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# Waste-derived nanobiochar: A new avenue towards sustainable agriculture, environment, and circular bioeconomy

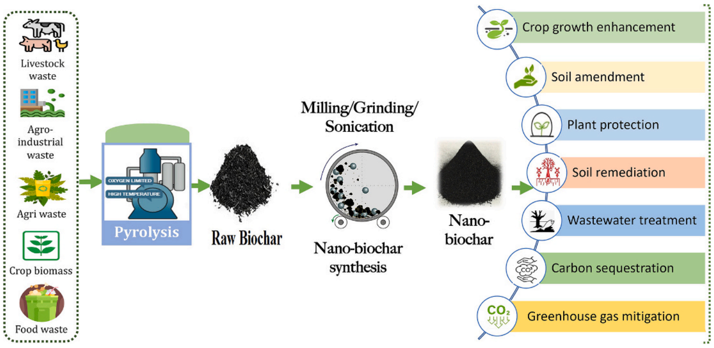
Md. Nasir Hossain Sani [a,*], Mehedi Amin [b], Abu Bakar Siddique [c], Saifullah Omar Nasif [d], Bhim Bahadur Ghaley [e], Liya Ge [f], Feng Wang [g], Jean Wan Hong Yong [a]

[a] *Department of Biosystems and Technology, Swedish University of Agricultural Sciences (SLU), 234 56 Alnarp, Sweden*
[b] *Faculty of Agriculture, Sher-e-Bangla Agricultural University, Sher-e-Bangla Nagar, Dhaka 1207, Bangladesh*
[c] *Tasmanian Institute of Agriculture, University of Tasmania, Prospect 7250, Tasmania, Australia*
[d] *Global Centre for Environmental Remediation, The University of Newcastle, University Drive, Callaghan, NSW 2308, Australia*
[e] *Department of Plant and Environmental Sciences, University of Copenhagen, Højbakkegård Alle 30, 2630 Taastrup, Denmark*
[f] *Nanyang Environment and Water Research Institute, Nanyang Technological University, Singapore*
[g] *Environmental Resources and Soil Fertilizer Institute, Zhejiang Academy of Agricultural Sciences, Hangzhou 310000, China*

## HIGHLIGHTS

- Nanobiochars offer improved specific surface area, adsorption and mobility properties in soil compared to traditional BC.
- Increased surface area of nanobiochar facilitates plant development, and soil biological activities.
- Nanobiochar contributes to sustainable development and circular bioeconomy, aligning with the fulfilment of SDGs.
- Gaps exist in understanding absorption capacity, allowable limits, and ecotoxicity of nanobiochar application.

## GRAPHICAL ABSTRACT



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## ABSTRACT

The greatest challenge for the agriculture sector in the twenty-first century is to increase agricultural production to feed the burgeoning global population while maintaining soil health and the integrity of the agroecosystem. Currently, the application of biochar is widely implemented as an effective means for boosting sustainable agriculture while having a negligible influence on ecosystems and the environment. In comparison to traditional biochar, nano-biochar (nano-BC) boasts enhanced specific surface area, adsorption capacity, and mobility properties within soil, allowing it to promote soil properties, crop growth, and environmental remediation. Additionally, carbon sequestration and reduction of methane and nitrous oxide emissions from agriculture can be achieved with nano-BC applications, contributing to climate change mitigation. Nonetheless, due to cost-effectiveness, sustainability, and environmental friendliness, waste-derived nano-BC may emerge as the most viable alternative to conventional waste management strategies, contributing to the circular bioeconomy and the

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* Corresponding author at: Biosystem och teknologi, Box 190, 234 22 Lomma, Sweden.
*E-mail addresses:* md.sani@slu.se (Md.N.H. Sani), maminsau77@gmail.com (M. Amin), abubakar.siddique@utas.edu.au (A.B. Siddique), saifullah.nasif@uon.edu.au (S.O. Nasif), bbg@plen.ku.dk (B.B. Ghaley), lyge@ntu.edu.sg (L. Ge), wangfeng@zaas.ac.cn (F. Wang), jean.yong@slu.se (J.W.H. Yong).

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broader goal of achieving the Sustainable Development Goals (SDGs). However, it's important to note that research on nano-BC is still in its nascent stages. Potential risks, including toxicity in aquatic and terrestrial environments, necessitate extensive field investigations. This review delineates the potential of waste-derived nano-BC for sustainable agriculture and environmental applications, outlining current advancements, challenges, and possibilities in the realms from a sustainability and circular bioeconomy standpoint.

## 1. Introduction

Escalating demand for products, raw materials, and services has resulted in massive amounts of biowaste generated by agriculture, forestry, and the processing industry, which is expected to reach 3.4 billion tonnes globally by 2050 (Kee et al., 2021). Roughly, three-quarters of this biodegradable waste is disposed of, with 37 % deposited in landfills and 33 % in open dumps. These open disposal practices are recognized as significant environmental hazards due to the emission of various greenhouse gases (GHGs), including nitrous oxide ($N_2O$) contributing to 50 % of global emissions, and methane ($CH_4$) contributing to 40 %. These emissions possess substantial potential to amplify global warming, with $N_2O$ and $CH_4$ exhibiting warming potentials 25 and 298 times higher than that of carbon dioxide ($CO_2$) respectively (Wang et al., 2017a, 2017b; Dijkstra et al., 2012). Besides, improper waste management has led to heavy metal and metalloid pollution of soil, water, and food chains, posing serious environmental and public health risks (Tchounwou et al., 2012; Zhang et al., 2022a, 2022b). Such environmental and social concerns spurred the European Commission (EC) to introduce and promote the concept of "circular bioeconomy". It encompasses the sustainable utilization of renewable biological resources such as waste biomass to produce renewable bio-based products, biofuel, and energy (Kaszycki et al., 2021). Aligning with the "circular bioeconomy" strategy, the possibility of producing biochar from organic waste has drawn massive interest recently. This approach offers the dual benefits of creating valuable products from waste while concurrently reducing landfill space, disposal expenses, energy usage, and GHGs emissions.

Biochar is an organic carbon-rich material produced typically through thermochemical conversion of waste biomass at high temperatures in absence of oxygen or with a limited supply of oxygen (Tomczyk et al., 2020). The conversion of waste materials into biochar provides a plethora of benefits, including long-term carbon storage, bioenergy generation, improved soil fertility and reduced GHGs emissions (He et al., 2021; Zhang et al., 2021). Over the years, numerous studies have established that applying biochar to soils can improve the soil's physicochemical and biological qualities, agricultural yields, and immobilization of heavy metals and metalloids in contaminated soils (Sani et al., 2020; Hasnain et al., 2023; Yuan et al., 2022). Additionally, biochar manufacturing is not only cost-effective and environmentally benign, but also efficient at reusing waste resources, which can help hasten the transition to a carbon-neutral economy (Liu et al., 2021a; Cheng et al., 2022; Muhammad et al., 2022). Thus, the synthesis of waste-derived biochar provides an alternate strategy for waste management and resource recovery which contributes to climate change mitigation and environmental protection.

With the advancement of nanotechnology, it became possible to further reduce the size of biochar particles to the nanoscale, down to 100 nm or smaller, thereby enhancing their physical properties and biological efficacy (Ramanayaka et al., 2020a). The reduction of particle size is associated with greater porosity, specific surface area (SSA), mobility, and other attributes of bulk particles which convert sub-optimal biochar to a desirable high-quality nanomaterial (Oleszczuk et al., 2016). Although, in certain instances, the production cost of nano-BC can be higher than that of bulk biochar, cost estimates performed prior to scaled-up production provide the opportunity to select the cheapest production method for a specific type of nano-BC (Song et al., 2022). Furthermore, being more hydrodynamically labile, water flows can easily transport the nano-BC both vertically and horizontally in the terrestrial and aquatic habitats. This feature enables nano-BC as a potential element to remove heavy metals, toxic substances, and pesticides and thereby reduce soil and water pollution (Liu et al., 2018; Lian et al., 2021). Even though environmental concentrations of carbon nanomaterials (CNM) are generally non-toxic to aquatic organisms, it is essential to recognize the possibility of toxicity under certain conditions. Factors such as the nature of the organisms, the duration of exposure, and the preparation techniques of CNM can influence the manifestation of toxicity and should be carefully considered (Freixa et al., 2018). Furthermore, nano-BC can effectively regulate the mobilization and sorption of critical macro- and micronutrients, as well as harmful pollutants such as toxic substance ions and pesticides (Liu et al., 2022; Rajput et al., 2022a). In recent times, nano-BC has been widely utilized to fabricate nano-composite materials for treating wastewater, energy production, and the adsorption of organic dyes and other impurities (Mazarji et al., 2021a). Hence, nano-BC is becoming an increasingly popular key research field in environmental science and agriculture since it combines the advantages of nanotechnology with the benefits of biochar technology (Wang et al., 2017a, 2017b; Song et al., 2022).

Over the years, nano-BC technology has been implemented primarily in the environmental and industrial domains, with a specific focus on its utility in soil and wastewater treatment (Chausali et al., 2021). Notably, intriguing results for the application of nano-BC in sustainable agriculture have been widely reported in recent years (Rajput et al., 2022a, 2022b). However, nano-BC applications in agriculture are still in their infancy, with a dearth of transferability to large-scale field applications. While some studies have demonstrated that the interaction of nano-BC with the soil rhizosphere environment promotes microbial growth and restoration of heavy metal contaminated soil, numerous questions regarding its applicability remain unanswered. Importantly, in addition to studies on nano-BC characteristics and application in the agro-ecosystem and environment, a deeper knowledge of nano-BC mobility/environmental dispersion and toxicity risk is required. Thus, a critical understanding of the current nano-BC research, including fabrication, distinctive features, and targeted applications in agriculture, is essential as we move towards real-world implementations of nano-BC in agriculture. Given the recent surge in interest, this timely review provides a comprehensive overview of recent advances in the fabrication of waste-derived nano-BC, its high-value applications and performance in agriculture, as well as the role and mechanisms involved in agricultural soil improvement and climate change mitigation. Additionally, we aimed to conduct a critical perusal of potential risks and toxicity during application, eliciting insights valuable for strategic future research directions. The relevance of nano-BC products to enhancing sustainability, fostering a circular bioeconomy, and meeting the SDGs was also explored.

## 2. Production and properties of waste-derived nano-BC: waste to resources

### 2.1. Fabrication of nano-BC from waste biomass

Before exploring the preparation and characterization of nano-BC, it is vital to define and differentiate it from other terms of biomass-derived particles. Both bulk-BC and nano-BC are manufactured from biomass carbonization under oxygen-deficient conditions. The sole difference between bulk-BC and nano-BC is the particle size range: 0.04–20 mm for bulk-BC and $<100$ nm for biochar nanoparticles (Liu et al., 2018).

