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Nature-Based Fertilizers for Sustainable Soil Fertility and Environmental Health

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THE INCREASING pressures of population growth, resource depletion, and climate change highlight the urgent need for sustainable agricultural practices. Soil fertility management in maintaining farm productivity and environmental health. However, excessive use of conventional fertilizers has led to soil degradation and contamination, making the need for sustainable solutions more pressing. Nature-based fertilizers offer eco-friendly alternatives to traditional chemical fertilizers. These nature-based solutions enhance soil structure, nutrient availability, and microbial activity by improving soil fertility, increasing crop yields, and reducing environmental impact. Biochar (BC), nanobiochar (NBC), and vermicompost (VC) are considered nature-based fertilizers because of their advantages to soil fertility and nutrient availability, thus environmental health. Biochar and nanobiochar contribute to carbon sequestration and soil health, while vermicompost accelerates organic matter decomposition and enriches soil biodiversity. Although the benefits and properties of nanofertilizers (NFs) make them better than traditional chemical fertilizers, there are some challenges and drawbacks when used to improve soil fertility. To overcome these challenges, nanobiofertilizers are used increasingly. This review explores the benefits and challenges of incorporating nature-based fertilizers (such as biochar, nanobiochar, vermicompost, and nanofertilizers into agricultural practices. These innovative fertilizers offer potential solutions to pressing global issues such as food security, climate change resilience, and environmental sustainability.

Keywords: Natural-Based Solutions; Soil Fertility; Biochar, Nanobiochar; Vermicompost; Nanofertilzers; Bionanofertilizers, Environmental Impacts.

1. Introduction

Climate change and population growth put tremendous pressure on the planet's natural resources. Agriculture depends on soil and water. Thus, maintaining these resources is crucial for economic and environmental sustainability. In addition to considering human safety and ecological functions, global challenges, including food and water insecurity, biodiversity loss, and livelihood threats, must be addressed. The integrity of the ecosystem is threatened by soil loss, which can significantly affect the supply of resources and food. Practical strategies that increase agricultural resilience mitigate the impacts of climate change, and enhance the environment include ecosystem-based adaptation, sustainable soil and water management, and nature-based solutions (Nalluri and Karri, 2024). In addition, the global-growing population drives food demand. Combined with limited agricultural land, it requires increased and enhanced agricultural production. Farmers use natural and manufactured fertilizers to improve soil fertility to overcome this issue. Soil fertilization supplies necessary nutrients, basically nitrogen (N), phosphorus (P), and potassium (K) , to promote plant development and growth. Nevertheless, fertilization involves more than just nutritional replenishment. It also includes the addition of substances to enhance soil structure and promote positive microbial activity. These treatments improve the physical, chemical, and biological aspects of soil, resulting in higher agricultural yields and better soil health (Rombel et al., 2022). However, the excessive use of these fertilizers has many negative environmental impacts. A significant environmental issue is soil contamination by organic and inorganic pollutants. The overuse of fertilizers, driven by the increasing demand for food from population growth, is a major contributor to soil

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pollution and degradation (Malik et al., 2024). Compared to chemical fertilizers, natural options offer numerous advantages, benefiting the soil, crops, water, air, and human health (Nalluri and Karri, 2024).

Therefore, this review addresses the utilization of biochar (BC), nanobiochar (NBC), vermicompost (VC), and nanobiofertilizer (NBFs)) as some nature-based fertilizers. It also examines their advantages, limitations, and challenges.

2. Nature-based solutions

To ensure sustainable food production globally, agricultural producers must prioritize farming techniques that revitalize greenery. Natural-based solutions are paramount in transforming our food systems, offering significant benefits. By 2030, these solutions can mitigate climate change, safeguard biodiversity, enhance food security and nutrition, and foster more integrated agricultural livelihoods. Achieving this transformation necessitates developing and implementing sustainable practices prioritizing soil health and conserving agroecosystems. Maintaining healthy soils rich in organic matter is crucial for boosting yields and enhancing resilience to environmental challenges (Nalluri and Karri, 2024). The efficiency of nature-based solutions (NBSs) has gained considerable interest at the United Nations Food Systems Summit (UNFSS) in September 2021 and COP26 of the UN Framework Convention on Climate Change in Glasgow in November 2021.

Nevertheless, research on the practical use of NBSs is rare. Adopting NBSs confronts challenges such as inadequate institutional preparation and a lack of motivation for farmers to improve ecosystem services. Successful implementation relies on coordination among researchers, policymakers, and land managers, with incentives provided to farmers for actions like carbon sequestration, biodiversity improvement, and adoption of nutrition-sensitive farming techniques (Lal, 2022). The NBSs philosophy is that nature may be promoted by addressing global ecosystem management concerns such as soil degradation, climate change, food security, natural catastrophes, etc. The NBS's philosophy attempts to employ natural alternatives rather than technological ones. The goal is to address broad issues, from ecosystem restoration and biodiversity conservation to NBSs development, to combat climate change and ensure a sustainable food supply. NBSs may be used to conserve and preserve natural resources while protecting ecosystems, ensuring their multifunctionality and sustainability. Ecological sustainability requires a paradigm change toward sustainable natural resource consumption and management and a function-driven strategy incorporating NBSs (Figure 1) (Mrunalini1 et al., 2021).

Food security represents a significant global challenge, primarily driven by the swift rise in population. Reducing arable land and declining agricultural productivity impact millions, contributing to malnutrition and poverty. The burden of ensuring food security increasingly rests on the limited agricultural lands. Farmers are utilizing a wide range of chemical fertilizers on smaller agricultural plots to maximize yields. However, the improper and excessive application of these fertilizers results in their buildup in the soil, ultimately leading to degradation. Current estimates indicate that approximately 30% of the world's soil is degraded (Malik et al., 2024). In addition, the prevalent use of chemical fertilizers can cause significant water pollution and biodiversity loss. As a result, fertilizer usage will lead to a decline in environmental quality.

Additionally, it is recognized that fertilizers frequently enter water systems, resulting in eutrophication, which fosters the development of harmful algal blooms. This process reduces oxygen availability in the water, negatively impacting aquatic life and lowering water quality. Furthermore, overapplication of these fertilizers can harm soil health by disrupting the natural nutrient equilibrium, leading to decreased soil fertility over time and a greater dependence on fertilizers. Concerning atmospheric pollution, the manufacturing and application of fertilizers release greenhouse gases, including nitrous oxide (N_2O), contributing significantly to climate change (Ozkan et al., 2024). Thus, natural solutions to enhance soil fertility is critical (Figure 2).

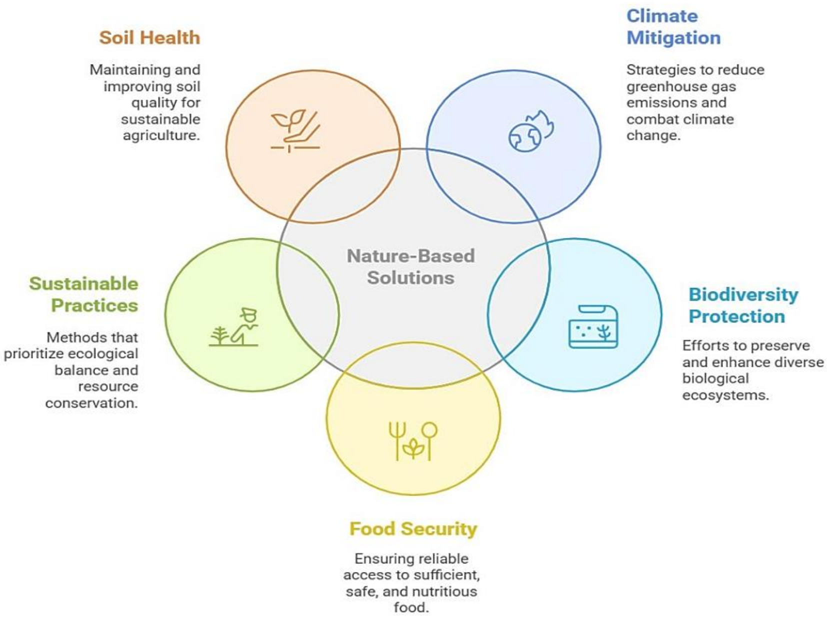

Fig. 1. Nature-based solutions for a sustainable environment.

