g kg^{-1}	Biochar application with chemical fertilizer increased wheat productivity	(Iqbal, 2017)
Akha biochar	Unknown	5 kg decimal^{-1}	Bangladesh Agricultural Research Council recommended dose with 5 kg biochar decimal^{-1} produced maximum yield of red amaranth	(Mahbubul Islam et al., 2020)
Unknown	Unknown	3 and 5 ton ha^{-1}	Significant positive effect on jute seed yield and quality.	(Nazrul Islam et al., 2021)
Wood of *Albizia saman* (Raintree), *Neolamarckia cadamba* (Kadam), and *Albizia richardiana* (Chambul)	Unknown	10 and 15 ton ha^{-1}	The 15 ton ha^{-1} application rate showed better growth of paddy (*Oryza sativa* L.)	(Shamim et al., 2018)
Unknown	Unknown	2, 4, 6, and 8 ton ha^{-1}	The 6 ton ha^{-1} application rate showed better growth and yield of sesame (*Sesamum indicum* L.)	(Roy et al., 2020)
Sugarcane bagasse	600 °C	5 and 10 ton ha^{-1}	Application of biochar @ 10 ton ha^{-1} increased maize and groundnut yield 40-60% in charland ecosystem.	(Rahman et al., 2021)
Unknown	Unknown	1, 2, and 3 ton ha^{-1}	Application of biochar @ 2 ton ha^{-1} increased wheat and maize yield in drought-prone region.	(Hossain et al., 2021)
Unknown	Unknown	1, 2, and 5 ton ha^{-1}	Application of biochar @ 5 ton ha^{-1} showed maximum yield of brinjal, tomato, cauliflower and chilli as 67, 74, 42, and 4.5 ton ha^{-1}, respectively.	(Hasnat et al., 2018)
Various biomass	Akha stove	10 ton ha^{-1}	Tomato yield increased in biochar treated plot.	(Murad et al., 2018)
Poultry litter biochar	Muffle furnace, 300 °C, 10 min	1, 2, 3, and 4 ton ha^{-1}	Dry weight of Gima Kalmi (*Ipomoea aquatica*) increased significantly (p<0.001) with increasing the rate of biochar.	(Sikder & Joardar, 2019)

4. Properties/characterization of biochar

Biochar has a wide range of qualities based on what it is composed of, and how it is manufactured and utilized (Fig. 4). Biochar's viability in terms of characteristics has previously been studied in a few research (Masud et al., 2020; Piash et al., 2017; Shashi et al., 2018). Except for a few exceptions, the pH of most biochar was found to be high (approximately pH=9.0-10.5) depending on the feedstock types. Other biochar parameters such as organic carbon content, cation exchange capacity (CEC), electrical conductivity (EC), and nutrients (N, P, K, S, Ca, Mg) differed depending on pyrolysis temperature, time, and feedstock. Based on the type of feedstock, biochar producing capacity ranged from 34 to 51% (Piash et al., 2017). A study by Mia et al. (2015) found that the varied amount of biochar produced was primarily attributed due to differences in biochar manufacturing kilns. They also stated that the thermal stability of biochar increased with increasing the length of pyrolysis time. The enhanced condensation of aliphatic carbon to polyaromatic nuclei was responsible for this. The specific surface area of biochar from farmyard manure (FM), water hyacinth (WH), domestic organic waste (DW), quick compost (QC), corn cob (CC) and rice straw (RS) were 4.0, 4.7, 3.3, 3.7, 1.8 and 4.9 m^2 g^{-1}, respectively (Piash et al., 2017). This suggests that the source of biochar feedstock plays a significant impact on the biochar's specific surface area.