Thermochemical carbonization at varying temperatures (200–700 °C) has been widely used for the synthesis of nano-BC from a variety of feedstocks, including agricultural waste, wood, and forest leftovers (Table 1). Several methods, such as ball milling, centrifugation, microwave pyrolysis, disintegration through sonication and thermal heat flash treatment are most commonly used for nano-BC fabrication (Kumar et al., 2020; Ramanayaka et al., 2020b; Anupama and Khare, 2021). There are six typically used nano-BC preparation methods that are suitable with a variety of lignocellulosic biomass feedstocks and share several key processes (Fig. 1). Biomass is firstly transformed into bulk-BC, and then subjected to following several size-reduction techniques to produce nano-BC within the desired size range. Grinding or milling is a simple and straightforward method to accomplish size reduction. Multiple earlier investigations employed manual grinding using mortars to reduce the particle size of various bulk-BC (Dong et al., 2018; Lonappan et al., 2016; and Lian et al., 2020). However, ball milling has been suggested as a promising method for industrial-scale manufacturing of nano-BC to increase yield while maintaining the ideal particle size (Kumar et al., 2020). The application of ball milling offers a notable enhancement in the efficiency of lignocellulosic biomass conversion. This efficacy stems from its influence on crucial biomass parameters, including the crystallinity index, degree of polymerization, surface area, thermal stability, and particle size. Complementary approaches, such as dilute acid treatment, microwave irradiation, and liquid nitrogen cooling, can be employed synergistically to minimize the energy consumption associated with the ball milling process, thereby establishing a more resource-efficient and effective pathway for nano-BC production (Shen et al., 2020a, 2020b). Nonetheless, several studies have favoured the usual approach of grinding, then sieving the aqueous suspension, as the most effective method for fabricating nano-BC. For this method, the separation of nano-biochar typically involves two primary processes: sedimentation and membrane filtration. A typical sedimentation procedure under static conditions may take 24 h to accumulate nano-BC (Song et al., 2019). Following centrifugation, nano-BC particles can be extracted from the supernatant, while larger particles settle in the precipitant. However, conditions for sedimentation are highly context dependent. For instance, Lian et al. (2020) and Yue et al. (2019) centrifuged biochar at 10,000 rpm for 30 min to extract nano-BC with a size distribution of 100–350 nm from rice straw and 50–280 nm from rice husk, respectively. In contrast, Xiao et al. (2020) extracted nano-BC (100–2500 nm) by centrifuging biochar from milled cow bone meal at a slower pace of 9000 rpm for 5 min. Xu et al. (2020) centrifuged biochar at 9500 rpm for 20 min to fractionate 1–100 nm nano-BC particles from a variety of feedstocks. In comparison to sedimentation fractionation, membrane filtration is a crucial procedure that offers more precise control over particle size selection. Applications that have strict particle-size restrictions must use a membrane separator. For instance, the nano-BC particles with a size of <220 nm were used to produce electrodes for chemical detection (He et al., 2020; Dong et al., 2018). Membrane filtration is sometimes advocated as a post-sedimentation step for removing larger particles, ensuring filtration efficiency, and promoting membrane reusability. However, the expense of the membrane makes membrane filtering a less cost-effective method of nano-BC synthesis than sedimentation fractionation. Although diverse approaches are explored independently in the existing literature, it is possible to combine these technologies to achieve greater consistency in nano-BC particle size and production. For example, by integrating pyrolysis for initial biochar production with mechanical milling and nanosizing techniques, this combined process offers a systematic approach to achieving greater uniformity in nano-BC particle size and production (Song et al., 2022).

### 2.2. Properties of waste-derived nano-BC

Nano-BC possesses a wide range of characteristics, which are mostly dependent on the production method and feedstock materials used to synthesize it. By tailoring the biomass feedstock type and adjusting pyrolysis conditions, it is possible to engineer biochar with unique surface physicochemical attributes (He et al., 2021). A recent study based on Fourier transform infrared spectroscopy (FTIR) analysis reported that nano-BC derived from lignin possesses multiple functional groups, including hydroxyl, carboxyl, carbonyl, ether, and aromatic characteristics (Jiang et al., 2020). The presence of phenolic, hydroxyl stretching, and bending in the nano-BC structure was demonstrated by Naghdi et al. (2017). Besides, substantial variations in particle size, specific surface area (SSA), major elemental content (C, H, N, S), electrical conductivity (EC), and trace metal content are identified in nano-BC produced from waste biomass (Naghdi et al., 2017, 2018; Ardebili et al., 2020). The differences between bulk-BC and their nano-BC counterparts in terms of particle size, elemental content, surface area, and pore size are summarized in Table 1. Nano-BC possesses distinctive properties when compared to bulk-BC, for example, the effects of size reduction on numerous parameters. As a first point, nano-BC particle size varies depending on the type of feedstocks and the process involving their preparation. Pyrolysis temperature was the most influential factor on biochar properties (He et al., 2021). For the same feedstock, increase in pyrolysis temperature can reduce nano-BC particle sizes. The particle size of rice straw nano-BC decreased from 403 nm to 234 nm when the pyrolysis temperature in a centrifuging separation method was raised from 400 to 700 °C (Lian et al., 2020). Using the same nano-BC fabrication process, the increase in pyrolysis temperature from 300 to 600 °C, reduced particle size from 190 to 59 nm (Yue et al., 2019). Elevating the temperature from 350 to 650 °C during ball milling, the nano-BC produced from wheat straw, rice straw, and maize straw exhibited a similar trend in terms of particle size reduction (Shen et al., 2020a, 2020b). In addition to affecting the particle size, the higher pyrolysis temperatures affect the pore collapse and matrix fracture of biomass which yielded higher production of nano-BC particles (Liu et al., 2018). Second, the chemical constituents of bulk biochar and its nano-BC derivative are different, despite being generated from the same biomass and pyrolysis (Table 1). Third, decreasing particle size leads to an increase in particle exterior surface area, hence the rise in SSA is to be expected in nano-BC compared to BC (Lian et al., 2020). For instance, the SSA of bulk-BC synthesized from pyrolysis (350–700°C) of silver grass was 0.76 $m^2/g$, while it increased to 36.4 $m^2/g$ in the nano-form (Oleszczuk et al., 2016). Lyu et al. (2018) identified ball milling as an efficient technique for enhancing the physical characteristics of biochar. Their research reported that after milling to nanoscales, the SSA of bulk biochar produced at 300°C increased from 0–2 $m^2/g$ to 5.6–10.8 $m^2/g$. These results suggested that ball milling can enhance the internal surface area by connecting the pores within the material by comparing the theoretical estimate of the changes in the external surface to the experimental measurement. However, contrasting results were also reported in the recent literature. For example, nano-BC generated by ball milling have a smaller average pore size than bulk ones, as demonstrated by Xiao et al. (2020). Naghdi et al. (2017) devised a modelling strategy involving statistical techniques and response surface methodology to optimize the parameters associated with ball milling. These parameters encompassed milling time, rotational speed, and the mass ratio of ball-to-powder. Through the developed model, the researchers identified optimal conditions conducive to obtaining nano-BC with diminutive dimensions, approximately 60 nm. The optimized parameters were determined as follows: a milling duration of 1.6 h, a rotational speed of 575 rpm, and a ball-to-powder mass ratio of 4.5 g/g. This systematic approach facilitated the synthesis of nanoparticles while simultaneously enhancing efficiency by strategically adjusting the key milling parameters. However, it is not yet well understood how the size and number of pores alter which necessitates further research into the nature of source materials, pyrolysis conditions, and nano-BC preparation techniques for definitive properties of nano-BC.

**Table 1**
Properties of waste-derived nano-BC in comparison to bulk-BC.

| Feedstock | Pyrolysis (°C/h) | Particle size | | Compositions (wt%) | | Average pore size (nm) | | Specific surface area (m$^2$g$^{-1}$) | | References |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Bulk-BC (μm) | Nano-BC (nm) | Bulk-BC | Nano-BC | Bulk-BC | Nano-BC | Bulk-BC | Nano-BC | |
| Cow bone meal | 300/2 | 1–20 | 100–2500 | C/H/O/N/P: 44.5/4.30/19.3/4.55/8.85 | C/H/O/N/P: 43.6/4.25/20.8/4.38/9.05 | 14.5 | 11.72 | 2.75 | 35.5 | Xiao et al., 2020 |
| | 450/2 | | | 42.4/2.35/22.2/4.25/9.58 | 40.2/2.35/23.5/4.04/10.2 | 10.3 | 8.65 | 22.8 | 200 | |
| | 600/2 | | | 39.5/1.45/24.3/3.45/10.3 | 39.1/1.79/24.0/3.46/10.7 | 8.22 | 6.45 | 52.8 | 315 | |
| Wheat straw residues | 400/2 | 1.35–5.26 | 57.8–232 | C/H/O/N/Ca: 64.9/3.65/24.2/1.50/1.25 | C/H/O/N/Ca: 50.1/2.63/25.2/0.97/1.50 | | | 2.95 | 47.4 | Li et al., 2020 |
| | 550/2 | | | 61.2/3.18/22.8/1.05/1.76 | 52.2/1.66/25.5/0.65/1.86 | | | 31.2 | 332 | |
| | 700/2 | | | 57.8/2.48/22.0/0.87/2.10 | 48.2/0.88/27.9/0.50/2.15 | | | 198 | 295 | |
| Pine wood waste | 525/0. 3 | | 60.1–212 | | C/H/N/MC/Ash: 83.2/3.5/<1.0/2.15/2.1 | 3.2 | 1.6 | 3.12 | 47.3 | Naghdi et al., 2017 |
| Corn straw residues | 500/2 | 200–600 | 100–600 | C/H/O/N/Ash: 79.0/4.72/10.36/0.76/5.15 | C/H/O/N/Ash: 77.6/3.28/12.0/0.95/6.30 | | | 185 | 291 | Ma et al., 2019 |
| Rice husk | | | | 54.5/3.50/9.75/0.55/31.7 | 53.2/3.45/11.5/0.59/31.6 | | | 96 | 214 | |
| Rice straw | 400/2 | 50–250 | 403 | C/O/N/Si/Ca: 76.8/17.8/2.4/2.8/– | C/O/N/Si/Ca: 76.9/17.8/2.4/2.9/– | 4.2 | 5.67 | 142 | 93.2 | Lian et al., 2020 |
| | 700/2 | | 234 | 79.7/16.3/0.9/3/– | 79.8/16.3/0.9/3/– | 4.05 | 5.12 | 155 | 254 | |
| Wheat straw | 350/2 | 2560 | 285 | C/H/O/N/S/Ash: 63.0/2.01/8.02/1.46/0.30/32.3 | C/H/O/N/S/Ash: 58.0/1.82/7.90/1.25/0.14/32.0 | | | | | Shen et al., 2020a, 2020b |
| | 650/2 | 2119 | 224 | 64.7/2.05/7.56/1.48/0.27/34.4 | 56.5/1.68/7.68/1.20/0.34/33.8 | | | | | |
| Rice straw | 350/2 | 1777 | 253 | 48.8/1.93/7.62/0.88/0.72/20.2 | 60.8/1.80/8.30/1.27/0.65/27.4 | | | | | |
| | 650/2 | 1276 | 202 | 49.6/1.82/7.70/0.88/0.30/16.2 | 54.6/1.58/7.52/1.10/0.40/37.9 | | | | | |
| Corn Straw | 350/2 | 1029 | 260 | 62.2/1.68/7.22/1.38/0.45/27.3 | 51.5/1.68/6.91/1.08/0.24/42.4 | | | | | |
| | 650/2 | 1480 | 252 | 62.8/1.48/7.46/1.32/0.41/30.2 | 55.4/1.78/7.65/1.15/0.28/34.4 | | | | | |
| Rice-hull | 300/2 | | 190 | | C/N/O/Si: 71.3/2.43/21.7/– | | 8.40 | | 21.7 | |
| | 400/2 | | 106 | | 71.2/3.29/20.3/0.37 | | 5.56 | | 80.2 | |
| | 500/2 | | 192 | | 81.3/1.91/15.0/0.97 | | 4.83 | | 90.9 | |
| | 600/2 | | 60 | C/N/O/Si: 79.6/1.09/12.2/1.85 | 80.8/1.30/14.9/1.35 | 5.35 | 5.95 | 27.3 | 123 | |
| Sugarcane Bagasse | 300/1 | | 100–560 | | C/H/O: 65.7/4.95/25.0 | | | | | Dong et al., 2018 |
| | 400/1 | | | | 72.2/4.12/19.3 | | | | | |
| | 500/1 | | | | 80.8/3.35/10.8 | | | | | |
| | 600/1 | | | | 82.7/2.65/8.12 | | | | | |
| | 700/1 | | | | 81.8/2.08/8.30 | | | | | |
| | 800/1 | | | | 78.8/1.8/10.15 | | | | | |
| Wood chip biomass | 500/2 | | <100 | C/H/O/Ash: 81.4/3.95/12.0/5.73 | C/H/O/Ash: 17.7/3.01/39.0/43.4 | | | | | Song et al., 2019 |
| Pine wood waste | | | | 86.2/3.42/9.16/0.91 | 44.9/3.40/19.1/32.6 | | | | | |
| Barley grass | | | | 62.4/2.54/7.83/26.4 | 5.02/1.50/24.8/67.5 | | | | | |
| Peanuts shell | | | | 77.6/2.74/9.84/12.3 | 13.1/2.39/21.9/61.3 | | | | | |
| Rice husk | | | | 57.2/1.85/4.01/38.9 | 16.0/3.60/12.2/68.4 | | | | | |
| Dairy manure | | | | 50.5/2.05/7.89/38.5 | 6.58/1.8/32.0/56.6 | | | | | |
| Pig manure | | | | 33.8/1.50/2.25/62.9 | 4.21/2.47/21.9/68.5 | | | | | |
| Sewage sludge | | | | 21.6/2.33/17.6/55.6 | 11.2/3.47/21.6/60.8 | | | | | |
| Pinewood biomass | 525 | | 60 ± 5 | | C: H: N: 83/3.5/<1 | | | | 47.3 | |
| Elephant grass | 700 | | | C: H: N: Ash: 69.58/3.11/0.62/6.00 | C: H: N: Ash: 56.16/2.44/0.38/24.74 | | | | 36.4 | Oleszczuk et al., 2016 |
| Wicker | | | | C: H: N: Ash: 69.58/3.24/0.79/8.53 | C: H: N: Ash: 51.57/2.11/0.44/30.97 | | | 11.38 | 18.25 | |
| Wheat straw | | | | C: H: N: Ash: 53.87/1.76/0.91/41.14 | C: H: N: Ash: 27.88/1.55/0.11/52.35 | | | 26.27 | 29.56 | |
| Softwood | 270 | | | | C: H: N: Ash: 78.54/3.25/0.59/1.0 | | | | | |