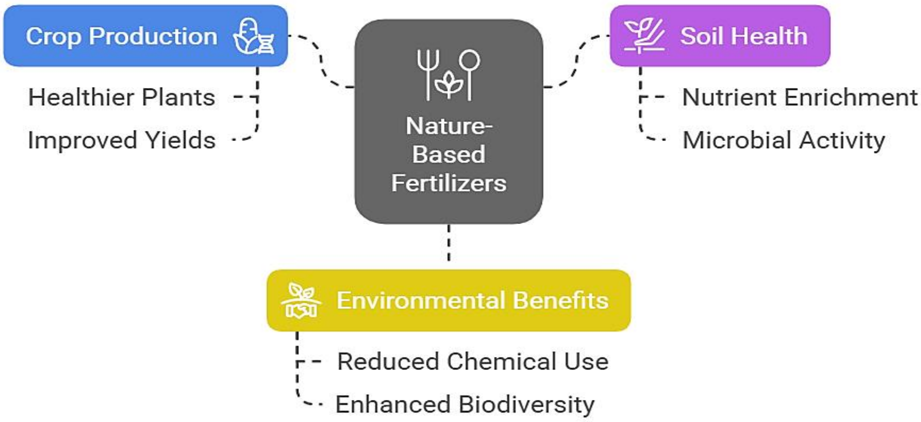

Fig. 2. Benefits of natural-Based fertilizers.

3. Biochar and nanobiochar as natural-based fertilizers

Biochar (BC) is synthesized from pyrolyzed organic materials (at 300 –900 C) and is used to overcome the problems addressed by using metallic NMs in agroecosystems (Liang et al., 2021; Rashid et al., 2023). Thus, BC is C-rich, possessing potent anti-decomposition properties and elevated degree of aromatization, high porosity and a stable, distinctive structure. Additionally, BC requires less energy-intensive production technologies and is more affordable and environmentally sustainable (Figure 3) (El-Ramady et al., 2020; Elbasiouny et al., 2023, Abdel-Motaleb et al., 2025). Pyrolysis is a novel strategy for organic waste management (such as agriculture waste, animal waste, food processing residues, solid litter, municipal sewage sludge, and industrial waste) in anaerobic conditions without harmful environmental effects. The BC can sequester C, reduce N_2O production, and thus enhance soil ecosystems. Biochar also alters chemical and biological soil properties; it elevates dissolved organic matter in the soil, optimizes the soil pH, improves soil cation exchange capacity (CEC) and macro- and micro-nutrients in soil, and is a likely source of Si for crops. Moreover, it enhances soil microbial activity and amplifies the fungal exploitation of C matter in soil. In addition, it has been proven that BC improves the soil's physical properties, including bulk density and soil structure. It also improves the environmental conditions for plant growth and crop production. Thus, it is directly applied as a biofertilizer or a supportive substance for the delayed release of fertilizers. Additionally, BC causes plants to photosynthesize more quickly and can regulate the growth and structure of their roots (Khan et al., 2021, Kaur et al., 2023, Malik et al., 2024, Abuzaid et al., 2025, Singh et al., 2025). Additionally, it is valuable in decreasing the environmental concerns of eutrophication and restoring degraded lands (Kaur et al., 2023).

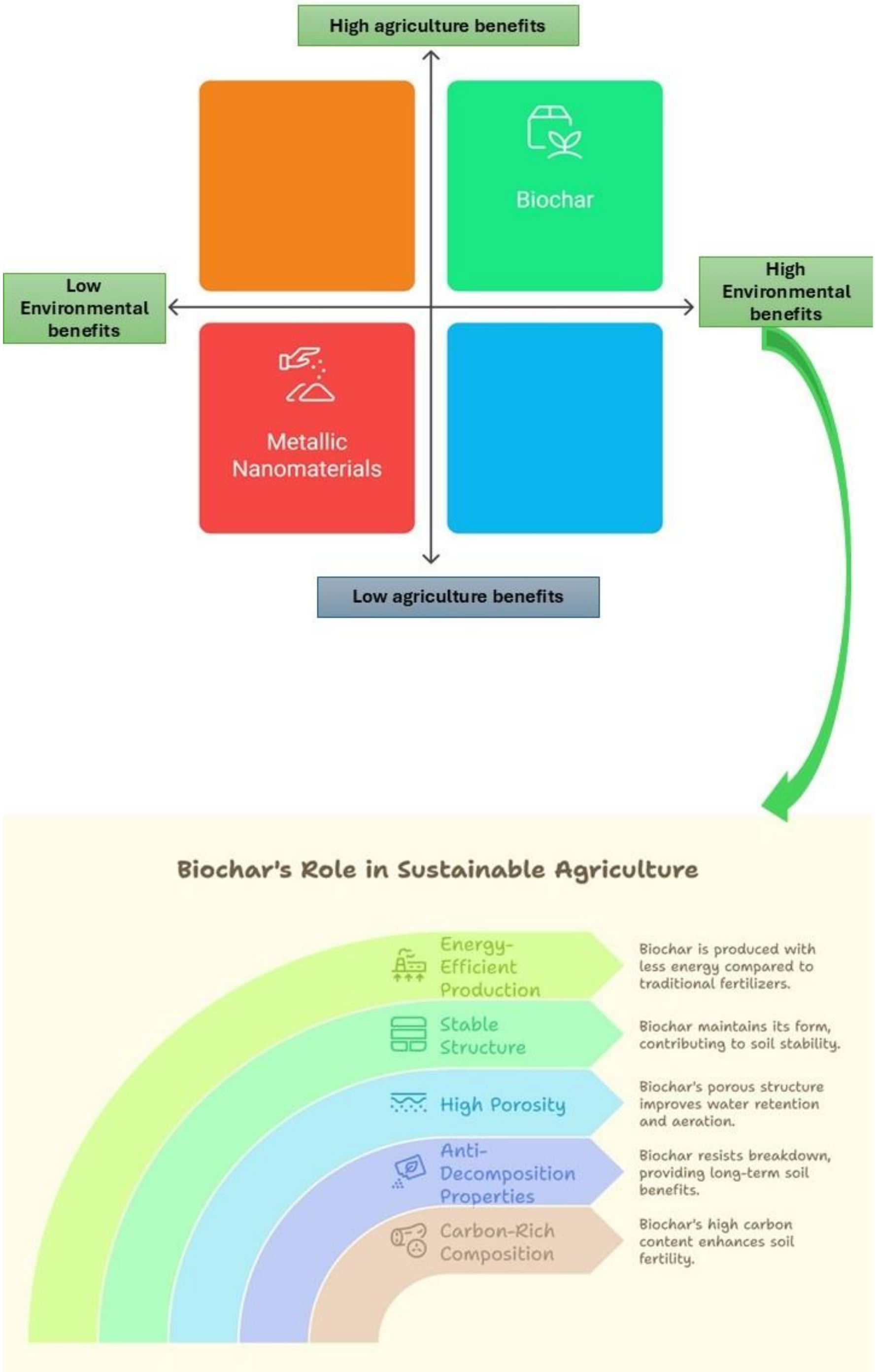

Fig. 3. Biochar vis nanometallic fertilizers.