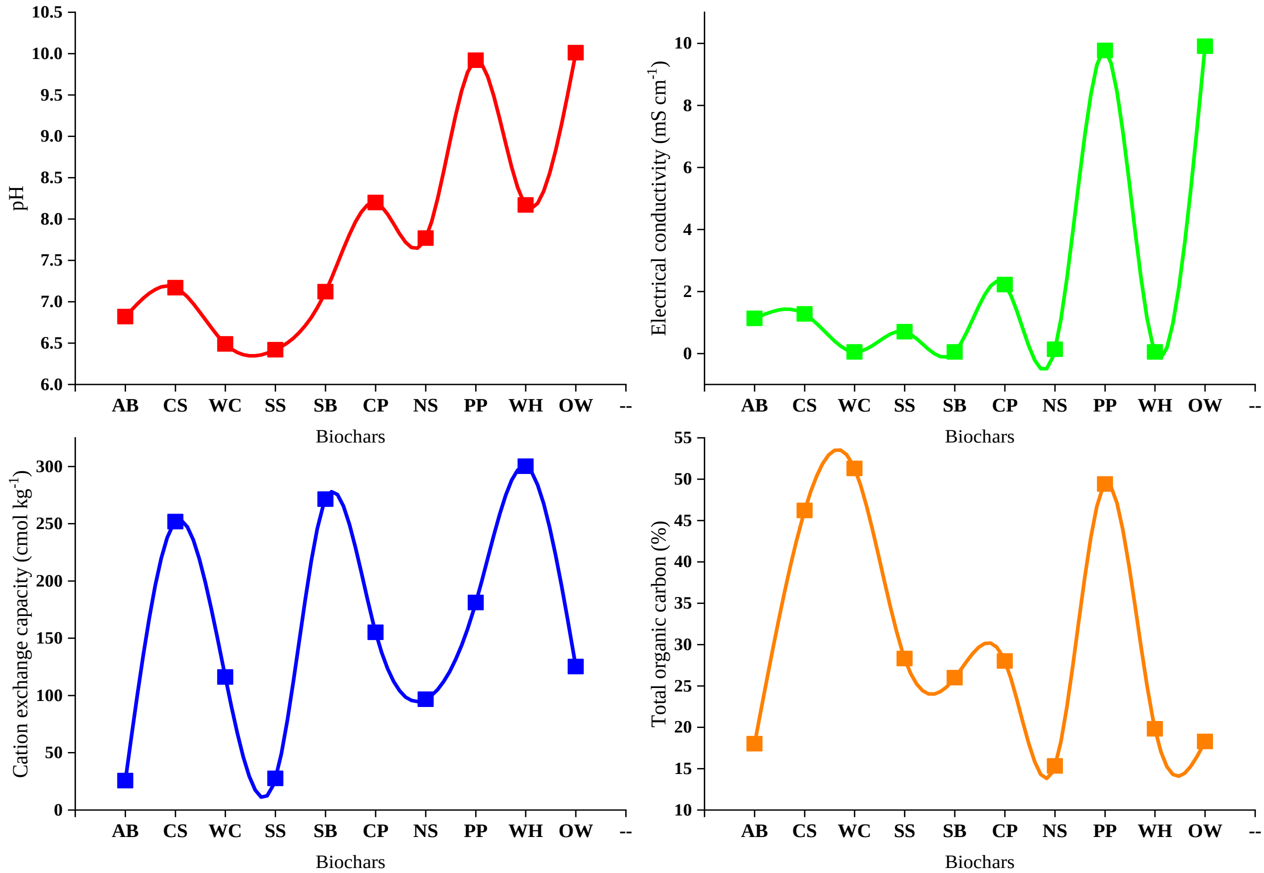

Figure 4. Biochars derived from different feedstocks (Animal Bone (AB), Corn Stover (CS), Wood Chips (WC), Sewage Sludge (SS), Sugarcane Bagasse (SB), Coconut Palm (CP), Nutshells (NS), Potato Peel (PP), Water Hyacinth (WH) and Organic Waste (OW)) show variations in pH, electrical conductivity, cation exchange capacity and total organic carbon of biochars (data extracted from Rabbani et al. (2021)).

In a previous work, it was found that the particle size of the pyrolyzed poultry litter biochar decreased with increasing temperature, but the surface area of the particles increases (Us Sakib & Aninda Dhar, 2018). In general, the porous structure of biochar is increasing with rising pyrolysis temperature. But, porous biochar can be produced from rice husk through leaching of ash using alkali treatments at low temperatures using the double crucible pyrolyzing method (Ahiduzzaman & Sadrul Islam, 2016). The surface area of biochar derived from coconut fibre is proportionate to the pyrolysis temperature (Dhar et al., 2020). However, molecular and nanoscale biochar research, on the other hand, has mostly been overlooked in Bangladesh.