(*continued on next page*)

**Table 1** (*continued*)

| Feedstock | Pyrolysis (°C/h) | Particle size | | Compositions (wt%) | | Average pore size (nm) | | Specific surface area ($m^2g^{-1}$) | | References |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Bulk-BC (μm) | Nano-BC (nm) | Bulk-BC | Nano-BC | Bulk-BC | Nano-BC | Bulk-BC | Nano-BC | |
| Wood waste | 100–650 | | <412.4 | C: H: N: O 90.2/2.0/<0.1 %/4.7 | C: H: N: O 84.2/2.2/<0.1 %/10.6 | | | 215.65 | 393.98 | Ramezanzadeh et al., 2021 |
| Jatropha seed | 180/3 | | 600 | C:O: K: Mg: Ca: I: 72.57/19.93/2.36/1.49/1.32/1.44/0 | C:O: K: Mg: Ca: I: 81.2/15.97/1.33/0.53/0.53/0.47/0 | | | | 3.67 | Khui et al., 2021 |
| Agri-residue | | | 70–80 | | C: H: N: Ash: 58.4/2.65/2.12/63.1 | | 2.12 | | 9.19 | Goswami et al., 2020 |
| Fruit tree branch | 350/2 | | 1–100 | | C: O: H: N: S: 27.75/12.14/3.61/0.04/2.99 | | | | 26.06 | Xu et al., 2020 |
| | 450/2 | | 1–100 | | C: O: H: N: S: 27.72/5.26/0.76/0.02/10.07 | | | | 10.72 | |
| | 550/2 | | 1–100 | | C: O: H: N: S: 77.32/3.22/0.68/0.53/5.13 | | | | 30.46 | |
| Corn Straw | 350/2 | | 1–100 | | C: O: H: N: S: 11.65/15.38/2.16/0.37/0.89 | | | | 5.58 | |
| Peanut straw | 350/2 | | 1–100 | | C: O: H: N: S: 29.67/20.67/4.70/0.70/6.05 | | | | 69.60 | |
| Sago effluent | | | 45–75 | | C: Ash: 99.9/0.08 | | | | 78.86 | Makshut et al., 2020 |
| Waste lignin | 800 | | 473.6 | | C: H: O: N: 84.44/1.60/8.67/0.99 | | | | 83.41 | Jiang et al., 2020 |
| Mixed biomass waste | 300/0.4 | | 17.4 ± 4.2 | | C: Ash: 50.2/6.89 | | | | 63.6 | Liu et al., 2018 |
| | 400/0.4 | | | | C: Ash: 54.8/7.6 | | | | 78.6 | |
| | 500/0.4 | | 25.3 ± 11.9 | | C: Ash: 61.1/8.93 | | | | 230 | |
| | 600/0.4 | | | | C: Ash: 61.4/9.16 | | | | 264 | |

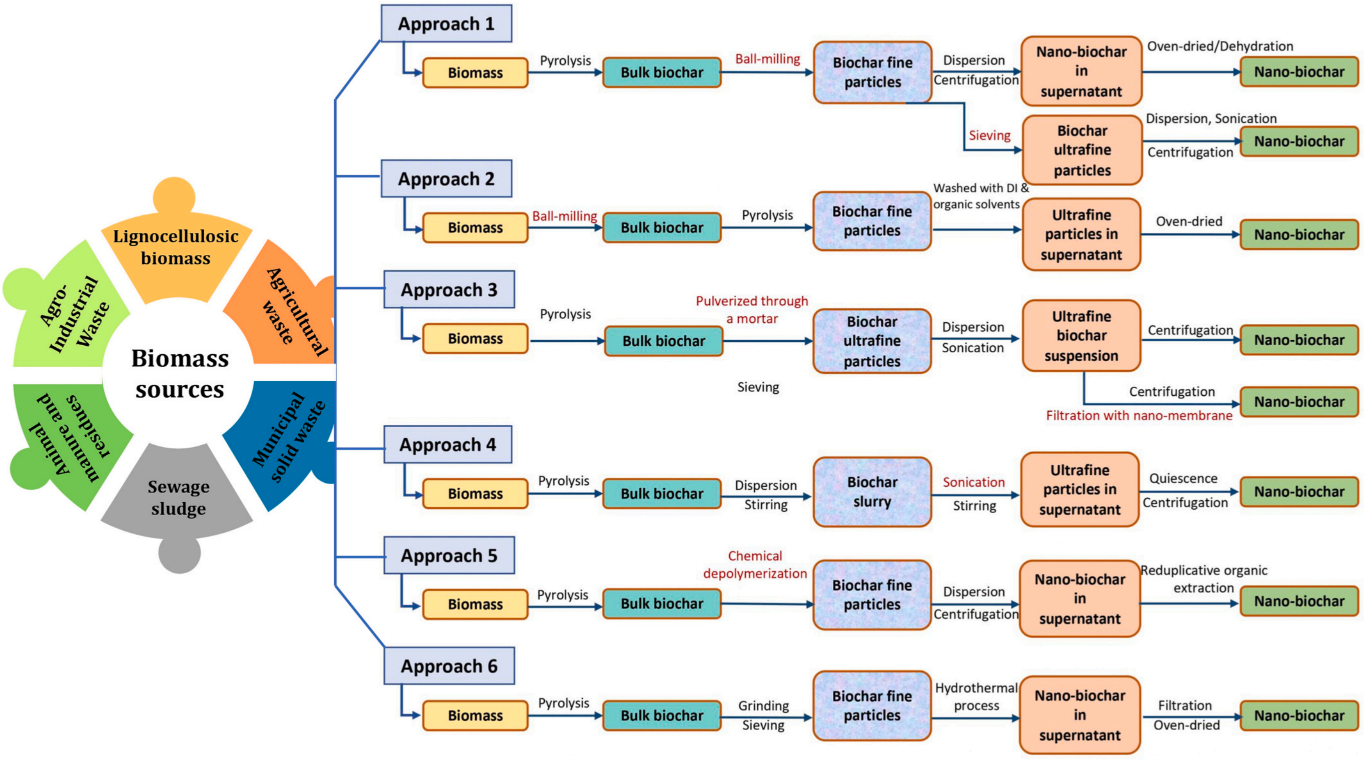

**Fig. 1.** Various production methods of nano-BC from waste biomass (Song et al., 2022; Dong et al., 2018; Ramanayaka et al., 2020a, 2020b; Naghdi et al., 2017; Li et al., 2017; Xiao et al., 2020).

## 3. Applications of nano-BC in sustainable agriculture

Nano-BC has been extensively studied due to its promising application in maintaining a healthy environment which is prerequisite for sustainable agriculture and food security. Its unique properties, including high surface area, porosity, and surface chemistry, make it a suitable candidate for a wide range of agricultural applications. Due to the presence of C and other macro- and micronutrients, it is used as fertilizers. Nano-BC has specific characteristics that make it very efficient to improve the soil physical, chemical, and biological activity (microbial community) along with the restoration of heavy metals and pollutants and thus increase soil productivity and fertility. Nano-BC has shown its efficiency in improving crop growth and development due to its roles in soil amendment, nutrient uptake, water uptake efficiency and water holding capacity. Nano-BC also has efficiency in ameliorating plant stress tolerance by sustaining plant growth and activating the plant's systemic acquired resistance and tolerance to biotic and abiotic stresses. These benefits can contribute to sustainable agriculture by increasing crop yields and reducing the need for synthetic fertilizers and pesticides. This section gives insights into the roles of nano-BC and some of the reported results on the impacts of nano-BC on the sustainable crop production (Fig. 2).

### *3.1. Plant growth improvement and soil amendment*

Anthropogenic activities such as industrialization, deforestation, and overgrazing, have all taken a toll on soil health in recent decades, reducing crop productivity and posing a threat to food security (Ramadan et al., 2020). Numerous studies have demonstrated that nano-BC holds the potential for significantly more profound effects on soil fertility, agricultural productivity, and plant growth compared to conventional bulk biochar. This elevated performance is attributed to the enhanced physiochemical properties which include tailored surface properties, enhanced reactivity, improved dispersion, and reduced agglomeration (Liu et al., 2018; Liu et al., 2022; Song et al., 2022). The diverse interactions between plants and soil that nano-BC facilitates are depicted in Fig. 3, demonstrating the important but under-appreciated biological role it plays in promoting plant growth. These collective enhancements collectively engender a distinctive capability to positively influence soil functions, facilitate nutrient availability, and promote optimal conditions for robust plant development.