Because of its advantageous physio-chemical characteristics, nanobiochar has gained significant traction and popularity in recent years among modified biochars. It is also one of the environmental sustainability strategies (Elbehiry et al., 2022). Despite abundant research on using BC in soil fertility, the use of NBC is still in its infancy. However, several studies have proven positive results (Figure 4), whether nanobiochar is used for this or other purposes such as remediation. For example, Rashid et al. (2023) used NBC (2, 5, 10% of applied N) combined with vermicompost on rice plants to examine N losses, control the release rate of nutrients, and increase soil nutrient availability. They also found that NBC addition in rice decreased the activities of superoxidase dismutase enzyme and malondialdehyde in the leaves of rice plants. The highest NBC concentration led to a decrease in ammonia emission and an increase in soil microbial biomass C and N, mineral N, P, and K markedly compared to vermicompost. Tarar et al. (2023) studied the effect of banana peel BC and its nano form on the first stages of growth parameters of Cucumber, Broccoli, and Red Okra. They found the viability of using NBC as a support fertilizer for the slow release of N, K, and P. They also noted that NBC improved soil physical properties more than BC. they also found that the salt index value of NBC performed better compared to the traditional fertilizers as a result of their safer application. A slow-release nutrient experiment in soil and water demonstrated the long-term availability of all enriched minerals to plants throughout the experimental cycle, which is optimal for encouraging germination and development. Also, Raza et al. (2023) used NBC (0, 0.5, 1, and 1.5 %) on the wheat plants and different levels of drought. Also they found in the experiment that NBC2 (1%) increased peroxidase activity, superoxide dismutase, in catalase, ascorbate peroxidase, and plant height compared to other concentrations of NBC. They also stated that NBC boosts crop growth in limited water conditions

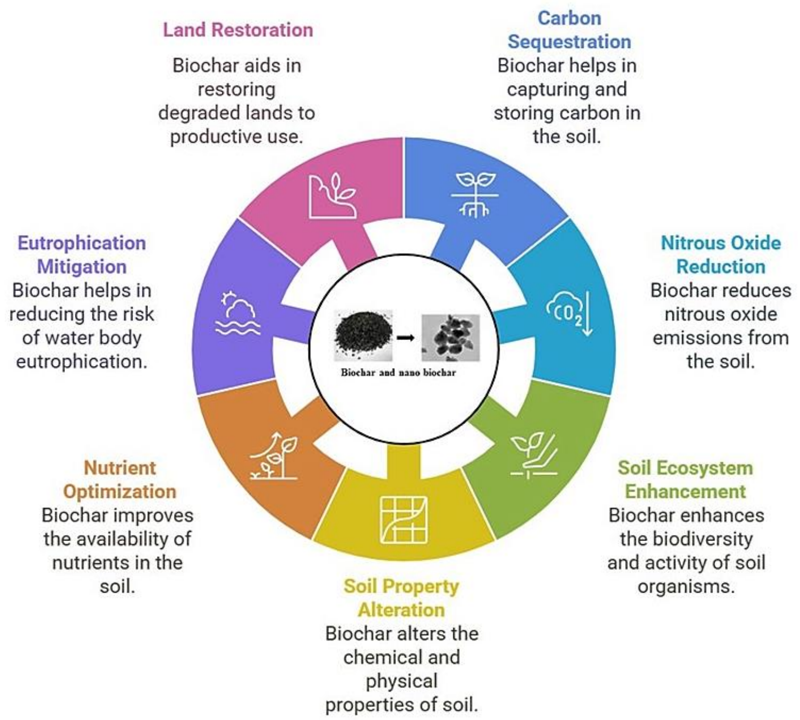

Fig. 4. Positive effects of utilizing biochar and nanobiochar in soil.

In addition, Yang et al. (2020) used NBC (0., 0.1, 0.5, 0.7, and 1%) on the maize plant pot experiment. Their result demonstrated increasing soil bulk density and aggregation (> 2mm in size) _with increased NBC rates. The application of NBC also increased soil moisture content significantly at the seedling and shooting stages, slowed the transport rate of N from the surface to deep soil profile, and increased the concentration available K. Tas well, higher NBC concentration significantly increased the weight of the 1000-grain and maize yield. Other examples of using BC and NBC in soil fertility are presented in Table 1 and a comparative analysis between BC and NBC is presented in Figure 5.

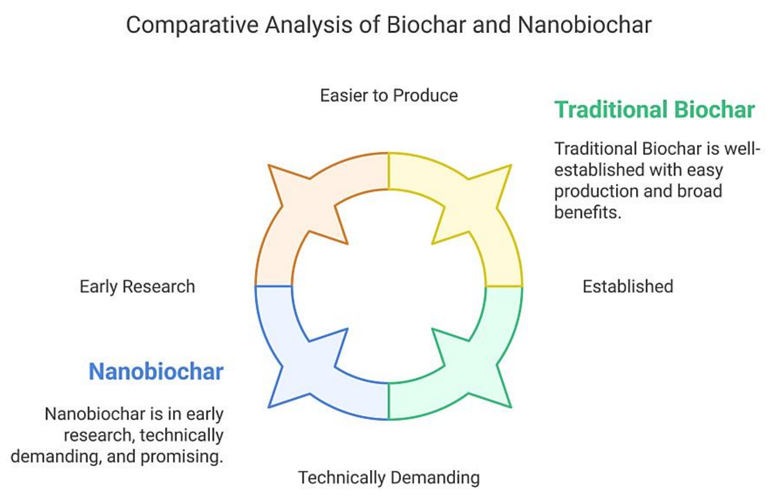

Fig. 5. Comparative analysis of biochar and nanobiochar in soil fertility.

Table 1. Utilizing biochar and nano-biochar in soil fertilization.

Biochar type/nano or bulk	Pyrolysis temperature/duration	Soil type	Outcomes	Experiment type	Plant	Reference
Chicken manure/BC	300/one hour	Haplic Fluvisol	BC outperformed compost and hydrochar in nutrient recovery, N release, and C stability.	Incubation	-	Piash et al. (2024)
Wheat straw /BC	450 ℃	Red soil	BC increased soil pH, available P, organic C, Ks, and water retention, soil total nitrogen (with increasing BC dosage), gradually increased NH_4^+-N, NO_3--N, improved the soil microorganisms and enzyme activities (through the first three years), increased the yield significantly in the first year, but the rapeseed yield decreased steadily after the second year.	Field experiment	Rape and sweet potato	Jin et al. (2019)
Biogas residue biochar/BC		Lateritic Red Earth	The BC application of enhanced soil nutrient levels, increased microbial community, declined soil acidification and reduced heavy metal pollution in soil.	Pot experiment	Chinese flowering cabbage	Luo et al. (2024)
Rice straw /BC	450 ℃ / 2 hour.	-	The use of BC improved the available soil nutrients and it quality and the abundance of bacteria correlated with the metabolism of C and N in the soil.	Pot experiment	Pakchoi plants	Wang et al. (2023)
Coconut shell/BC	450, 500, 550, and 600 ℃ / 4 hours	Sandy clay loam	The BC significantly improved soil quality and enhanced Cd removal.	Incubation		Chu et al. (2024)
Corn straw or cattle manure/BC	500 ℃ / 2 h	-	The addition of chitosan-modified straw BC reduced the addition of NPK-CF and participated in concurrently controlling N loss, releasing P, immobilizing Pb, adjusting pH, enhancing soil quality, and controlling nonpoint pollution.	Pot experiment	Ryegrass	Liu et al. (2023)
Corn stalks/BC	300 ℃ / 2 h	The Cd-contaminated soil/yellow loam soil	Biochar can offer a promising solution for remediating Cd-contaminated agricultural soil and synergistically enhancing soil fertility.	Incubation	-	Li et al. (2024)
Sugarcane straw/BC	550–650 ℃	-	The BC application improved soil fertility, suppressed the presence of pathogens/parasites, and led to rejuvenating sugarcane growth and yield.	The field experiment	Sugarcane	Fallah et al. (2023)

Nanobichar)Purchased) / NBC	-	Loamy soil	Foliar and soil-applied NBC increased the growth properties, photosynthetic pigments, primary and secondary metabolites, antioxidants, N metabolic enzymes, ion contents, soil physio-biochemical characteristics	Pot experiment	Wheat (Zincol and Akbar)	Mehmood et al., (2024)
Sugarcane press mud / NBC	-	Local soil	Foliar NBC application effectively alleviated the Cr toxic effect on Nigella sativa and improved the growth, photosynthesis, osmoprotectants, and antioxidant enzyme activity.	Greenhouse (in seedlings tray)	Nigella sativa	Ramzan et al., (2023)
Rice husk / BC	500 °C	Sandy loam-textured Petroplintic Cambisol	BC, especially when combined with NPK, led to a superior response in soil nutrient retention, soil structural stability, and potential total C and total N sequestration in micro- and macro-aggregates.		vegetable-based rotation system	Okebalama and Marschner (2023)
Cattle dung / BC	500 ℃ / 4 h	Different derived soils	BC endorsed the nitrification process with higher community diversity, increased community alpha-diversity, and activity of nitrifying bacteria in soils.	Incubation		Hou et al. (2021)
Orchard prunings/ BC	500 °C	Sandy-clay-loam	Biochar incorporation into the soil showed a potential to increase of C sequestration in soil, shift of soil microbial activity, increase of TOC and total P, while reducing P availability, significantly changing soil microbial biomass and respiration, enzyme activity and volatile organic compounds (VOCs) emission.	Incubation		Giagnoni et al., (2019)
Modified six types of Rice husks BC /BC	500 ℃	Purple soil	BC, particularly $BCNH_2$, BCC_2H_5O, and BCSH, significantly improved soil OM, total N, available P, and K, boosted the NPK uptake by rice leaves, and enhanced photosynthesis and rice yield.	Field and Greenhouse plastic pots	Rice	Li et al. (2023)