5. Effect of biochar on crop yield

The majority of research in Bangladesh found that biochar application resulted in a considerable improvement in agricultural productivity. Crop production increased variably with biochar application, with a maximum of 116% compared to control treatments (without biochar) (Table 1). In a study, it was also found that the application of biochar increased soybean yield but reduced plant water availability (Mannan et al., 2021). However, crop production is in great demand in Bangladesh due to the country's expanding population. Notwithstanding that crop production has surged, it is mainly a farming system reliant on chemical fertilizers. Therefore, sustainable land management strategies for agricultural production are crucial to preventing further land degradation. In this context, biochar would be a potential soil additive that would increase crop yields sustainably (Karim et al., 2020).

Additionally, biochar has the potential to enhance soil quality. However, biochar research with many of the key crops (rice, maize, wheat, etc.) in varied soil environments in Bangladesh has been overlooked. Thus, to aid farmers in selecting biochars, production methods, and application rates suited for diverse soil environments, climates, and crops, investigations of the impacts of different biochars derived from various feedstocks on different crops growing across multiple soil conditions are required.

Biochar is a carbon-rich, stable compound that may last for an extended period in the soil (Wang et al., 2016). So, the use of biochar can completely alter soil properties over time. To the best of our knowledge, no long-term research has been conducted on the influence of biochar on crop production. Thus, long-term field research is being carried out to understand better how biochar treatments impact crop productivity.

6. Effect of biochar on nitrogen use efficiency and phosphorus availability

Nitrogen (N) is an essential plant nutrient element. N deficiency is one of the most common nutrient deficiencies in

Bangladeshi soils, posing a severe threat to agricultural production. Therefore, nitrogenous fertilizers are widely utilized for getting maximum crop yield. But, their efficiency is only approximately 30-40% (Sharna et al., 2021). It is estimated that there is a requirement for 3 million metric tons of urea fertilizer in Bangladesh (BBS, 2020). Farmers frequently use inorganic N fertilizers for crop productivity and to fulfill the country's food requirements. Because of low usage efficiency, the extensive use of fertilizers (especially urea-N is around 80% of total chemical fertilizers) frequently causes various environmental concerns, including soil acidification and eutrophication. If the current fertilizer usage pattern continues, soil productivity will be severely harmed (Ahmmed et al., 2018). In addition, Bangladesh's government imports approximately 1.6 million metric tons of chemical fertilizers each year, of which 1.1 million metric tons are urea fertilizer (BBS, 2020). As a result, foreign currency is wasted to import these chemical fertilizers. The farmer's dependence on chemical fertilizers is also a significant barrier to establishing an organic farming system in Bangladesh.

Thus, the use of biochar might be a promising soil amendment to enhance the nutrient use efficiency and, thereby sustainable agricultural production. Thus, biochar may be a potential soil additive for improving nutrient use efficiency and ensuring sustainable agricultural production.

According to a field experiment conducted in Bangabandhu Sheikh Mujibur Rahman Agricultural University, Bangladesh, the application of rice husk biochar in paddy fields increased ammonium-N and nitrate-N at 45 and 60 days after transplanting, respectively (Alam et al., 2019). The application of biochar reduced the nitrogen percentage of vermicompost made from beverage industry sludge and cow manure (Tasnim et al., 2021). The use of biochar in combination with fertilizer resulted in the most significant N accumulation by rice plants. As a result of the maximum N uptake in the combined application of biochar and fertilizer treatments, the yield increased by up to 49 % compared to solely fertilizer application (Piash et al., 2019). In a study by Naher et al. (2021), 16 field experiments and 18 farmer's field demonstration trials during 2017–2020 were conducted in various areas of Bangladesh to assess the effects of biochar with other amendment's application on N use efficiency. They found that a combined application of biochar and other amendments reduced 30% of synthetic N use. Although some studies indicated no notable influence of biochar on N use efficiency (Karim et al., 2020), many aforementioned results showed that biochar treatments could improve N uptake and potentially reduce N fertilizers need for crop growth.