Several studies have proposed that the application of biochar with some advanced technologies and engineered nanomaterials may yield better outcomes. Due to their unique characteristics, nano-BC is a promising approach to restoring soil fertility and productivity (Yue et al., 2019; Oleszczuk et al., 2016; Ahmed et al., 2017). Several studies

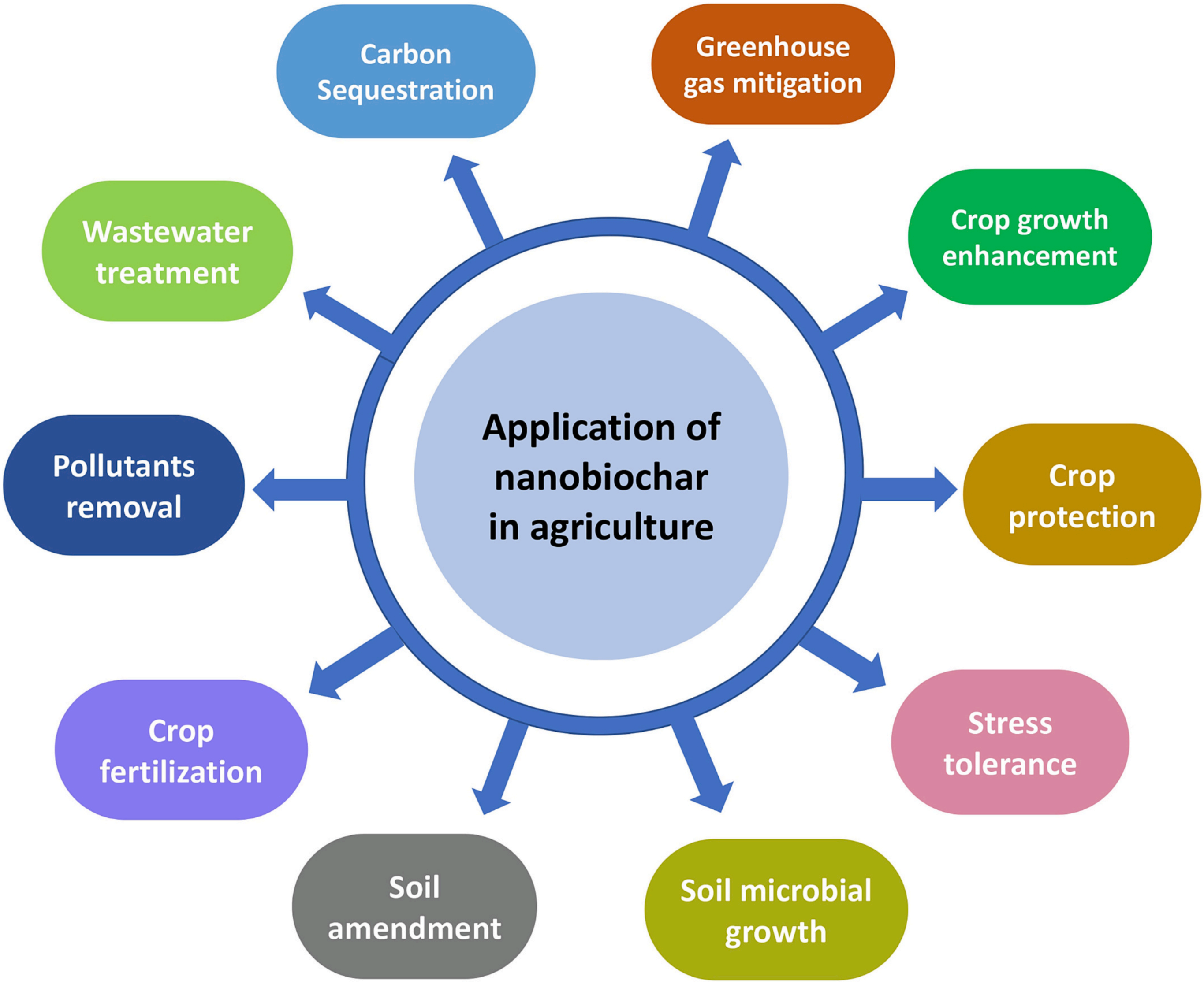

**Fig. 2.** Applications of nano-BC in sustainable agriculture.

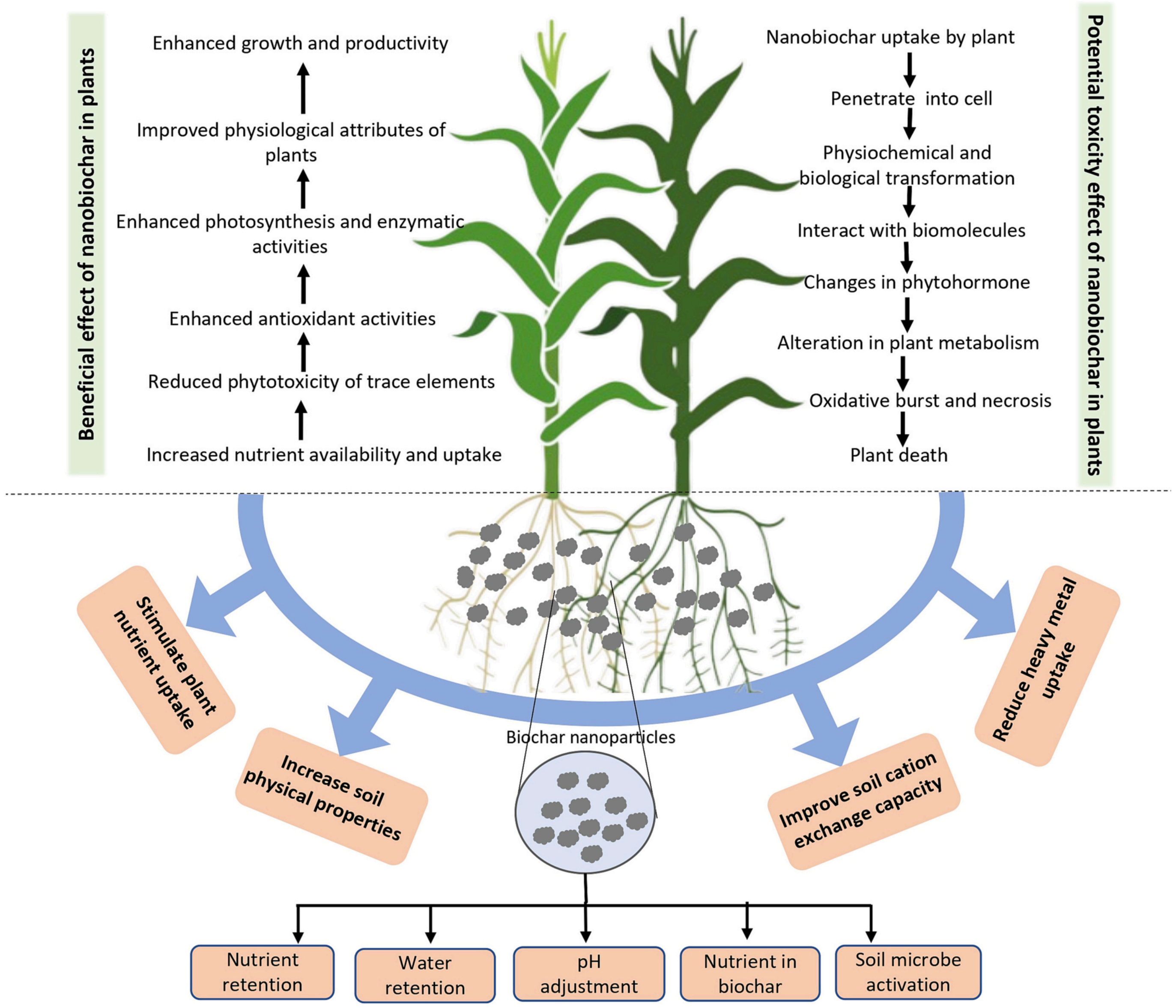

**Fig. 3.** Interactive effects of nano-BC in plant-soil system.

have demonstrated that the application of nano-BC can improve soil physical properties, including bulk density, soil arrangement, and soil structure (Rajput et al., 2022a, 2022b; Jiang et al., 2023; Zhang et al., 2022a, 2022b). Besides, the application of nano-BC has been found to improve soil chemical properties, such as soil pH, soil organic matter, soil electrical conductivity, soil organic carbon (SOC), soil cation exchange capacity (CEC), and macro- and micronutrient content (Liu et al., 2019a, 2019b; Zhou et al., 2020). The most probable effects of nano-BC on soil chemical properties can be attributed to the organic matter, nutrient content, oxygen containing functional groups, and cation exchange capacity (Fig. 3). In addition to soil physiochemical properties, soil quality is determined by the nature and diversity of microbial organisms which are referred to as soil “biologicals” or biostimulants. Higher microbial activity of certain groups at the rhizosphere enhances nutrient and biostimulant availability for plants and improves the growth. Nano-BC contains carbon which increases the soil C content and increases microbial activities (Bashir et al., 2018; Bolan et al., 2022). Moreover, in a study conducted by Khan et al. (2021), it was demonstrated that the use of nano-BC can effectively enhance the biological characteristics of soil.

Nano-BC applications reduce the soil erosion, runoff, and nutrient leaching which results in enhanced soil quality and fertility (Chen et al., 2020; Khan et al., 2021). Nano-BC improves the soil porosity and increases the organic matter content which results in higher water holding capacity and thus lowers the rate of runoff and nutrient leaching (Tan et al., 2016; Chen et al., 2020). As an example, application of 0.1 %–1.0 % coconut shell nano-BC on the sloping land soil reduced cumulative runoff by 39.7 %–74.4 % (Chen et al., 2020). Additionally, nano-BC application effectively decreased nitrate loss from soil by 13.6 % 59.8 %, when coconut shell nano-BC was applied in Chinese loess plateau soil (Lateef et al., 2019). Another study investigated the effects of woodchip-derived biochar nanoparticles (NPs) on phosphorus retention and transport in two acidic and two alkaline soils by column mobility experiments (Chen et al., 2018). Biochar NPs enhanced phosphorus retention by 24 % and 16 %, respectively, in acidic paddy and red soils by facilitating phosphorus retention by stabilizing soil Fe/Al oxides and dissolved organic carbon associated phosphorus (Chen et al., 2018). These studies revealed that nano-BC could potentially reduce soil erosion, runoff and nutrient leaching which improves the soil quality and fertility.

Due to their positive effects on improving soil quality, fertility and productivity, nano-BC promotes plant growth. In addition to modulating the soil fertility and productivity, nano-BC enhances nutrient availability and uptake through enhancing the adsorption, desorption, and transformation (Cui et al., 2021; Mahmoud et al., 2020). Biochar application increases the water and nutrient uptake and availability which are associated with better plant growth, higher seed germination, and stimulates the plant growth through root and shoot elongation (Chausali et al., 2021; Saxena et al., 2014; Zhang et al., 2020; Ahanger et al., 2021). Nano-BC plays a substantial role in various physiological, metabolic, and phytohormonal regulatory mechanisms. Additionally, nano-BC modulates the soil and root associated beneficial microbes and improves plant growth. Based on the recent studies, Table 2 summarizes the reported positive impacts of nano-BC on crop growth and productivity.