4. Vermicompost and nano-vermicompost as natural-based fertilizers

Vermicomposting is a novel biological and eco-friendly, non-thermophilic process involving the decomposition of organic matter by earthworms and their microbial partners, resulting in VC. Vermicomposting has spread widely in recent years. The process predominantly utilizes the epigeic species Eisenia fetida (Savigny) and Eisenia andrei (Bouché) known for their high reproductive rates and ability to consume litter. The final product, vermicompost, resembles peat and is characterized by high aeration, porosity, adequate drainage, water retention, and abundant microbial activity (Kaur et al., 2023; Rashid et al., 2023; Huang et al., 2024). Earthworms are considered vital "engineers" within soil ecosystems and essential for soil processes. Hence, they have been widely utilized as indicator species for the early detection of soil pollution, assessing heavy metal ecotoxicological effects, and the assessment of soil fertility and structure. Their activities significantly enhance the breakdown of organic matter and facilitate the release of nutrients through their feeding, digestion, and excretion processes (Huang et al., 2024; Abd El-Rahim et al., 2025). Thus, VC has many benefits (Huang et al., 2024) attributed to earthworm activity, as summarized in Figure 6.

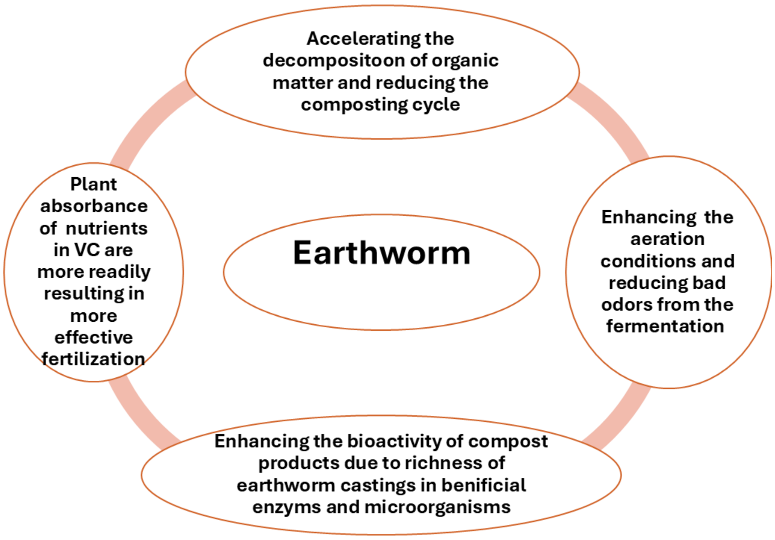

Fig. 6. Benefits of Earthworms in Vermicomposting and Organic Matter Decomposition.

By enriching soil biodiversity, VC is vital in supporting beneficial microbes that enhance plant growth by secretion of growth-promoting enzymes and hormones. Furthermore, it contributes to plant health and increases crop yield by managing nematodes, pathogens, and pests (Figure 7). Compared to traditional composting, vermicomposting presents several benefits and notable differences. One key advantage is its ability to enhance the decomposition process two to five times quicker and yield a more uniform product that boasts more excellent humus content than that produced through thermophilic composting. There are notable differences between the microbial populations in VC and composts, resulting in divergent microbial processes. Thus, VC is recognized as an essential element of organic fertilizers, being rich in key plant nutrients such as soluble potassium, nitrates, exchangeable magnesium, phosphorus, and calcium, all in forms that are readily accessible to plants (Figure 8) (Kaur et al., 2023).

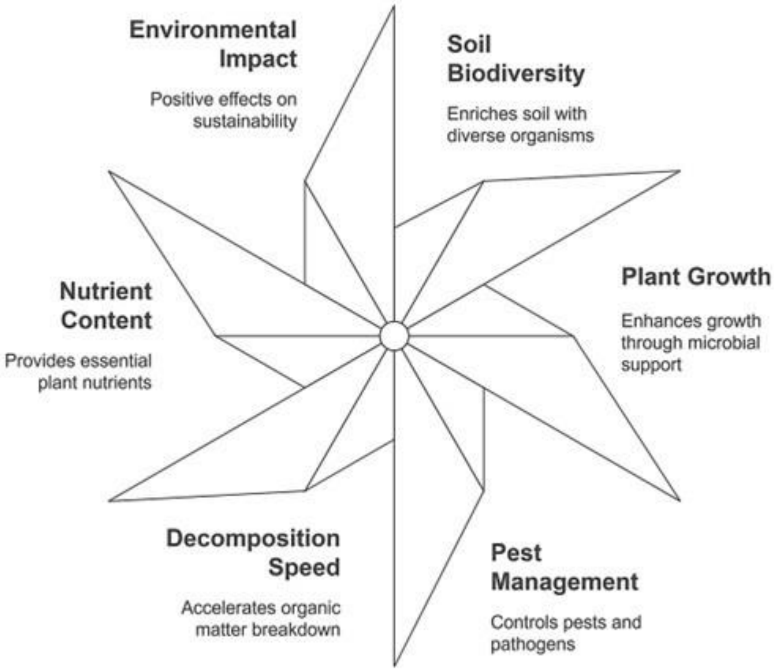

Fig. 7. The Multifaceted Benefits of Vermicomposting.

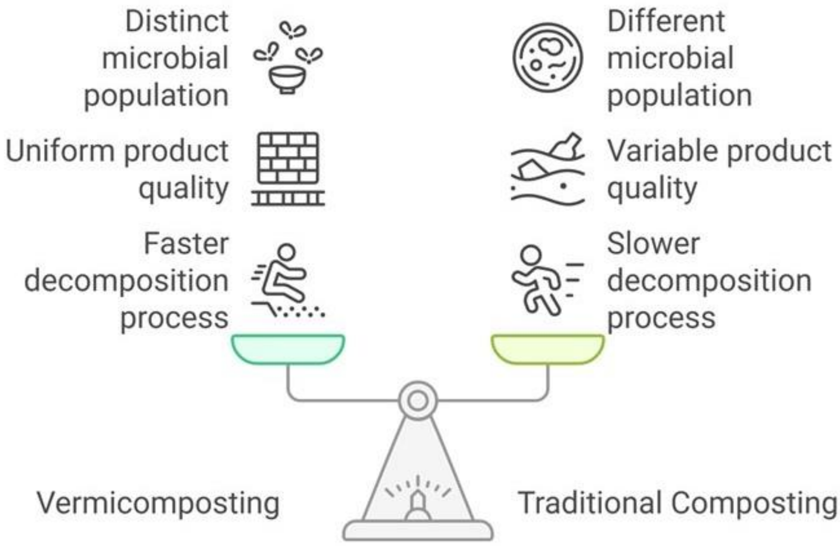

Fig. 8. Comparing Vermicomposting and Traditional Composting Benefits.

Recent research has demonstrated that the application of VC enhances soil quality and productivity and promotes the growth and development of various crops. The use of VC increased particle aggregation boosted the population of N-cycling bacteria, and enhanced the mineralization of N from wheat straw in lattice-grown fields. Furthermore, substituting 50% of chemical fertilizers with VC resulted in a tenfold increase in soil C storage during the cultivation of Cajanus cajan while also improving microbial soil health in degraded areas (Rashid et al., 2023).