Similar to N, the status of P in Bangladesh soils appears to be low to extremely low (Karim et al., 2020; Shil et al., 2016). Biochar derived from farmyard manure enhanced P uptake in vegetables considerably (Piash et al., 2019). Furthermore, Masud et al. (2020) investigated the influence of chicken litter biochar on acid soil fertility using incubation and pot studies with maize growth and they revealed that the availability of P increased compared to the control due to the addition of biochar. They also reported that the rate of biochar application was one of the most important parameters influencing the effect of biochar on soil bioavailable P concentration. Increased biochar rate reduced soil acidity, thereby increasing P availability in soils. Palansooriya et al. (2019) also experimented on the research farm of the University of Rajshahi, Bangladesh, and they investigated the impact of rice husk biochar on P content in wheat grains under alkaline soil conditions.

In comparison to other treatments, it was found that biochar amended treatments enhanced the most P translocation in wheat grain under improved physicochemical properties due to biochar addition to soils. Interestingly, P availability was found to be lower in biochar amended incubated soils compared to non-amended treatments. Although the addition of biochar decreased soil pH from 8.3 to 8.0, this was mainly due to the P fixation with Ca at high soil pH. On the other hand, in acid soils of Bangladesh, it was found that the addition of biochar derived from wastes increased soil pH as well as bioavailable P. This was attributed to biochar's alkalinity and the presence of carboxylic functional groups in biochar (Rabbani et al., 2021). Thus, it is concluded that biochar affects P availability by altering soil sorption and desorption capabilities, which mainly depends on soil and biochar types.

7. Effect of biochar on soil microbial properties and organic matter

Biochar's impact on soil microbial communities has been widely established in the literature (Nguyen et al., 2018; Palansooriya et al., 2019; Sheng & Zhu, 2018; L. Wu et al., 2021; Q. Wu et al., 2021). A change in biomass, community composition, and soil microbes has been observed in several studies after adding biochar to soils in Bangladesh. For example, Al Mamun et al. (2021) reported a significant increase in crop yield after the integrated application of biochar and vermicompost due to changes in microbial community structure. Moreover, Sani et al. (2020) examined the effect of the combined application of *Trichoderma* and biochar on tomato productivity under NPK fertilizer stress conditions. They showed that applying biochar to the soil encouraged establishing rhizosphere fungal and bacterial communities, resulting in better tomato yields. But, it was found in a study by Khan and Didar-Ur-Alam (2018) that bacterial populations were more remarkable in tannery waste-treated soils than in biochar produced from tannery waste. In addition, Khan and Imamul Huq (2014) also investigated that biochar treatment had a detrimental impact on the distribution and growth of soil microorganisms, thereby affecting soil quality and crop yield.

Haque et al. (2019) found that the total organic carbon in soils improved by 25 to 41% from its original values, indicating significant changes. Ahmed et al. (2017) studied the influence of biochar on soil characteristics, mulberry plant growth, yield, and foliar disease incidence. They found that biochar treated soils significantly increased organic matter content. Beside Karim et al. (2020) reported that the addition of biochar increased the amount of organic matter in the soil and enhanced the fertility of degraded soils in Bangladesh. Moreover, Alam et al. (2019) investigated that the highest organic carbon was sequestered in rice husk biochar treated plots compared to poultry manure and vermicompost treated plots.

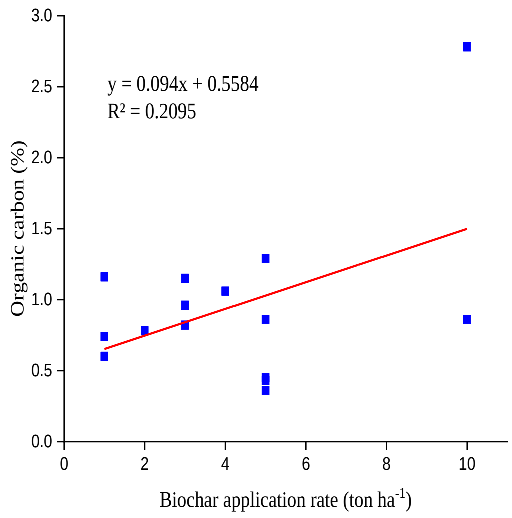

Figure 5. Relationship between biochar application rate (ton ha^{-1}) and organic carbon content (%) in Bangladesh soil (n=15)

A study by Iqbal (2017) investigated that the application of both compound and rice straw biochar improved the organic matter status of the soil throughout incubation. Furthermore, a study by Rabbani et al. (2021) conducted an incubation experiment with waste-derived biochar and found that biochar addition enhanced the organic carbon content of the soil substantially (P<0.01) after 120 days of incubation. Biochar can improve soil organic matter by 0.08 percent in a wheat-maize land-use system in a drought-prone area of northern Bangladesh (Hossain et al., 2021). Total soil organic carbon was increased in biochar treated soil than in control (0.25%), but sawdust (0.45%) derived biochar showed a higher potential to change soil organic carbon than rice husk (0.36%) and rice straw biochar (0.43%) (Khan et al., 2016b).