However, the application of nano-BC may pose some potential threats to plants and plant associated microbes (Godlewska et al., 2021; Phoungthong et al., 2018). Due to their source materials, some nano-BC contain heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), copper (Cu), nickel (Ni) and chromium (Cr) which interact with the physiological and metabolic processes and result in phytotoxicity (He et al., 2019; Yang et al., 2018). Besides, the pyrolysis process generates free radicals in nano-BC which overproduces reactive oxygen species (ROS) that cause spontaneous cell death in plants and phytotoxicity (Ruan et al., 2019). Furthermore, the impact of nano-BC application on altering soil properties, such as soil pH and contaminant levels, can not only influence plant growth positively but may also induce stress on plants in certain cases. A study by Kumar et al. (2021) demonstrated that changes in soil pH due to nanomaterial application can lead to changes in nutrient availability and uptake, affecting plant growth and development. Nano-BC alters the soil physiochemical properties which might have a certain negative impact on the abundance, and community composition of plant associated microbial communities (Lehmann et al., 2011; Liu et al., 2022). Consequently, even though nano-BC has positive effects on plant growth, the potential for inducing stress on plants due to alterations in soil properties should be taken into account when designing and implementing nano-BC for soil and crop enhancement.

### 3.2. Nano-BC as slow-release fertilizers

The ability of nanocarbons generated from biochar to retain water and nutrients has sparked considerable attention and may be employed effectively as nano-fertilizers. Numerous scientists concur that the use of nanocarbons generated from biochar has beneficial impacts, such as retaining soil moisture and plant nutrients. A recent study on nano-BC produced from wheat straw waste showed that it can store nutrients for extended periods, which is crucial for plant growth and production, and might be utilized as a slow-release fertilizer for sustainable and eco-friendly agricultural applications (Khan et al., 2021). Yang et al. (2020) reported that application of nano-BC showed improved nutrient retention and uptake resulting in increased spring maize growth and yield. A study on the slow-release pattern of nutrients over an extended period using biochar nanocomposites revealed that the synthesized nanocomposite is an eco-friendly substance that may be utilized as a slow-release fertilizer for sustainable agriculture (Lateef et al., 2019). In addition, a field experiment was conducted to evaluate the effects of incorporating nanocarbons into slow-release fertilizer on rice yield and nitrogen loss in paddy soil surface water. Following the application of nanocarbon-containing slow-release fertilizers, rice grain yield and nitrogen utilization efficiency increased considerably. These results suggested that nanocarbon might be employed as a covering material for slow-release fertilizer, minimizing water contamination. Saxena et al. (2014) analyzed how wheat responded to varying concentrations (10–150 mg/L) of water-soluble carbon nanoparticles (ws-CNPs) isolated from the biochar's naturally occurring raw carbon nanoparticles. Their study revealed that the root and branch lengths of plants treated with 50 mg/L ws-CNPs in the soil for up to 20 days were as much as three times those of untreated controls. Recent field studies compared the locally available recommended fertilizer to a nanocarbon water-retaining fertilizer with the same quantity of practical composition to determine the influence of each on mustard yield, quality, and fertilizer application efficiency. The study demonstrated that even applying a 30

**Table 2**
Previous trials on nano-BC application and its impacts on plant growth and productivity.

| Nanobiochar/biochar-based nanomaterials | Application rate | Plant species | Prominent effects at soil–plant interface | References |
|---|---|---|---|---|
| Sugarcane press mud nano-BC | 100 mg/L | Black cumin | Increased overall plant growth parameters, chlorophyll content, and osmoprotectants, while decreased the levels of oxidative stress markers ($H_2O_2$ and MDA) | Ramzan et al., 2023 |
| Biochar based nano-zeolite | | Pak Choi | Reduced the exchangeable Cd and its bioavailability resulting in enhanced growth | Feng et al., 2022 |
| Nano-BC | 250 mg/L | Shallot | Increased plant height and tuber weight | Purbalisa et al., 2021 |
| Rice hull nano-BC | 200 mL nano-BC suspensions/10 plants | Rice | Alleviated Cd toxicity with enhanced growth and chlorophyll content | Yue et al., 2019 |
| Biochar nanoparticles | | Cucumber | Direct exposure to biochar nanoparticles resulted in hyperplasia and deformation of root hairs in the hydroponic system, while there was no negative impact observed on seedlings grown in soil | Liu et al., 2022 |
| Nano-BC | 0.7–1.0 mg/L | Maize | Increased grain weight and yield of maize | Yang et al., 2020 |
| Corn straw nano-BC | 400 mg/L | Tobacco | Enhanced plant defense system by SA-induced systematic resistance | Kong et al., 2022a, 2022b |
| Nano-BC | 200 and 400 mg/kg | Rice | Ameliorated the allelopathic effects of *Imperata cylindrica* on seedlings | Shen et al., 2020a, 2020b |
| Nano-BC | | Rice | Alleviated Cd-phytotoxicity and increased biomass and chlorophyll contents | Yue et al., 2019 |
| Nano-BC | 100 mg/L | Pack Choi | Reduced uptake of Cd and As with improved growth | Ouyang et al., 2021 |
| Nano-BC | 100 mg/L | Rice | Higher root vitality, dry biomass, and plant height; increased antioxidant enzymes activities; alleviated Cd toxicity | Yue et al., 2019 |
| Water-soluble carbon nanoparticles | 50 mg/L | Wheat | Increased wheat growth | Saxena et al., 2014 |
| Fe (III)-(oxyhydr)oxide coating nano-BC | 10 mg/L | Rice (Hydroponics) | Facilitated formation of iron plaque (IP) with improved role in promoting the growth of aquatic plants | Gu et al., 2022 |
| Nano-BC | Root zone application: 0.3 %<br>Foliar application: 1 % | Carrot | Induced more growth and improved pigments in the shoot and storage root of the carrot | Khaliq et al., 2023 |

% reduction in water-retaining nanocarbon fertilizer greatly increased mustard yield and productivity over local fertilizer (Guo et al., 2018). Another study reported that liquid nano-carbon fertilizer had a considerable impact on enhancing the growth and yield of Chinese cabbage (Zhao et al., 2017). Further, a biochar nanocomposite made from corn cobs was synthesized to examine maize cob biochar's (CB) potential for slow-release nutrient delivery to plants. They argued that this approach will not only aid in waste disposal and management, but also in pollution prevention by converting waste into usable products and eliminating the leaching concerns that afflict traditional fertilizers (Lateef et al., 2019).

### *3.3. Remediation of contaminants/pollutants from agricultural soil*

The composition and specific chemical and physical properties of nano-BC such as SSA, porous activity, and ability to participate in soil reactions, have made it a promising tool for remediation of inorganic and organic pollutants from agricultural land (Table 3). Nano-BC implies a diverse mechanism in reducing the soil pollutants (Fig. 4). Pollutant removal through surface complexation, ion exchange and electrostatic interaction are the most prominent ones. As nano-BC application is still in their early stages, there is a lack of information on their bioavailability during long-term exposure. Pesticides or other agrochemicals remain in the soil solution in an ionic condition. Nano-BC contains chemicals with different charge which results in bonding with pesticidal ions (Elbehiry et al., 2022). For example, the carboxylic (-COOH), hydroxide (-OH) and other functional groups on the surface of nano-BC can effectively capture ionized guest chemicals. Due to the high surface area and pore arrangements of nano-BC, it offers more space to attach ionized molecules than bulk ones. However, surface functionalization of nano-BC will further garner the adsorption through ion exchange processes (Uchimiya et al., 2012). Modification of nano-BC with metals or inorganic particles enhance the surface adsorption properties of nano-BC to a great extent. Zhou et al. (2017) formulated functionalized nano-BC with nano Manganese oxide ($MnO_2$) to study the electrostatic adsorption of copper ions in nano-BC. They reported a maximum 142 mg/g adsorption of Cu (II) onto nano-BC and argued that this adsorption was mainly due to the presence of $O_2$–, $C_2H_3O_2$–, and –OH in nano-BC.

In addition to interaction with the pesticidal component, microporous and mesopores of nano-BC accommodate different groups of contaminants through the diffusion process (Wang et al., 2017a, 2017b). As maximum transfer occurs, the pore filling process reaches equilibrium terminating any further filling which depends on the diffusion potential of guest molecules and pore properties e.g., SSA, pore diameter, and pore volume of nano-BC. It is argued that molecules in liquid condition diffuse better in nanopores than those in solid conditions (Islam et al., 2021). Moreover, the size of guest molecules is inversely proportionate to the filling efficiency whereas, concentration of biochar is positively correlated. Pollutant remediation by pore filling process is reported by (Zhang et al., 2013a, 2013b; Islam et al., 2021). Though these works are based on organic contaminants such as dyes, pore filling mechanisms can also be attributed to the remediation of inorganic contaminants such as pesticides.

Pi stacking or Pi-Pi interaction is another widely used term to understand the mechanism of biochar mediated pollutant removal. Though it is very difficult to differentiate Pi stacking and normal ion exchange in real experiments, it has already caught the attention of researchers in explaining inter aromatic molecular interactions. The prerequisite of such interaction is that the guest molecules and host (e.g., nano-BC) must be aromatic or contain an aromatic moiety where π–electron takes the leading role (Liu et al., 2012). The π–electron resides in the π–bonds of aromatic moieties are shared when polarization of aromatic compounds leads to formation of aromatic π–cloud (Jia et al., 2012). Since aromatic moieties are more flat and rigid than aliphatic ones, their unique geometric positions (e.g., face-to-face, edge-to-face) facilitate Pi stacking (Martinez and Iverson, 2012). Nano-BC containing graphene or other aromatic moieties through controlled pyrolysis or surface functionalization are outstanding carriers of π–electrons in which they can stack π–electrons of guest aromatic molecules. Many agrochemicals including insecticides, herbicides, and fungicides contain benzene rings that remain as residue after application (Wang et al., 2020). It is expected that huge residues of aromatic agrochemicals can be effectively adsorbed on the surface of nano-BC through Pi-Pi interactions. Silicate binding can be the next generation strategy for removal of organic and inorganic contaminants. Silica ($SiO_2$) is one of the most widely available natural minerals found on earth. Being anionic in nature, silica can react with diverse range of cations over a broad pH level from 1 to 11. The surface hydroxyl groups of silicate ions are responsible for ligand exchange between silica and other cations. Further, silica surface can be functionalized by zwitterions to accommodate both cations and anions.