In a study by Mustafa et al. (2022a) in Egypt, the effects of two types of vermicompost (VC)—fish sludge and cow dung—were evaluated at varying doses in conjunction with nano-fertilizers on strawberry plants. Every kind of VC was applied separately at two different levels (1 kg or 1.5 kg per pot). Concurrently, nano-fertilizer (NPK) was added at two concentrations (200 and 400 ppm). The findings indicated a beneficial effect of the combination of VC and NF on nutrients, fresh and dry weight, fruit quality, and soil health. This study is part of a broader collection of evidence that affirms the positive influence of VC and NFs on enhancing plant growth and maintaining soil health. Moreover, using VC and NFs can help farmers reduce their reliance on mineral fertilizers, bringing their usage down to environmentally safe levels that are also beneficial for consumer health.ᛜ Also, Ali & Amauri (2018) conducted research in Iran focusing on Black Raspberry (Rubus occidentalis) to evaluate the influence of nano-iron fertilizer and VC on several growth parameters. The study aimed to measure the effects on flower diameter, fruit weight, yield, sugar levels, and the content of vitamins C and iron. Researchers applied three different levels of nano-iron fertilizer (0, 500, and 1000 mg L^{-1}) alongside four varying amounts of VC (0-, 0.1-, 0.2-, and 0.4-ton ha^{-1}) to fulfil the fertilizer needs of Black Raspberry in Mazandaran province. Findings revealed that combining 1000 mg L^{-1} of nano-iron fertilizer with 0.1-ton ha^{-1} of VC led to a significant increase in fruit weight (11.05 g) and yield (45.73 g).

In their study, Mustafa et al. (2022b) revealed that utilizing 10 kg of washed sand in conjunction with three different concentrations of VC (0.5, 1, and 1.5 kg per seedling) paired with two levels of foliar applications of Nano-NPK (20:20:20) fertilizers at concentrations of 200 and 400 ppm. Nano-NPK fertilizers were applied twice a month during the active growth with bi-weekly irrigation of fig seedlings. The results indicated that substituting half of the recommended spray dosage with NFs at a concentration of 400 ppm positively impacted most of the vegetative growth parameters, with no deficiency symptoms evident in the seedlings. The microbial and enzymatic activities within the soil are significantly linked to the content of organic matter and are affected by various soil management practices, including applying fertilizers. It is essential to highlight the positive effects of organic matter sources such as VC and nano-fertilizers. Furthermore, all treatments of VC and NFs demonstrated enhanced enzyme activity compared to the control. Notably, at a consistent level of NFs, increasing the doses of VC boosted enzyme activity, especially at the 200-ppm fertilizer concentration.

Razmandeh et al. (2020) reported that using 10 t ha^{-1} VC with 0.006 L ha^{-1} iron NFs produced the highest crop production chlorophyll content and the best morphological traits of corn. In the experiment of Razmandeh et al. 2020, they applied three levels of VC (V0: control, V1: 5 t ha^{-1} VC, V2: 10 t ha^{-1} VC) at the planting stage. They also used four levels of iron NF (F0: control, F1: 0.002 L ha^{-1}, F2: 0.004 L ha^{-1}, and F3: 0.006 L ha^{-1} iron NF) were used at three to four stages. Their results were significant in most properties. In addition, Roozbahani and Mohammadkhani (2017) investigated the effect of VC and iron NFs on maize yield and its components. The results showed that VC and NFs iron significantly affected all traits. The application of VC had the best result compared to the control for almost all examined traits. Application of iron on NFs significantly enhanced dry weight, stem height, total chlorophyll, yield, and harvest index. Their results suggested that the application of VC and NFs should be in the form of seed-coated and foliar application.

Kamali et al. (2023) Studied the effect of different levels of VC (0, 5, 10, 15, and 20 g per pot), NBF (0, 1, 2, and 3 g per pot), and BC (0, 1.25, 2.5, 5 and 10 g per pot) as well as a combination of VC + Nano-compost (10 g VC -2 g NBF) and VC-BC (10 g VC-2.5 g of BC and 10 g VC and 5 g of BC) was conducted on some morphological properties and the phenolic compounds content of Echinacea purpurea L. The highest results were in plants grown in VC-BC combination regarding root length, dry shoot weight, and leaf area compared to other treatments. In addition, VC-compost-NBF showed the highest fresh and dry root weight. The highest fresh stem weight was observed in BC 5 g compared to other fertilizers. Furthermore, the Echinacea cultivation combined with VC and BC showed the highest phenolic compound content.

5. Nanobiofertilizers as a natural-based fertilizers

5.1. Using nanoparticles in soil fertility

Nanoparticles are particulate matter with dimensions of 1 and 100 nm in at least one dimension (Chaitra et al., 2021). Because of their composition, which enables the selective release of nutrients associated with temporal and environmental conditions and regulates nutrient release with crop uptake, it is stated that applying nano-nutrients as fertilizers can minimize the leaching of nutrients and volatilization losses. Furthermore, due to the previous advantages and the unique properties of NFs, it can be considered an intelligent system for nutrient delivery (Rameshaiah et al., 2015). As such, these nutrient compositions may be adequate replacements for conventional fertilizers, offering a regulated and gradual release of nutrients. The NFs have the potential to reduce soil pollution caused by the excess of chemical fertilizers while also increasing yields and optimizing nutrient utilization (Naderi and Danesh-Sharaki, 2013). These fertilizer compositions are thought to promote crop growth and development because of increasing reactivity, improved absorbance, and ability to penetrate cells via cell wall pores. Different types of NFs may be produced using a variety of carrier materials, including hydroxyapatite NPs, zeolite, mesoporous silica NPs, Ni, Cu, Zn, Si, C, and polymeric NPs (Chaitra et al., 2021).

Nanofertilizers (NFs) have garnered interest among soil scientists, agricultural engineers, and environmentalists because of their potential to boost crop yields, positively impact soil fertility, reduce pollution, and identify an active ecosystem that supports microorganisms (Toksha et al., 2021). Nano-fertilizers are a viable solution to improve production and address growing agricultural issues (Kumar et al., 2024). Nanofertilizers can minimize the losses of nutrients by leaching and prevent fast changes in their chemical composition, hence increasing nutrient usage efficiency (Kaur et al., 2023). Thus, NFs are one of the most promising technologies for achieving sustainability in agriculture. Applying nano-nutrients has been shown to positively impact crop productivity and soil characteristics, which might lead to the development of more nutritionally valuable and balanced foods to feed the world's growing population (Hussein et al., 2024).

Compared to traditional bulky chemical fertilizers, NFs have a higher capacity for absorption and retention due to their large surface area and large surface area to volume ratio (Babu et al., 2022). This effectively increases the efficacy of nutrient use due to higher nutrient uptake by plants. This may happen due to improved nutrient-surface interaction by nanomaterials. Because the nanoparticles that encase NFs break down gradually, the nutrients are delivered in a regulated manner by diffusion (Kaur et al., 2023). The nutrients released from NFs occur progressively and slowly reducing the unfavorable adverse environmental effects.

The essential properties of NFs are their strong ionization power, enhanced chemical stability, more excellent absorbability, higher tension at the surface, increased pH leniency, and mobility. Thus, NFs can potentially reduce soil chemical loads, improve nutrient use efficacy, reduce the adverse effects of traditional fertilizers, and reduce their frequent application (Babu et al., 2022). Thus, nutrients can be absorbed gradually by plants sustainably because of the previous properties of NFs, which result in more significant number of active sites for biological actions (Kaur et al., 2023).

NFs can be applied as a foliar spray or absorbed via seeds to leaves and roots, affecting the bioavailability, behaviour, and plant uptake. The efficacy of NF absorption, distribution, and accumulation depends on many factors, including pH, organic matter, soil texture, and properties related to the NPs, such as size and coating (Kaur et al., 2023). In this regard, nitrogen-NFs (N-NFs) are created by encapsulating urea accompanied by hydroxy apatite nanoparticles, implying the gradual release of N in plants. Likewise, P-based NFs help direct P absorption by agricultural plants, hence minimizing P losses. In addition to being effectively absorbed by plants, NFs provide minor leftovers in soil, atmosphere, or groundwater, preserving environmentally clean production (Kaur et al., 2023).

5.2. Advantages of Nanofertilizers over Conventional Chemical Fertilizers

Nanofertilizers pose less risks to the environment and human health than conventional fertilizers. They also reduce costs, optimize profits, and enhance crop quality, yields, and soil fertility (Raj et al., 2021). It is worth mentioning that the loss of nutrients from agricultural lands due to leaching and gaseous emissions plays a significant role in environmental pollution and climate change. NFs present a viable solution to address these challenges. Research indicates that NFs can decrease gas emissions, enhance nutrient transport, promote organic matter retention, and facilitate the formation of new minerals in the soil. Additionally, they improve seed germination, plant enzyme activity, resilience to tolerate adverse circumstances, C sequestration, N fixation, photosynthesis, and respiration. However, despite their promising potential, further investigation is essential to fully comprehend their effectiveness in enhancing crop production in climatic change conditions, particularly regarding their performance in various climatic zones and their effects under heightened heat stress (El-Ramady et al., 2021; Shalaby et al., 2022).