The mineralization of organic carbon was higher in mahagony biochar amended soils than in rice husk and eucalyptus biochars (Hasnat et al., 2018). It indicates that the source of feedstock plays a vital role in organic carbon mineralization. In addition, the biochar application rate impacts organic carbon content in the soil. The amount of organic carbon increased with the increasing biochar application rate, but it shows a weak correlation (r^2=0.20) (Fig. 5).

8. Effect of biochar on greenhouse gas emission

Bangladesh is a wet paddy rice-dominated ecosystem country. Therefore, there is enormous potential to produce greenhouse gases like CO_2, CH_4, and N_2O from the wet paddy field. But, the sequestration of soil organic carbon is the leading way to mitigate the above-mentioned gases in Bangladesh (Begum et al., 2018). Biochar is one of the most critical materials for reducing greenhouse gases through sequestering carbon (Ali et al., 2019; Ali et al., 2015). But, biochar has both beneficial and harmful effects on specific greenhouse gas emissions (Table 2). The incorporation of biochar into the soil decreased the levels of gases emission such as CO_2, phosphine, and N_2O while increasing the levels of CH_4 and CO. Furthermore, the application of biochar was not effective in lowering emissions of volatile organic compounds (VOCs). However, the use of biochar also increased the emission of CO_2 (Murad et al., 2018) which is not similar to the results found by Mahmud et al. (2014). They found that the application of biochar reduced the emission of CO_2 remarkably. The mentioned contradictory results might be due to the differences in biochar application rates. However, it is difficult to link biochar and greenhouse gas emissions due to a lack of available data and limited study. Thus, more studies on primary processes of increasing or decreasing greenhouse gas emissions due to the incorporation of biochar into the soils should be explored.

Table 2. Impact of biochar amendment on greenhouse gas emissions in croplands in Bangladesh

Feedstock	Production condition	Application rate	Impact of biochar	References
Farmyard manure, water hyacinth, domestic organic waste	380˚C ± 20˚C	10 ton ha^{-1}	1. Biochar reduced the CO_2 significantly from submerged soils. 2. The use of biochar showed inefficient in controlling the emission of CH_4 and CO into the atmosphere.	(Piash et al., 2018)
Unknown	-	2 ton ha^{-1}	1. Biochar additions to paddy soils reduced seasonal cumulative N_2O emissions by 20%. 2. Biochar additions considerably enhanced CH_4 emissions by 9.5–14.0%.	(Ali et al., 2015)
Rice straw, rice husk, saw dust	Slow pyrolysis, 45 min	5 ton ha^{-1}	1. Biochar reduced CO_2 and phosphine (PH_3) emissions significantly (P<0.05). 2. Biochar was unable to reduce CO and volatile organic compounds (VOC) emissions.	(Mahmud et al., 2014)
Various biomass	-	10 ton ha^{-1}	The CO_2 emission occurred in biochar amended soil.	(Murad et al., 2018)
Sugarcane bagasse	400-500 °C, 2 h	1 ton ha^{-1}	Incorporating biochar enhanced the overall global warming potentials of methane (CH_4) and nitrous oxide (N_2O) during rice cultivation by 4.0%.	(Ali et al., 2013)

Table 3. Impact of biochar application on the mobility and bioavailability of heavy metals in soils