### *3.4. Crop protection and stress tolerance*

The escalating impacts of climate change globally have led to greater occurrences of biotic and abiotic stresses on plants, and reducing

**Table 3**
Nano-BC application in remediation of pollutants/contaminants from agricultural soil.

| Feedstock | Type of nano-BC and biochar based nanoparticles | Contaminant/ Heavy metal | Action/Mechanism | References |
|---|---|---|---|---|
| Rice hull | Nano-BC suspension | Cd | Higher adsorption affinity for Cd and effectively decrease it's abosorption and harmful effects on plants | Yue et al., 2019 |
| Bark Chips | Biochar nanocomposite | Cu, Pb, Zn | Higher adsorption capacity comapred to bulk-BC in immobilization of heavy metals from acidic soil | Arabyarmohammadi et al., 2018 |
| Wheat straw | Nano-BC | Cd | Reduecd phytotoxicity in Cd contaminated soil | Liu et al., 2020 |
| Wood | Biochar nanoparticles | Cd | Enhanced Cd sorption from contaminated sandy soil | Ramezanzadeh et al., 2021 |
| Corn straw | Biochar nanoparticles | Cd, Pb | Reducing Cd and Pb toxicity stress on maize plant through decreasing soil mobiity and plant accumulation | Zhang et al., 2022a, 2022b |
| Agricultural residue | Nano-BC | $NH_4^+$ and $H_2PO_4^-$ | Instant supplier and as a reservoir preserving nutrients for plants through adsorption and desorption | Liu and Feng, 2022 |
| Wheat straw | Nano-BC (300 °C) | Cd, As | Nano-BC reduced the Cd and As uptake Pak Choi | Ouyang et al., 2021 |
| Ramie straw | Ball milling nanoparticles (700 °C) | Cd | Enhanced $Cd^{2+}$ adsorption capacity 40.65 mg/g | Zhou et al., 2021 |
| Pine shoots | Biochar based nanoscale zero-valent iron (nZVI-BC) | Cr (VI) | Remediation of soil contaminated with Cr (VI) | Sun et al., 2020 |
| Wood chips | Biochar based Zero-valent iron nanoparticles (nZVI-BC) | Cd | Increased accumulation capacity of *T. repens* for Cd maximizing phytoremediation potential | Zand et al., 2020 |
| Forest residue | Biochar based nanoscale zerovalent iron (SN) | Cd | Reduced Cd toxicity in plants | Gong et al., 2021 |
| Wood (remains of pruning) | Biochar based nanoscale zerovalent iron (SN) and compost | As, Cu, Pb and Zn | Remediation of soils contaminated by metals and metalloids | Baragaño et al., 2020 |

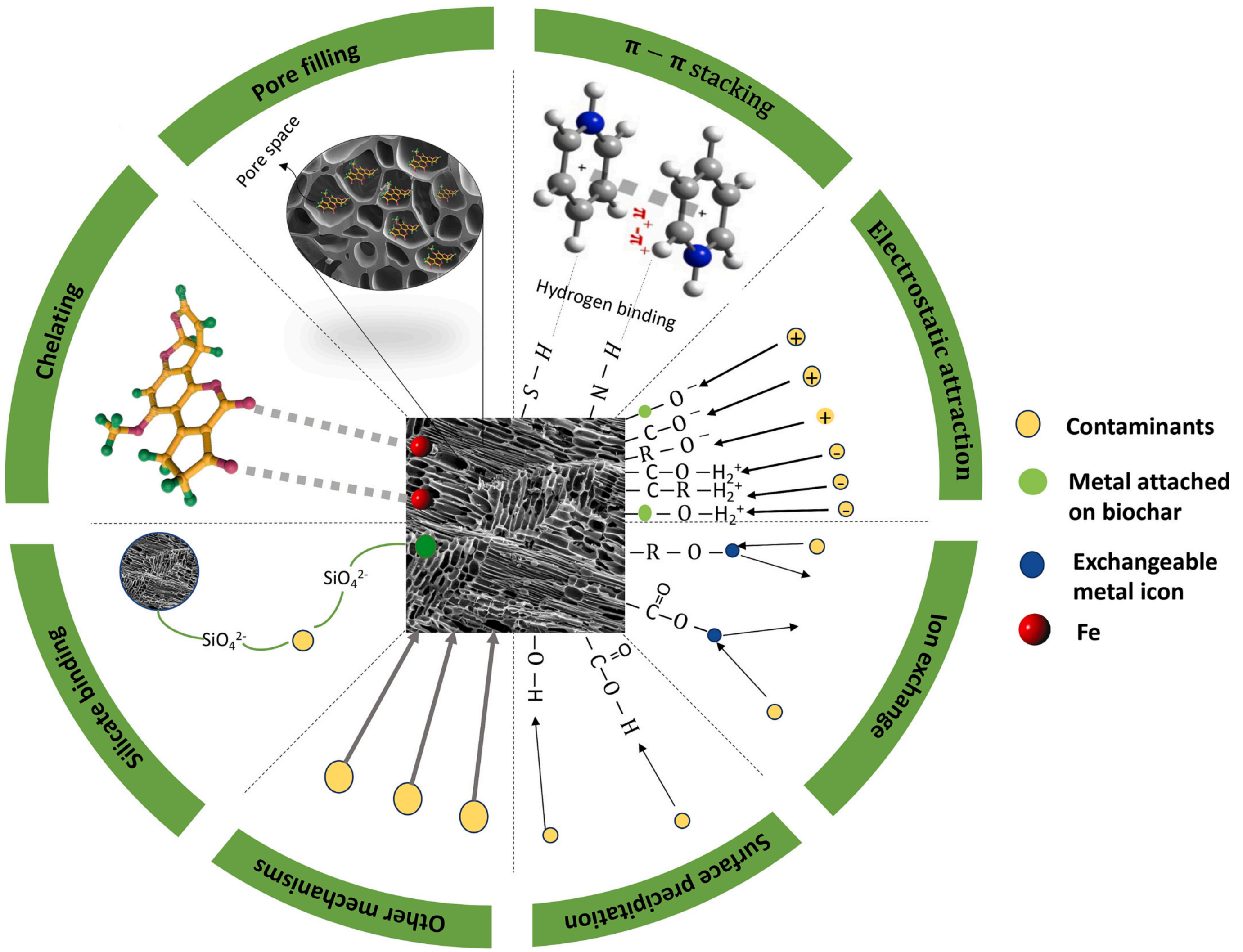

**Fig. 4.** Mechanisms of nano-BC for contaminants removal.

growth, and yield which threaten the food security for the growing population. Owing to their constructive influence on soil and plants, the utilization of nano-BC has emerged as a prospective strategy for mitigating agricultural losses as evidenced by its incorporation in various studies (Kumar et al., 2017; Jaiswal et al., 2015; Zhang et al., 2021; Kong et al., 2022a). Several studies have demonstrated the biochar as an effective tool in preventing fungal foliar diseases in numerous plant species (Elad et al., 2010; Jaiswal et al., 2015; Mehari et al., 2015; Kumar et al., 2017; George et al., 2016). Nano-BC facilitates several mechanisms for enhancing the plant's tolerance to biotic and abiotic stresses. Nano-BC increases the diversity, composition, and activity of plant-associated microbial communities which trigger plant growth through increasing nutrient availability, hormonal biosynthesis, and enzymatic activities (Viger et al., 2015). The increased microbial activity reduces the pathogens by antibiosis, competition, and parasitism (Blanco-Canqui, 2017).

Nano-BC application triggers and activates the plant systemic acquired resistance (SAR) against biotic stresses in plant either by induced microorganisms' colonization or the chemicals involved in phytohormonal and enzymatic activities (Elad et al., 2011). Biochar increases the colonization of plant growth promoting rhizobacteria and plant growth promoting fungi which assists in the phytohormone synthesis and play role in activating the SAR (Azami-Sardooei et al., 2010; Van Der Ent et al., 2009). Kong et al. (2022a) carried out an experiment to determine the effect of nano-BC on different components of the SAR. The results indicated that plants treated with nano-BC showed less lesion caused by *Phytophthora* in tobacco plants. This work highlighted the crucial roles of nano-BC on the induction of SAR in plants under the biotic stresses.

In addition to enhance plant tolerance towards the diseases and insects, nano-BC application showed potential roles in improving the plant tolerance to abiotic stresses such as salinity and drought (Ali et al., 2017; Alfadil et al., 2021; Haider et al., 2020; Ahluwalia et al., 2021). A study conducted by Ghassemi-Golezani and Farhangi-Abriz (2021) revealed that the use of magnesium-based nano-BC was efficacious in ameliorating plant growth under salinity stress conditions by improving the shoot and root growth. Zulfiqar et al. (2021) demonstrated that the application of nano-BC under salinity conditions reduced the $Na^+$ content in the vegetative parts of the safflower plants and thereby enhancing tolerance. Interestingly, the addition of nano-BC helped to regulate the soil pH and improved cation exchange capacity and thereby lowering the salinity stress. Furthermore, nano-BC application was found to enhance tolerance to both drought and salinity by increasing the water use efficiency (Zhang et al., 2020). Nano-BC was shown to increase N availability in rhizosphere which are required for heat shock protein biosynthesis and improving resilience to heat stress mediated cellular damages (Huang et al., 2019; Liu et al., 2019a, 2019b).

Anthropogenic activities lead to the discharge of different heavy metal and metalloids in soils which reduce plant growth due to metal toxicity. Nano-BC possesses certain features such as high adsorption affinity, SSA and pores which make it a potential tool for heavy metals remediation. Yue et al. (2019) revealed that nano-BC are able to significantly alleviate the phytotoxicity of $Cd^{2+}$ compared to low-temperature and bulk biochar, as evidenced by the increased biomass, root vitality, chlorophyll content, decreased Malondialdehyde (MDA) content, and relative electrical conductivity of rice plants. A recent study carried out by Liu et al. (2020) showed the nano-BC application improves plant growth and reduces Cd content in Cd contaminated soil. The root exudate-forming genes that are expressed in response to nano-BC bond with heavy metals, decreasing the metals' bioavailability to the plant. Increased microbial growth that produces complexes with heavy metals is another mechanism by which nano-BC decreases heavy metal bioavailability. Root exudates and microbial activity aid in the direct binding of heavy metals, and erosion carries the bound metals away from the root zone (Zhang et al., 2022a, 2022b).

### 3.5. Microbial growth in rhizosphere

The rhizosphere is a narrow zone defining the point of interaction between a plant's root and the soil. It is occupied by root microbiome and controlled by root secretions called exudates (Korenblum et al., 2020). Rhizosphere microbial communities play a critical role in plant-soil ecosystem performance by sustaining soil health and nutrient cycling which impacts the crop growth and resilience (Singh et al., 2021). Being a carbonaceous substance, nano-BC has a highly porous structure and contains, macro and micro nutrient, allows it to affect the physicochemical properties of soil and rhizosphere microbial dynamics. In addition, nano-BC directly stimulates the proliferation of microorganisms in the rhizosphere. Nano-BC treated soil displayed higher microbial biomass and diversity compared to untreated soil which highlighted their roles in regulating the microbial composition in soil (Liu et al., 2020). These findings were corroborated by prior research that provided experimental proof that biochar amendment altered the soil microbial population by assimilating plant-derived carbon (Liao et al., 2019). As stated previously, the use of nano-BC may increase microbial biomass and, consequently, microbial metabolites. The microorganisms and microbial metabolites, that geophagous earthworms rely on for nourishment, are more numerous on nano-BC amended soils (Lehmann et al., 2011). This interaction facilitates an amplification in both horizontal and vertical pathways for pore water, air, and solute movement within the soil matrix, hence promoting microbial proliferation. The C:N ratio is one of the most influential factors which determines the patterns, diversity, and composition of microbial communities in soil. Application of nano-BC in the soil may alter the adsorption dynamics of fast mineralizable carbon and nitrogen fertilizers, hence altering the patterns and behaviours of rhizosphere microbial communities (Ramadan et al., 2020). Biochar and nano-BC share specific features which could explain this observation. Firstly, like biochar, nano-BC is an organic matter source that increases the quantity of easily absorbable soil nutrients for microorganism (Lehmann et al., 2011; Ojeda et al., 2015; Zhang et al., 2021). Secondly, both biochar, nano-BC may absorb and detoxify substances that inhibit microbial growth (Elad et al., 2010). However, compared to biochar, nano-BC has a far better capacity for such absorbing and detoxifying processes due to its larger specific surface area and functionality. Thirdly, nano-BC improves soil physical quality by supplying massive and diverse microsites that are ideal for the survival of soil microorganisms (Shen et al., 2016; Wagner and Kaupenjohann, 2015). Furthermore, since nano-BC may alter the pH and oxidation potential of the soil, it can influence microbial activity and population structure (Hafeez et al., 2022). However, research on the effects of nano-BC on soil microorganisms and community composition is still in its infancy. Thus, before recommending nano-BC for large-scale application, it is crucial to conduct extensive field research on its potential impact on microbial community composition. Understanding how nano-BC influences the variations and functions of microbial populations might provide a crucial knowledge foundation for the development of nano-BC-based systems to restore degraded soils and sustain soil health.