Chemical fertilizers, although they are derived from non-organic agricultural components, are widely used by farmers to increase crop yields. Chemical fertilizers act faster than organic fertilizers since they are less costly, easily soluble in water, and accessible in granular or liquid forms. On the other hand, microbes in the soil degrade organic substances such as animal manure, bird feces, food waste, and sewage sludge, releasing essential nutrients. This natural fertilizer is more friendly to the environment since it improves soil texture, increases the activity of soil bacteria and fungus, and retains water longer. Its major nutrients are NPK, which protects plants from pests and diseases. The biggest drawback of using this sort of fertilizer over chemical fertilizers is the delayed release of nutrients. Biofertilizers are effective alternatives to synthetic fertilizers since they improve soil quality and include vital elements for plant fertility and productivity. In addition, they are inexpensive, sustainable, and environmentally friendly (Nongbet et al., 2022).

The role of NFs in physiology, crop yields, and nutritional value are essential to assessing their effectiveness NFs. The precision that NFs might have is a handy feature for efficient nutrient management on the time scale of the growth stage of a crop. The NFs are primarily manufactured and incorporated to increase crops' productivity and quality, in addition to an increase in their nutritional value. The macro- and micro-nutrients delivered by the NFs can also improve organic matter and microorganisms (Toksha et al., 2021). Kumar et al. (2020) reported that the effectiveness of nutrient use can be improved significantly by 50 % urea saving through two sprays of Nano-N. Thus, they considered NFs a novel approach to nutrient saving, especially N, and environmental protection.

In addition, using Zn-NPs to enrich Zn-deficiency in soils with Zn permits investigations into potential soil applications of ZnO-NPs to improve plant health and crop yield. Tanha et al. (2020) studied the possible effect of ZnO-NPs on seed yields, focusing on ZnO particle size, morphology, and concentrations related responses of multiple antioxidant defence indicators, in soil grown with soybean (Glycine max cv. Kowsar) through its lifecycle of 120 d. Their findings revealed that significant particle size, morphology, and concentrations dependent responses of ZnO-NPs on seed yields, lipid peroxidation, and various antioxidant indicators in soybeans.

Almendros et al. (2022) conducted a pot experiment to determine the effect of commercial ZnO-NPs at different dosages for use as NFs on the nutrient uptake and its distribution in the cherry tomato (Solanum lycopersicum L var. cerasiforme) plants in an acidic soil (pH 5.5) and calcareous soil (pH 8.5) from the Mediterranean area. They determined crop yields; the concentration of macro- (N, P, K, Mg, S, and Ca) and micro-nutrients (B, Cu, Fe, Mn, Na, and Zn) in the different parts of the plant (root, shoot, leaves, and fruits) and the nutrient translocation extent to the aerial part of the plant. The concentration of N, P, K, and Mg in the fruits cultivated in both soils was adequate regarding nutritional requirements. However, the Ca concentration in the fruits in the calcareous soil did not reach the required concentration to be sufficient. This result was attributed to the properties of this calcareous soil. They found some variations in the concentration of other nutrients, such as B, Cu, and Mn, while Fe and Na weren't affected. They revealed that ZnO-NPs can be used to enhance crop yields and get adequate Zn biofortification in cherry tomato crops. Nutrient concentrations in such fruits after biofortification are acceptable for human consumption.

The recent use of nano-Cu compounds in agroecosystems has improved crops' physiological performance and agronomical properties as found in (Cota-Ruiz et al., 2020). Also (Cota-Ruiz et al., 2020) found that the P and S contents significantly declined in bulk and ionic Cu-exposed plants than controls. In addition, The Fe and Zn contents increased in leaves due to all Cu forms. Ciurli et al. (2023) evaluated the potential of P fertilization of a novel nanosized FePO4 NF to enhance plant properties and nutrient uptake. They tested the efficacy of a $FePO_4$-NF in sustaining the growth of cucumber plants in a pot experiment compared to a conventional triple superphosphate fertilizer. Although their results showed insignificant variation in dry weight, leaf area, and root growth between fertilized plants by NF and TSP, available P concentration in soil and P concentration in plant tissues were significantly higher at the end of the experiment after TSP fertilization compared to $FePO_4$-NF. Furthermore, no significant variations were noticed for other nutrients. Among their evaluated soil enzyme activities, only the protease activity was higher in NF-fertilized soils than in TSP.

Saurabh et al. (2023) studied the effect of Fe2O3-NF on the growth, crop, and quality of cauliflower (Brassica oleracea var. botrytis L.) cv. combined with Azotobacter, farmyard manure, and phosphorus-solubilizing bacteria. Fe_2O_3 -NF enhances photosynthetic activity and promotes catalyzed enzyme activity in plant leaves, affecting plant health and remarkably increasing crop production. In combination with other biofertilizers, Fe_2O_3-NF encourages growth effects to enhance cropping behaviour. Effects of NFs on sustainable agriculture are presented in Figure 9, as well as the effect of nanofertilizers on plant productivity, nutritional value, and quality in Table 2.

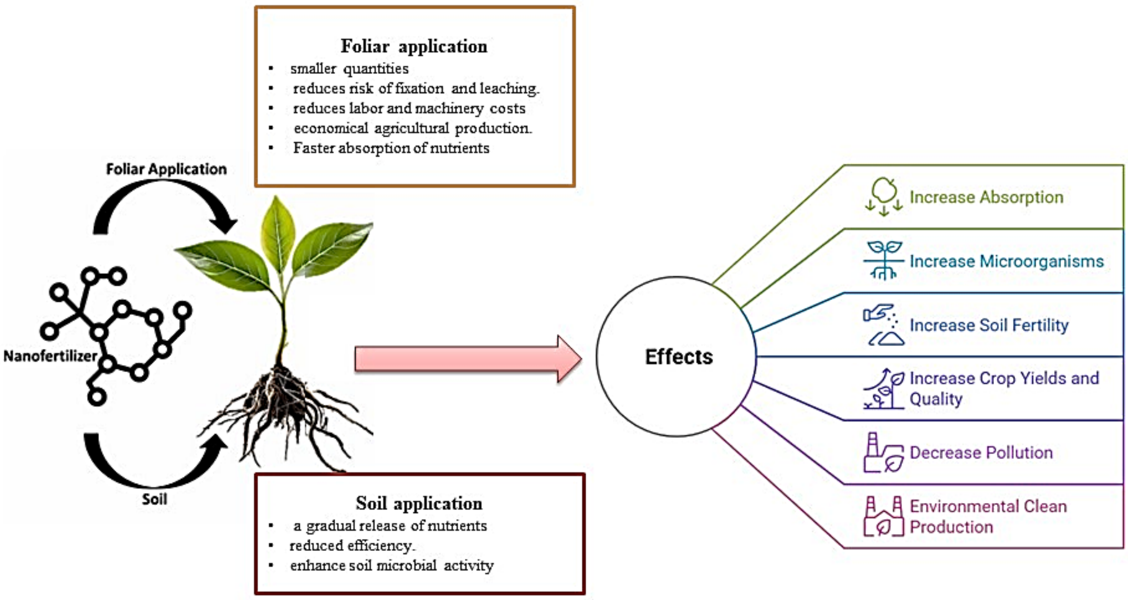

Fig. 9. Effects of nanofertilizer for sustainable agriculture.

Table 2. Effect of nanofertilizers on plant productivity, nutritional value, and quality.