Feedstock	Production condition	Application rate	Effects/ Contaminant	References
Rice straw, rice husk, saw dust	Slow pyrolysis, 45 min	5 ton ha^{-1}	No significant amount of bioavailable Cd, Cu, Pb and Zn was retained in biochar.	(Khan et al., 2016b)
Sawdust	350 °C	5 ton ha^{-1}	1. Significantly ($p < 0.05$) reduced plant Cd concentration by 72%. 2. Significantly reduced the plant uptake of Cr by 37%.	(Al Mamun et al., 2021)
Cowdung, sawdust, rice husk	Local biochar making stove	4%	All the biochar significantly reduced the As-induced oxidative stress due to decreased As uptake.	(Alam et al., 2019)
Rice husk, sawdust	Local biochar making stove	40 g kg^{-1}	As content in grain was reduced by 53% than control.	(Alam et al., 2020)
Rice husk, rice straw, sawdust	Open fire system	5 ton ha^{-1}	1. The accumulation of As increased in Kalmi Sak (*Ipomoea aquatica*). 2. As content was decreased in biochar amended soil.	(Noor et al., 2015)
Cow dung, poultry manure and sewage sludge	Slow pyrolysis, 250 °C, 45 min	5 ton ha^{-1}	The accumulation of As decreased in Kalmi Sak (*Ipomoea aquatica*).	(Ferdousi & Imamul Huq, 2020)

9. Remediation of contaminated soils using biochar in Bangladesh

Among the heavy metals, arsenic (As) is one of the most common in the soils of Bangladesh (Hossain, 2006; Islam et al., 2018). As contamination in soil is often due to irrigation water, mostly in paddy fields. To minimize the risk of As for human health, biochar application in As contaminated soil is suggested in Bangladesh since biochar can potentially adsorb the As from soil (Ferdousi & Imamul Huq, 2020). A study by Alam et al. (2020) found that the application of rice husk and sawdust biochar reduced the mobilization of As in root, shoot, and grain of pea crop under As stress conditions. The accumulation of As in Kalmi Sak (*Ipomoea aquatica*) was reduced in cow dung, poultry manure, and sewage sludge-derived biochar amended soil (Ferdousi & Imamul Huq, 2020). But, opposite results were obtained from a study by Noor et al. (2015).

They found that the application of rice straw, rice husk, and sawdust biochar increased the As accumulation in Kalmi Sak (*Ipomoea aquatica*). They also pointed out that the As dynamics was variable depending on feedstock types. Both positive and negative results in As accumulation might be due to the variation of feedstock types.

Biochar can form a complex with metal ions on their surface and reduce the potential risk of heavy metals in biochar amended soils. But, a study by Khan et al. (2016a) found that the bioavailability of cadmium (Cd), copper (Cu), lead (Pb), and zinc (Zn) was not reduced in rice husk, rice straw, and sawdust biochar amended soil. On the other hand, the Cd and chromium (Cr) uptake by crop plants was significantly reduced in sawdust biochar amended soil.

It is noted that biochar was applied at a single dose in almost all the studies (Table 3). Therefore, due to contradictory results on heavy metals uptake by crop plants, it is suggested to consider different rates of biochar to investigate the effects of biochar on the dynamics of heavy metals.

10. Effect of biochar on soil acidity amelioration

Acid soils (pH below 6.5) account for about 6.1 million hectares or 42% of the total land area of Bangladesh (Hasan et al., 2020). As biochar is characterized by high pH and alkalinity, there is a vast scope for ameliorating acid soil using biochar, especially in the Northern and Northeastern parts of Bangladesh. These areas are mainly affected by soil acidity and hamper crop growth and yield. A study conducted in the Northeastern part of Bangladesh by Karim et al. (2020) found that biochar application reduced soil acidity by increasing soil pH in all three different land use systems (tea monoculture, tea agroforestry, and forest). However, the magnitude of change in pH was high in the monoculture land-use system. They also suggested applying biochar produced from wood feedstock to alleviate the soil acidity in this region. In another study by Khan et al. (2016b), biochar application @ 5 tons ha^{-1} in moderately acidic soil (pH=5.60) increased soil pH by 0.42, 0.53, and 0.38 units in rice husk, rice straw, and saw dust treated soils, respectively. Instead of plant biomass biochar, the application of poultry litter biochar also increased soil pH with an increasing rate of biochar and growth of Gima Kalmi (*Ipomoea aquatica*) (Sikder & Joardar, 2019). Another study found that poultry biochar application @ 5, 10, and 15 g kg^{-1} in acid soil (pH=5.45) increased pH by 0.30, 0.70, and 1.20 units, respectively. They also found that biochar application @ 15 g kg^{-1} increased maize yield by reducing the exchangeable acidity and increasing the base cations of acidic soils. A study of biochar application in acidic soils (pH=4.33-4.39) was established by Rabbani et al. (2021) and found that the addition of biochar increased soil pH near neutral soil pH due to the alkalinity of biochars initially. But over time, soil pH decreased gradually and finally to 5.5 to 6.0 at 120 days of incubation depending on biochar types. Instead of biochar generated from plant biomass, biochar derived from poultry litter exhibited alkalinity effects and enhanced maize growth through acid soil amelioration. It was recommended that 15 g kg^{-1} of poultry litter biochar be applied to acid soil for maize production (Masud et al., 2020).