### 3.6. Wastewater treatment for nutrient recovery and irrigation

Over time, several anthropogenic activities have led to a higher accumulation of toxic heavy metals in water, posing a significant environmental threat to aquatic life. Unlike most organic and inorganic contaminants, heavy metals cannot be degraded in water hence necessitates to find a way to eliminate them. Nonetheless, scarcity of irrigation water has shifted human thinking about waste-water treatment with the goal of achieving economically viable and ecologically sustainable solutions that offset some of the exploitation of valuable resources (Goswami et al., 2022). Nano-BC has attracted recent interest as a potential adsorbent for the mitigation of pollutants, exhibiting promising efficacy in the realm of water pollution management (Xia et al., 2023; Li et al., 2020). However, the absorbency of typical biochar for ionic contaminants was limited (Xia et al., 2023). Chausali et al. (2021) reported that by turning pristine magnetic biochars (PMBCs) into ball milled magnetic nano-biochar (BMBCs) synthesized from wheat straw, the removal of tetracycline (TC) and mercury Hg (II) from contaminated irrigation water was greatly improved. According to Nath et al. (2019), iron oxide permeated mesoporous rice-husk nano-BC are the most effective at removing arsenic from contaminated water. Similarly, Zhang et al. (2013a, 2013b) prepared micro- and nano-bone char from cow bone meal and investigated their adsorption properties for heavy metals such as Cu (II), Cd (II) and Pb (II). They found that the micro- and nano-bone char had high adsorption capacities for these heavy metals, with maximum adsorption capacities of 218 mg/g, 166 mg/g and 559 mg/g for Cu (II), Cd (II) and Pb (II), respectively (Lian et al., 2021). According to a study by Ramanayaka et al. (2020a, 2020b) graphitic nano-biochar synthesized from thermal power plant waste may effectively remove Cr (VI) and Cd (II).

Biochar-based nanocomposites can be synthesized to develop unique composites that combine the advantages of biochar with nanoparticles. In most cases, the composites possess vastly improved functional group composition, pore properties, surface active sites, catalytic degradation capability, and separability. Moreover, biochar nanocomposites are an excellent way to combine the advantages of nano-BC and other nanomaterials, as well as to improve the physical and chemical characteristics of biochar itself. Most recently, several nanocomposite materials based on a vast array of substrates have been produced for purifying wastewater, including nuclear effluent (Eskandari et al., 2020; Bassyouni et al., 2019). Research experiments on adsorption efficacy of biochar nanocomposites showed that these composites were very effective at removing various impurities from water including heavy metals, metalloids, organic and inorganic contaminants (Zhang et al., 2012). Adding chitosan to a pyrolyzed nanocomposite produces a composite with amine functional groups on its surface, hence enhancing the composite's capacity to absorb heavy metals such as Cu (II), Cd (II) and Pb (II) (Wang et al., 2018; Mandal et al., 2021). Recent research has provided evidence that a properly synthesized and characterized nano cerium oxide-functionalized maize straw biochar (Ce-MSB) exhibits effective removal of phosphorus from agricultural wastewater. The hydroxyapatite-biochar nanocomposite may show to be an efficient adsorbent for extracting metals from wastewater in terms of cost and environmental impact (Wang et al., 2018). In addition, biochar-based nanocomposites contain distributed catalytic elements on the biochar surface which can adsorb and remove the organic contaminants (Ahmaruzzaman, 2021; Huang et al., 2019). Therefore, the impregnation of foreign materials onto raw biochar to fabricate biochar-based nanocomposites has become a crucial practice for expanding the environmental applications of biochar-based nanotechnology.

## 4. Role of nano-BC in GHGs mitigation from agricultural soils

Greenhouse gases (GHGs) play a substantial role in the acceleration of global warming and climate change. Agricultural activities during crop cultivation largely act as a major source of several GHGs such as carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$) (Shakoor et al., 2021). Therefore, mitigating GHGs emissions from agricultural lands is crucial. Application of nano-BC has demonstrated a positive role in reducing the GHGs from agricultural lands through their impact on various mechanisms involved in GHGs generating and emissions from soil. Nano-BC affects several mechanisms involved in the production and release of ammonia ($NH_3$) which is a major step in GHGs generation and emission from agricultural soil (Guo et al., 2010; Steiner et al., 2010). Firstly, nano-BC application reduces the $NH_3$ volatilization by increasing the soil temperature, pH, aeration, and organic matter mineralization (Guo et al., 2010). Secondly, nano-BC possesses higher surface area which can adsorb $NH_3$ and $NH_4^+$ via its pores or surfaces. Thirdly, nano-BC has been shown to enhance the nitrification process, leading to the formation of NOx- and ultimately reducing the accumulation of nitrous oxide ($N_2O$). In addition to the direct adsorption, biochar activates several enzymatic activities and increases the microbial activity which consume $NH_4^+$ and thus reduced their total content in the soils. Nitrous oxide is another GHGs which are generated from agricultural lands. Nano-BC application increases the aeration by improving the soil porosity and organic matter which results in decrease in anerobic respiration as well as reduction in the production of nitrous oxide (Karhu et al., 2011; Abalos et al., 2022). Biochar increases aeration by changing the soil properties which results in the reduction of anerobic respiration as well as lowers the production of nitrous oxide (Karhu et al., 2011). Thus, combination of biochar with inorganic or organic fertilizers or in singly can alleviate the GHGs generation and emission from the agricultural lands without affecting the crop production.

Application of inorganic fertilizers contributes to the generation of GHGs like nitrous oxide which is one of the most important GHGs. In addition to their direct influence on the processes involving the GHGs emission and generation, nano-BC can replace the inorganic fertilizers and thus contributes to reduce the global GHGs generated by the agricultural sector. However, the total replacement of inorganic fertilizers can drastically reduce the crop production which necessitates the combination of both inorganic and nano-BC fertilizers which have been reported in recent studies (Maurer et al., 2017). Application of biochar alone or in combination with inorganic fertilizers reduced the $CH_4$, $N_2O$, and $CO_2$ significantly (Khan et al., 2022). Due to the superior characteristics of nano-BC compared to biochar, their efficiency to control the GHGs has been tested recently (Kong et al., 2022b; Liu et al., 2021b). Biochar modified with nano-zero-valent-iron showed higher removal of nitrate, nitrous oxide, and carbon dioxide by affecting the microbial activity, denitrification functional genes and methanogenesis process (Kong et al., 2022b). However, depending on the nano-BC composition and process, their roles in reducing the GHGs emissions vary significantly. For example, biochar modified by phosphorus and nano-zero-valent iron (nZVI) which showed opposite impact on GHGs emissions. P based biochar reduced the release of $CO_2$ and $N_2O$ whereas modified nZVI-BC enhanced their release (Liu et al., 2021b). These discrepancy results indicated that the effect of nano-BC is needed to explore in depth in diverse targeted soil and agricultural lands.

## 5. Perspectives for waste management, circular bioeconomy, and SDGs

### 5.1. Role of nano-BC in promoting sustainability and bioeconomy

The current state of Earth's climate necessitates rapid progress towards the transition to a carbon-neutral or -negative future to relieve the pressure on the environment driven by anthropogenic activities. In this context, circular bioeconomy approach is becoming increasingly popular as a solution to this problem since it is a methodical strategy that helps the economy while also protecting the environment. The European Union's current action plans aim to reduce waste and pollution via recycling and the efficient use of renewable resources following the concept of circular bioeconomy (Stegmann et al., 2020; Giampietro, 2019; Carus and Dammer, 2018). In this context, nano-BC production and utilization have developed into a very effective approach for reclaiming resources from waste biomass (Duan et al., 2020; Liu et al., 2021b). Manufacturing the carbonized product such as nano-BC from the waste biomass provides an alternative environment-friendly waste management strategy. Identifying and optimizing nano-BC production, and applications in crop fields could increase soil C contents and stocks along distinct soil profiles, reducing GHGs emissions from the soil-crop system (Zheng et al., 2020). Moreover, through pyrolysis, carbon-rich wastes biomass can be converted into nano-BC, hence closing $CO_2$ and C loopholes in the circular bioeconomy. As a result, producing nano-BC from biomass waste and using it extensively in agriculture is a practical strategy for fostering a circular bioeconomy regarding climate change mitigation. It is noteworthy to mention here about the novel nano-BC material that may reduce metal contamination in soil merits special attention in terms of agroecosystem sustainability (Li et al., 2020; Rajput et al., 2022b). Nano-BC, in modest doses, when blended with chemical nutrients, has been found to boost crop productivity, which may help farmers' net income by increasing crop production and reducing chemical fertilizer use (Zhang et al., 2017; Shrivastav et al., 2022). Removing harmful contaminants from water and wastewater with the use of nano-BC can help conserve precious water supplies. Soil amendment using nano-BC is an eco-friendly way to improve soil quality, lessen health risks from soil pollution, and cut down on GHGs emissions. When one benefit of nano-BC is utilized, it sets off a domino effect of further advantages. Consequently, nano-BC manufacturing and application enormously contribute to promoting sustainability and circular bioeconomy.

### 5.2. Contribution of nano-BC in fostering SDGs

The United Nations has established 17 ambitious SDGs to be achieved by 2030 (Arora and Mishra, 2019). Strategies for sustainable development have emphasized the significance of conserving natural resources, generating power efficiently, providing access to healthy water and sanitary facilities, and limiting GHGs emissions (Kaygusuz, 2012; Jones et al., 2016). Since nano-BC may boost food production, efficiently absorb pollutants in wastewater, and transform bio-waste into bioenergy at a low cost, it has emerged as a promising and appealing option in the quest to achieve some of the SDGs (Yang et al., 2022). The manufacturing of nano-BC from waste biomass and its potential applications could play a massive role in the accomplishment of several SDGs. For instance, increasing crop yields while decreasing input costs (through methods such as the use of nano-BC derived from waste feedstocks can contribute to the achievement of SDG 1 (no poverty) by allowing farmers to become economically independent. Nano-BC, in the form of mineral-rich composites as slow-release fertilizers, may play an important role for widespread applications in raising agricultural productivity, contributing to SDG 2 (zero hunger) (Mazarji et al., 2021b). Moreover, increased agroecosystem resilience and increased crop yields will ensure food safety. Applying nano-BC to soil can improve crop yields, remediate soil, and purify wastewater, all of which contribute to SDG 3 (good health and well-being). Nano-BC is a proven adsorption agent for controlling water pollution and treating wastewater (Kamali et al., 2021) that directly contributes to SDG 6 (clean water and sanitation). Producing nano-BC from biomass pyrolysis has the potential to shift our reliance on carbon-rich non-renewables (SDG 12, responsible consumption, and production) (Qin et al., 2020). Furthermore, to fulfil SDG 12, soil treatment with nano-BC could potentially boost agricultural productivity. Due to its relatively high recalcitrance, biochar organic C contributes to climate improvement by reducing emissions of $N_2O$, $CH_4$, and $CO_2$ from treated soils, hence promoting SDG 13 (climate action)

(Woolf et al., 2010). Increasing the resilience of agroecosystems with nano-BC applications aids in responding to and mitigating expected future climate change effects.