Nanofertilizers	Plant	Impact	Concentrations	Applied	References
NPK-NFs	Potato	Higher potato yield and quality, higher profit: cost ratio of potato yield.	50 % of the recommended level	Foliar	Abd El-Azeim et al., 2020
Commercial products of micronutrients and nano-micronutrients,	Pomegranate	Increasing yield and physical characteristics of fruits, improving the total soluble solids %, flavonol, total phenols anthocyanin pigment, antioxidant activity, and nutrient status	1000 and/or 1500 μg mL^{-1}	Foliar	Hussein et al., 2023
Nanofertilizers (NF-A and NF-B)	Spinach	NF-A at the highest dosage: modified the surface composition of leaves' nutrient content, added new elements, and increased the content of others. NF-B at the highest doses: had negative impacts on leaves, reduced chlorophyll, flavonols, and polyphenols, contents and decreased antioxidant activity, increased oxidative damage, and the cellular and ultrastructure deterioration	100 and 500	Foliar	Gil-Díaz et al., 2022
N nanofertilizer	Zaghloul date palms	Using NF-N at 60 % of the recommended dosage on the soil surface in fertilization caused significant improving in growth, yield, and fruit quality.	20, 40, 60 and 80%	Soil surface and foliar spray	Abd El-Rahman, and Abd-Elkarim, 2022
Cu-nanofertilizers	Cowpea	Marked and significant increments in morphological characteristics, antioxidant concentration, and chlorophyll contents, while a detrimental impact was observed with increasing NF concentration.	20, 40, 60, and 80 ppm foliar, 25, 50, 75, and 100 mg/kg soil	soil and foliar	Mustafa et al., 2024
nSiO2, $nTiO_2$ nZnO, nFe_3O_4 , nCuO ,/$nCeO_2$	Lettuce	Alleviating Cd toxicity, significantly increased antioxidant enzyme activities, plant growth, biomass production, and photosynthetic efficiency.	$nSiO_2$ (50/100), $nTiO_2$ (20/60), nZnO (50/100), nFe_3O_4 (100/200), nCuO (50/100), $nCeO_2$ (50/100) mg L^{-1}	Seed nano-priming	Bano et al.,2024

5.3. Nanofertilizer types

Nanofertilizers are divided into three categories: nanostructured micronutrients (such as hydroxyapatite), nanostructured macronutrients (such as zinc oxide nanoparticles (ZnONP)), and nanostructures that transport nutrients (such as chitosan NPs) (da Silva Júnior et al.,2020). Bernela et al. (2021); Abd-Elsalam & Alghuthaymi (2023) divided NFs into three categories: macro-nutrients, micro-nutrients, and biofertilizers. Macro-nutrients are classified into primary and secondary macro-nutrients. Primary macronutrients (i.e., N, P, and K) are taken in larger quantities. At the same time, secondary ones (i.e., Ca, Mg, and S) are also essential for plant growth.

Nanofertilizers can also be classified depending on the material utilized. For instance, some NFs are manufactured from carbon nanotubes, whereas others are made from polymers or metals. Each form of NF has specific characteristics and impacts plants (Yadav et al., 2023). As well as, NFs can be categorized into five types: plant growth-stimulating, controlled-release, action-based, targeted delivery, and water and nutrient loss controlling. Thus, NFs are inorganic or organic materials that vary based on the chemical or physical method used (Figure 10) (Nongbet et al., 2022; Yadav et al., 2023).

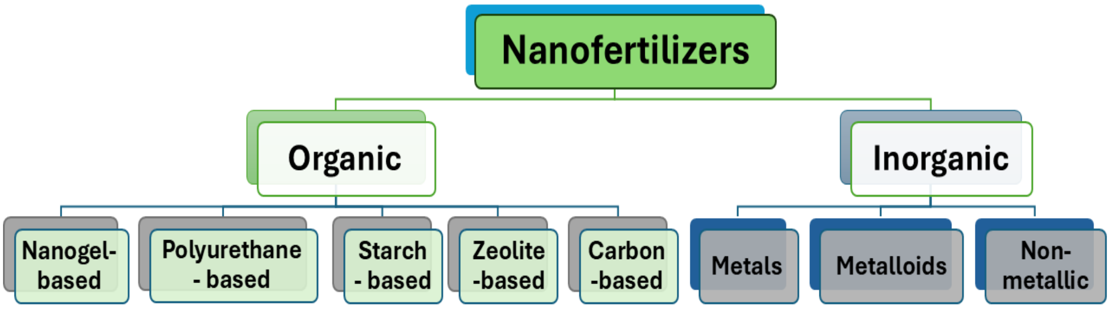

Fig. 10. Organic and inorganic nanofertilizers types.

5.3.1. Inorganic Nanofertilizers (INFs)

Inorganic NFs include metals, metalloids, and non-metallic NPs that can supply essential nutrients, such as N, P, and K, to plants. These fertilizers can be utilized to increase crop production since they are made to improve plants' efficiency in absorbing nutrients. Inorganic NFs have unique advantages because they can be designed to specific nutrient requirements of focused plants, thus allowing directed applications to improve yield.

5.3.1.1. Macronutrient inorganic nanofertilizers

Sufficient macro- and micro-nutrients are necessary for plant nutrition, including C, O, H, N, P, K, Ca, S, and Mg. The first three nutrients are structural elements obtained from the environment, whereas the other six are obtained from soil. Although all the macro-nutrients are essential, primary macro-nutrients are absorbed in higher amounts than secondary ones. These primary macro-nutrients are considered fertilizer elements as the familiar “N-P-K” identified on fertilizer labels (Bernela et al., 2021). The macro-nutrient-based NFs comprise one or more encapsulated nutrients inside a specific nanomaterial (Nongbet et al., 2022). Macro-nutrient NFs offer substantial advantages for plant growth and development and environmental sustainability (Yadav et al., 2023).

Nitrogen NFs combine N molecules with NPs such as metal oxides, C nanotubes, and graphene. These particles help to increase the soil available and accessible N to plants. The gradual N release from NFs into the soil decreases the N amount released into aquatic systems, reducing the environmental risks from runoff and leaching. Phosphorous-NFs are a relatively new type that can potentially revolutionize growing food. They are more effective, cost-efficient, and eco-friendly than traditional fertilizers. Utilizing slow-release P supplies the crop with P during its life cycle, which can preserve this element. It is also noticed that P NFs are effectual in soil reclamation processes and enhance plant growth and production in degraded soils (Yadav et al., 2023). Also, P NF displayed promising effects for seed treatment. Improving P uptake motivates natural P mobilization by micro-nutrient-based NPs (such as Fe and Zn) or by creating P-based NPs. This will enhance plant growth and decrease the ecological impacts of eutrophication induced by the limited P availability (Nongbet et al.,2022). Potassium-NFs are made of microscopic particles, which enable them to diffuse deeper inside the soil and reach the plant roots. Consequently, they are absorbed higher than traditional fertilizers and deliver essential nutrients to plants more rapidly and effectively. It also effectively increases chlorophyll content, leaf area, grain and biological yields, harvest index, disease and pest resistance, and drought tolerance due to enhanced nutrient absorption. Moreover, nano K is more soluble in water and more resistant to leaching, which reduces its loss by irrigation or rainfall (Bernela et al., 2021; Yadav et al., 2023). Calcium-based NFs effectively increase the plants' growth and yield, improve the quality of fruits and vegetables, and increase the plant resistance to pests and disease. Several different types of Mg-based NFs have been developed. Some are made from Mg oxide, while others are from Mg sulfate. Mg-based NFs are effective in increasing crop growth and yield. Magnesium improves the nutritional quality of vegetables and fruits while boosting plants’ resistance to pests and diseases and pests. Sulfur nano-coated fertilizer materials are valuable slow-release fertilizers. They supply primary nutrients and sulfur. The coating stability slows the dissolution rate, resulting in sustained fertilizer release (Yadav et al., 2023). Bernela et al. (2020) observed that S NPs reduced Mn uptake, raised the seedling's water content, and reduced physiological drought, implying that S NFs can control the harmful impacts of Mn stress.

5.3.1.2. Micronutrient-Based Nanofertilizers

Micronutrients play a crucial role as mineral constituents within the agricultural framework, facilitating the appropriate growth of vegetative and reproductive plant tissues (Sahu et al., 2023). These elements, while vital for plant development and the optimal growth of plants, are needed in significantly smaller quantities. The key micronutrients include boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), zinc (Zn), and chloride (Cl). Micronutrient deficiency-induced stress in plants can lead to several detrimental effects, such as reduced crop yield and quality, abnormal plant morphological structures, increased susceptibility to a range of diseases and pests, diminished activation of phytosiderophores, and decreased efficiency in fertilizer utilization (Preetha & Balakrishnan, 2017, Bernela et al., 2021).