11. Future challenges and research directions

The incorporation of biochar can significantly change the soil environment for a long period. However, Bangladesh is still in the early stages of implementing a biochar-based farming system compared to other countries. Therefore, a suitable policy should be established before using biochar on a large scale in Bangladesh (Fig. 6).

Our present review, however, based on existing literature, identifies the following information gaps or obstacles that must be addressed by future research studies associated with the biochar application in Bangladesh:

- Almost all individuals who live in rural regions depend mainly on agricultural residues for cooking. Furthermore, domestic animals rely on agricultural straw residues. As a result of Bangladesh's limited biomass, improved waste recycling technology is required for biochar manufacturing.
- Due to biomass scarcity, alternative sources for biochar feedstock must be identified. Municipal waste has the potential to be a source of feedstock for biochar synthesis. Because municipal wastes contribute to environmental contamination, converting them into biochar should be a great solution to reduce pollution and utilize them as soil supplements. Currently, no advanced technique is available for producing biochar from municipal waste. Furthermore, municipal waste can contribute to the accumulation of heavy metals in biochar and further contamination of rural areas. Thus, the potential risk of using municipal wastes as biochar must be considered during the selection of feedstock.
- Biochar's characteristics are highly varied. There are concerns regarding the potential benefits of utilizing biochar due to differences in the properties of feedstock materials. Due to the inconsistency of the biochar characteristics, quality control must be performed before applying to the soils. A routine evaluation procedure for biochar analysis should be considered to preserve biochar quality. In Bangladesh, however, there is no such scheme. As a result, a biochar evaluation program must be developed to offer the farmers confidence in using biochar to enhance their soils.
- According to the literature, biochar can last for a long period in the soil. Therefore, the use of biochar can significantly alter the soil environment. According to our knowledge, no long-term biochar amendments research is being conducted in Bangladesh. Moreover, toxicity due to the application of biochar must be addressed prior to field application. Thus, before applying biochar on a broad scale, it should be necessary to perform long-term field experiments using biochar to understand how it affects soil characteristics.
- Paddy fields outnumber all other crops in Bangladesh. As a result, the paddy field is a significant contributor to greenhouse gas emissions. Thus, more emphasis should be placed on how the application of biochar might reduce greenhouse gas emissions and the mechanisms involved.