## 6. Potential risks and toxicity of nano-BC application

While nano-BC has numerous potential uses and benefits, its increased mobility in terrestrial and aquatic ecosystems also raises serious concerns about its impact on the environment (Feng et al., 2022). Nano-BC being smaller size and complex physicochemical properties enable interactions between these nanoparticles in the plant-soil system, which may pose some risks and toxicity for humans and the entire agroecosystem (Fig. 5). Some recent research revealed that the potential risks associated with nano-BC and plant, risks associated with environmental and ecosystem level need to be identified. Researchers have identified three distinct types of dangers related to nano-BC: i) risks during preparation and synthesis of nano-BC, ii) risks during application of nano-BC, and iii) risks following application of nano-BC. The production and release of polycyclic aromatic hydrocarbons (PAHs) is a potential risk during preparation of nano-BC. PAHs are mainly produced during incomplete combustion of biochar consisting of two or more benzene rings joined by carbon atoms. Most PAHs are formed between 400 and 500°C, the range of pyrolysis temperatures often used in the production of nano-BC. Extensive cellular damage in humans was shown to arise from PAH exposure in several investigations. A cytotoxicity study on biochar revealed that PAHs has negligible effect on fibroblast

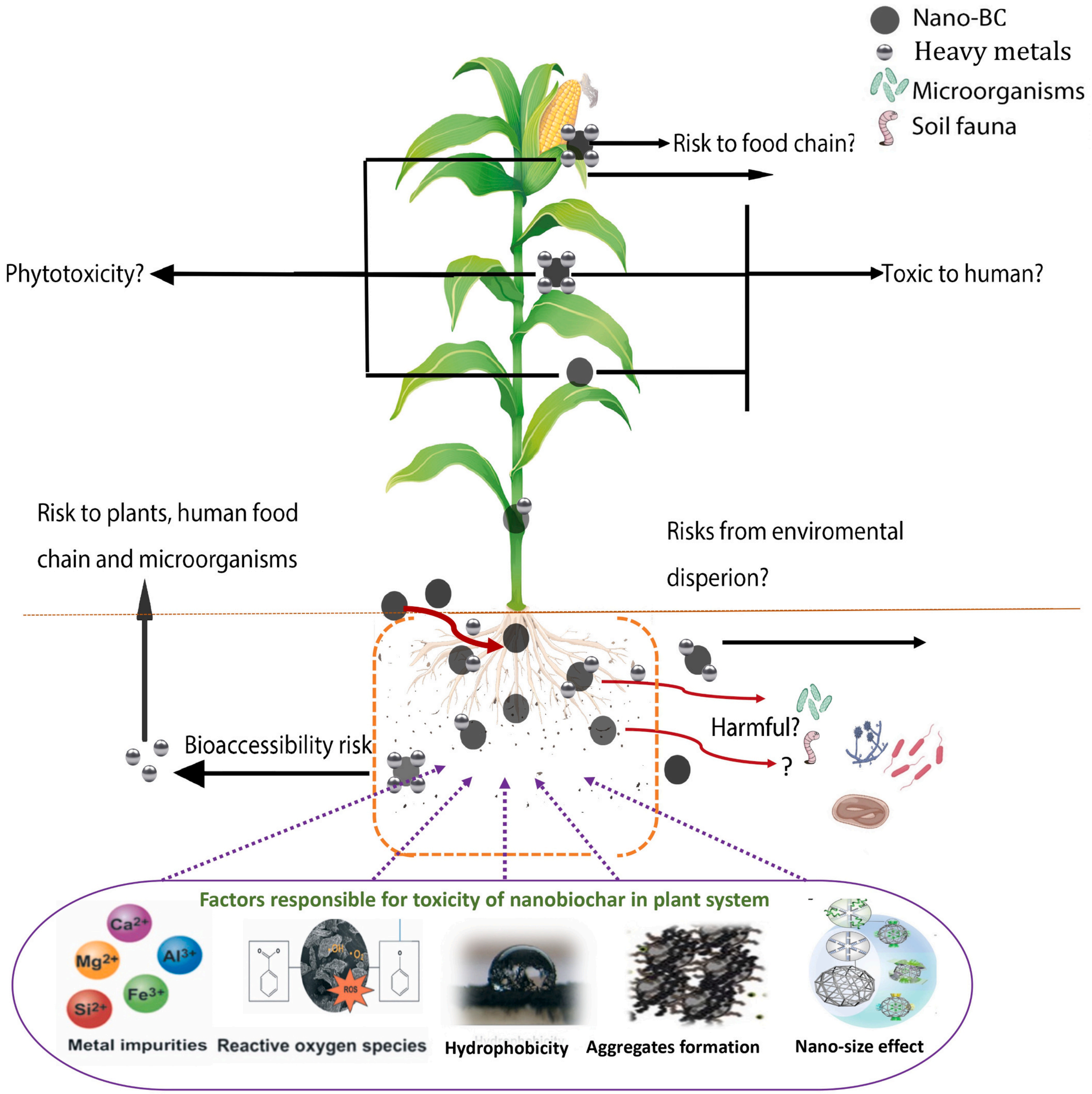

**Fig. 5.** Potential toxicity and risk of nano-BC application in agro-ecosystem.

cells which is due to their high adsorption capacity (Sigmund et al., 2017). However, there is no extensive research available on the toxicity of nano-BC generated PAHs. Still, precautionary measures should be taken during the preparation and application of nano-BC in field. Full face respiratory mask should be worn during preparation of nano-BC to whereas, nano-BC should not be applied in dust form rather in slurry or mixed with soil to avoid inhalation or accidental exposure.

The major concern of nano-BC toxicity is its post-application effect e.g., ecotoxicity. Liu et al. (2019a, 2019b) prepared nano-BC by ball milling and compared its toxicity on *Streptomyces coelicolor* with graphene oxide and carbon nanotubes. They reported higher cell damage by nano-BC than the other ones which might raise questions the use of nano-BC in large scale. However, they also found higher amount of antibiotic production from nano-BC induced effect on *Streptomyces* which may open a further window of nano-BC research. For their high surface area and size effect, nano-BC exhibit greater adsorption properties than bulk biochar. In field level scenario, nano-BC may adsorb the essential nutrients from soil solution causing nutrient deficiency. This phenomenon may result in movement of nutrients deeper into the soil profile, decreasing nutrient retention and possibly endangering groundwater (Xiang et al., 2021). Moreover, metal impurities obtained from incomplete or partial combustion of biochar feedstock is a potential agent to cause nutrient imbalance and can change the cationic exchange capacity (CEC) of soil. Although it was demonstrated by Zhang et al. (2020) that nano-BC particles might be absorbed by and translocated vascularly through plants, it is yet unknown whether nano-BC-sorbed pollutants, such as heavy metals and metalloids, may be desorbed after absorption and what impact this phenomenon will have on plants. It can be speculated that different nano-BC concentrations and degrees of aggregation adjacent to plant roots and rhizosphere may account for the varying toxicity. It is currently impossible to provide solid conclusions or suggestions about nano-BC toxicity in plant systems due to the small number of existing studies and their conflicting results; yet this issue should not be ignored. Moreover, the most prevalent theory on the toxicity of underivatized nano-BC postulates that nano-BC harms cells' delicate membranes. Since nano-BC is easily dispersible in water, it can easily be uptaken by plants through their xylem vessels. Besides, agro-nanotechnologies may directly release nanomaterials into the environment and incorporate them into the human exposure pathway through the food chain. Due to the possible migration of nanomaterials via the food chain, nano-BC application may face hurdles; therefore, a safety assessment is urgently needed. In addition, no research has been conducted so far to investigate the interactions between soil microorganisms and nano-BC. The complex physicochemical properties of nano-BC have a significant impact on their environmental behaviour, and understanding this influence is just as important as understanding the negative consequences that nano-BC have on soil microbiota. Conditions in the environment, including as temperature fluctuations, precipitation, and microbial activity, might alter the physicochemical properties of nano-BC after they have been applied in the field, leading to possible erosion/fragmentation, oxidation, and deagglomeration/disaggregation (Wang et al., 2020). Therefore, to fully comprehend the toxicity and associated risks of nano-BC on microbiota, humans and plants should be thoroughly investigated prior to recommend for large-scale commercial applications.

## 7. Conclusion and future remarks

The necessity of having a cost-effective, environmentally friendly, and highly efficient strategy to handle enormous amounts of biowaste has led to the development of nano-BC-based solutions, which offer greater prospects for sustainable agriculture practices than their bulk counterparts. The extremely small size of nano-BC offers greater SSA, large pore size, easy separation and abundant functional groups allow for efficient remediation of soil contaminants via high adsorption capacities, improving overall status of soil health and hence crop performance and sustainability of agroecosystem. In addition, the increased SSA of nano-BC offers microorganisms suitable habitats to establish and suitable sites for the uptake of vital nutrients, promoting plant development, microbial diversity, and soil biological activities. Sustainable development advances through continual transformation where nano-BC offers a strategic solution in developing a circular bioeconomy and contributes to fulfilling the SDGs. However, there are still significant gaps in our understanding of absorption capacity, allowable limit, and ecotoxicity of nano-BC applications. Importantly, research into the mobility/environmental dispersion and toxicity of nano-BC is required in addition to research into nano-BC characteristics and environmental biogeochemical behaviour. Developing nanosafety methods for rapidly assessing nano-BC and their mobility to different parts of the soil profile are essential to limit the negative effects. Notwithstanding, the following are some significant gaps in our understanding that should guide the course of future investigation:

- ❖ Nano-BC can have a wide range of characteristics depending on the feedstock used and the pyrolysis conditions. Thus, it is critical to find the best feedstock and pyrolysis conditions to extract the full potential of nano-BC.
- ❖ Very few research on the impact of nano-BCs on soil fauna has been conducted to date. In turn, the mechanisms through which soil fauna may influence the remediation of heavy-metal/metalloid-contaminated soil by nano-BC are still unknown.
- ❖ Nano-BC promotes the heavy metals-metalloids remediation by adsorbing the metal contaminants and thus heavy-metal-metalloid contamination residues within nano-BC itself. Uncertainty exists as to whether these heavy metals and metalloids are bio-accessible and could therefore be reintroduced to the soil; more research along these lines are needed.
- ❖ The potentiality of nano-BC for remediation of heavy metals and metalloids have been mostly investigated in lab and small-scale trials which may be impractical at large scale. Large-scale field experiments are needed before implementing large-scale treatment programs.
- ❖ A concentration-dependent analysis of the nano-BC in the natural soil system is needed to determine the lowest effective dose for its field applications while still ensuring that the material is non-toxic.
- ❖ It is essential to integrate life cycle assessment, techno-economic analysis, and cost-benefit analysis to optimize the design of nano-BC production systems for broad adoption in agricultural communities.
- ❖ Finally, we recommend extensive investigation into biosynthesized nano-BC as an alternative to synthetic nano-BC. Consequently, there may be minimal to no toxicity associated with the environmentally friendly protocol, and hence, future research must focus on their functional efficiency.

## CRediT authorship contribution statement

**Md. Nasir Hossain Sani:** Conceptualization, Investigation, Writing – original draft, Visualization, Writing – review & editing. **Mehedi Amin:** Writing – original draft, visualization. **Abu Bakar Siddique:** Writing original draft & editing. **Saifullah Omar Nasif:** Writing – original draft. **Bhim Bahadur Ghaley:** Writing – review & editing, Funding acquisition. **Liya Ge:** Conceptualization, Writing – review & editing. **Feng Wang:** Writing – review & editing. **Jean Wan Hong Yong:** Writing – review & editing, Validation, Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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