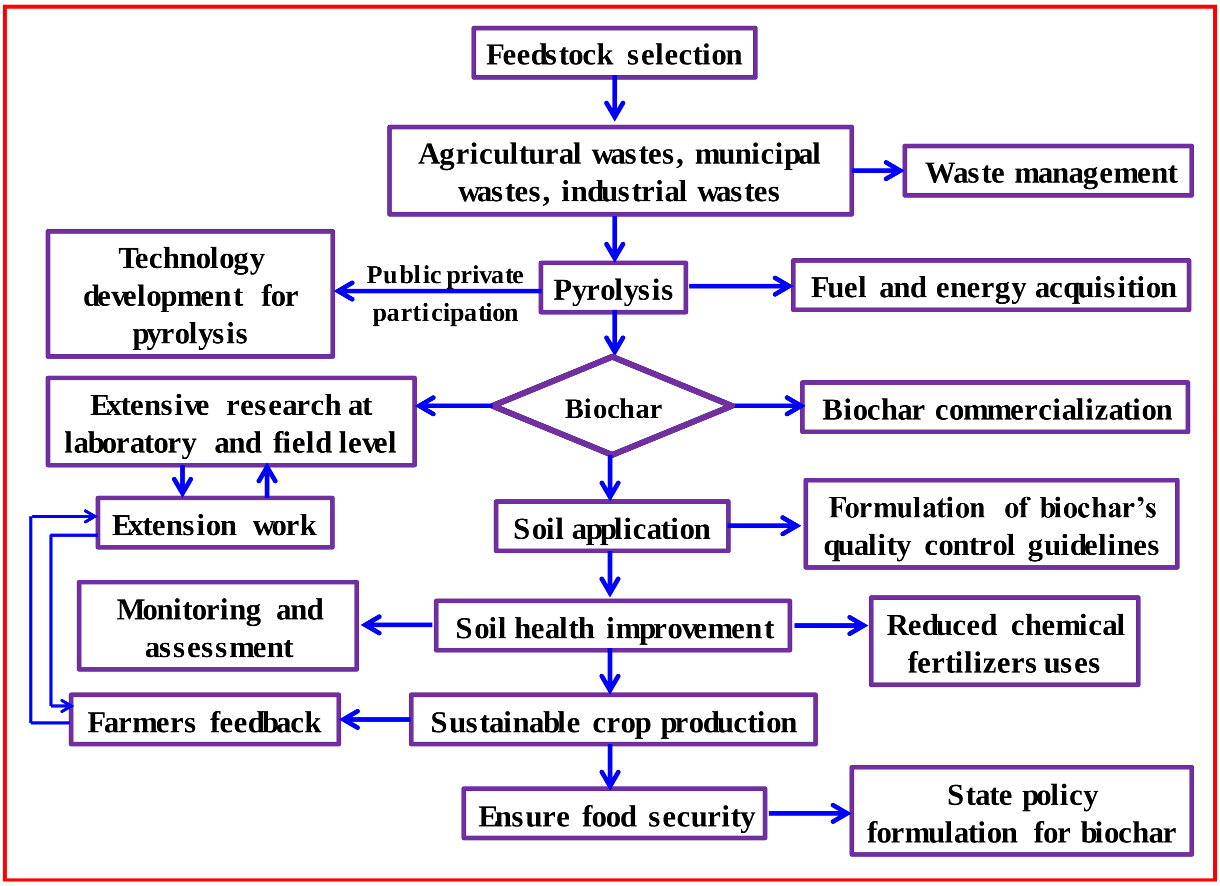

Figure 6. A suggested roadmap for the formulation of biochar policy of Bangladesh in terms of soil improvement

- There is a shortage of risk assessments for heavy metals studies in biochar-mediated soils. Heavy metals are typically adsorbed on the surface of biochar. However, a little transfer of heavy metals from the biochar surface to the soils may pose a greater danger of heavy metal contamination. Speciation or fractionation studies of various heavy metals in biochar enriched soil are thus necessary.
- Soil acidity is escalating as a result of the use of chemical fertilizers. Aluminium toxicity and low phosphorus levels are the primary constraints on crop productivity in acidic soils. Biochar's high nutrient retention and alkaline nature may help to improve soil productivity. Therefore, considerably more study into acid soil management with biochar is recommended.

12. Conclusion

The soils of Bangladesh are degraded continuously due to sub-optimal addition of biomass derived amendments to soils. To enhance soil health as well as sustainable crop production application of biochar might be a promising soil amendments for Bangladesh. Data obtained from biochar research in Bangladesh indicated both positive and negative results of biochar application as soil amendment depending on feedstock types, biochar production techniques, biochar application rate and crop species. The application of biochar increased crop yield as well as decreased soil acidification. Microbial activity was reduced in biochar amended soils. Due to contradictory findings on nitrogen availability, heavy metals accumulation and greenhouse gas emission, further study on biochar as a soil amendment must be carried out. However, more biochar research at the molecular level must be conducted to ensure the safe use of biochar for sustainable and profitable agriculture.

Acknowledgements

The first author wishes to express gratitude to Dr. Jackson Nkoh Nkoh for his assistance during the literature search.

Funding

This study was carried out with the assistance of funding (R & D: 02, 2021-2022) of the Ministry of Science and Technology, People's Republic of Bangladesh.

Declaration of Competing Interest

The authors declare no competing financial or personal interests that may appear and influence the work reported in this paper.

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