Nanofertilizers focusing on micronutrients represent a sophisticated category of agricultural inputs that utilize NPs to supply essential micronutrients to plants more efficiently than traditional fertilizers. These micronutrient NFs provide various benefits, such as improved nutrient absorption, plant growth and development, plant metabolic process, higher yields, nutritional quality, and greater resilience against biotic and abiotic stresses (Kumar et al., 2023; Yadav et al., 2023).

As a crucial micronutrient, copper plays a significant role in plant growth by engaging in numerous biochemical reactions, including redox processes, enzyme activity regulation, and the synthesis of cell walls. Furthermore, copper is instrumental in promoting photosynthesis and respiration, which are essential for the healthy growth and development of plants. Various studies indicate that copper-based nanomaterials can function as efficient nano-fertilizers, enhancing crop nutrition, decreasing disease occurrence, and boosting stress tolerance, thereby improving crop yields and ensuring food safety (Kaleem et al., 2024; Su et al., 2024). Iron NFs enhance the availability of iron for plants, boost agricultural crop yields, rehabilitate iron-deficient soils, and contribute to improved water quality in aquatic ecosystems. Additionally, these NFs can aid in the remediation of contaminated soils and mitigate the impacts of acid rain (Yadav et al., 2023). Lian et al. (2024) demonstrated that iron-based agents serve as effective foliar treatments for promoting safe wheat production, reducing cadmium levels and enhancing plant characteristics, and contributing to biofortification in nano-enabled agricultural practices. Zinc plays a vital role in various physiological functions, including activating enzymes, maintaining protein structure, and regulating gene expression (Shoukat et al., 2024). Zinc and zinc oxide NPs have gained considerable attention for their positive impact on sustainable agricultural practices. They facilitate seed germination, promote early flowering, enhance enzyme activity, and lead to improved yields (Anusuya and Rajan, 2024). Zinc oxide NPs have also been utilized as NFs to mitigate some plant stresses, such as heavy metal toxicity, salinity, drought conditions, extreme temperatures, and particularly nutrient deficiencies, while enhancing overall plant yield (Hanif et al., 2024). Manganese is a critical trace element that plants require for optimal growth, participating in essential processes like photosynthesis, respiration, and nitrogen metabolism.

Additionally, Mn aids in developing resistance to root and shoot pathogens. The positive agronomic effects of Mn application have been observed across multiple crops, with notable increases in growth and yield for maize, beans, soybeans, wheat, and sugarcane when treated with Mn in ionic format suitable dosages (Dimkpa et al., 2018)—the manganese NP's influence on growth (Ali et al., 2021). Manganese NPs have been proven to be a better Mn source than commercially available MnSO4 salt (Bernela et al., 2021). Boron is an essential micronutrient crucial for the growth of plants, contributing significantly to cell wall integrity, photosynthesis, sugar transport, and fruit development. A boron deficiency can adversely affect chlorophyll levels, photosynthetic efficiency, enzyme function, and overall fruit yield. However, achieving optimal boron concentrations is difficult due to the narrow margin between deficiency and toxicity, which ranges from 10 to 100 $mg.kg^{-1}$ (Noaema et al., 2020). Boron-based NFs solve soil boron deficiencies by delivering precise and efficient doses directly to crops. These fertilizers, which combine borate with substances like humic acid, can be applied to the soil or used as foliar sprays. Their nanoscale dimensions facilitate effective penetration into plant cells, enhancing nutrient absorption. Research indicates that applying boron and zinc NFs can significantly improve crop yield and quality, including higher levels of leaf micronutrients and enhanced production of pomegranate fruits (Yadav et al., 2023). Molybdenum has an essential role in plant metabolism that cannot be overstated. This crucial micronutrient serves multiple functions, including being a structural element in the enzyme Nitrate Reductase, which is critical for nitrogen assimilation. Additionally, molybdenum is an integral component of a complex organic pterin known as the molybdenum cofactor, which interacts with molybdoenzymes across various biological systems (Muñoz-Márquez et al., 2022). Molybdenum NPs, serving as a micronutrient source of molybdenum, can enhance the yield, performance, and disease resistance of legumes and various other crop species. (Bernela et al., 2021).

5.3.2. Organic Nanofertilizers

Organic nanoparticles (NPs) are commonly synthesized from atoms or molecules through synthetic chemistry, resulting in various formulations such as capsules, polymer conjugates, vesicles, micelles, liposomes, polymersomes, dendrimers, and polymeric NPs. A notable example is NonoMax-NPK, which features a blend of organic acids (protein-lacto-gluconates) that are chelated with nitrogen, phosphorus, potassium, oxygen, amino acids, and organic carbon. This formulation is complemented by organic micronutrients, trace elements, vitamins, and probiotics, making it an all-encompassing nano-nutritional fertilizer for various crops (Fatima et al., 2021). Using organic nutrient fertilizers (NFs) can greatly benefit plant growth, as their gradual release of nutrients facilitates better absorption and utilization, resulting in improved crop development and increased yields. Moreover, incorporating organic NFs can significantly enhance soil quality by encouraging soil aggregation and porosity and improving water infiltration, aeration, and root penetration. The organic components found in these fertilizers also provide essential nutrients for soil microorganisms, boosting their growth and metabolic activity (Saurabh et al., 2024).

5.4. Mechanisms for nutrient uptake by plants

Nanoparticles can penetrate plants by many routes, including roots, shoots, and leaf tissues (e.g., stomata, trichomes, stigma, cuticles, nd hydathodes), as well as root junctions and wounds (Meghana et al., 2021). Among those routes, leaves represent an essential pathway. The leaf's waxed cuticle, made up of wax, cutin, and pectin, provides a natural barrier toward NPs penetration and water loss in growing leaves. On the other hand, the waxed cuticle has hydrophilic and lipophilic canals with diameters ranging from 0.6 to 4.8 nm. Hydrophilic NPs less than 4.8 nm may spread through hydrophilic routes, whereas lipophilic NPs can reach the cuticle surface via lipophilic ones (Singh et al., 2023).

Bernela et al. (2021) stated that for foliar applications, NPs may penetrate via cuticles or stomatal openings. Cuticles in leaves represent the first barrier, which restricts NPs smaller than 5 nm. Nanoparticles that enter via stomatal pores can spread the vascular system through apoplastic or sympathetic pathways. While the particles that range from 10–50 nm favor the sympathetic pathway, whereas the large ones (i.e., 50–200 nm) favor the apoplastic pathway. da Silva Júnior et al. (2020) added that NFs penetrate plants via endocytosis, allowing the elements to transport from the extracellular media into the cell via ---bound vesicles (. Plant protoplasts can take up particles smaller than one µm by endocytosis, although there is no size selectivity (Singh et al., 2023).

The cell wall's pore diameter controls NPS passage into the cell wall (5-20 nm) and the plasma membrane. The largest size of NPs that may enter and accumulate inside plant cells is typically 40-50 nm, which is known as the exclusion limit (Meghana et al., 2021).

5.5. Limitations, drawbacks, and challenges of nanofertilizer application

The development of ecologically sound fertilizers is crucial for achieving the goal of decreasing agrochemical usage in sustainable agriculture (Bhatista and Singh, 2021). However, due to the scarcity of resources, a notable rise in the costs of agricultural inputs, such as fertilizers and pesticides, is projected. As the implementation of nanoparticles in nanotechnology-based nutrient delivery systems is still in the preliminary stages, further investigation is needed (Figure 11) (Lang et al., 2021).

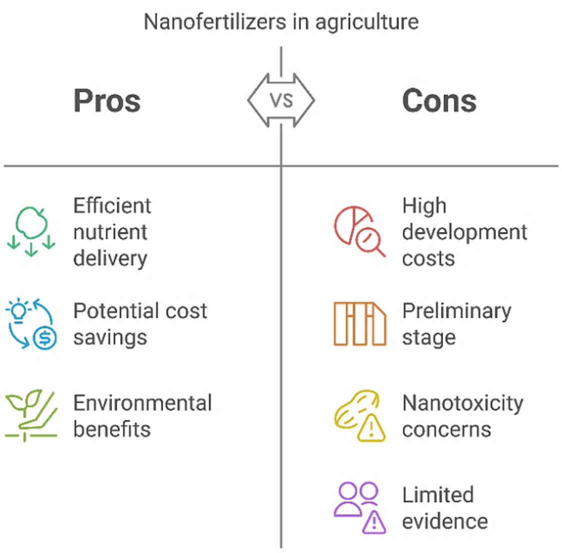

Fig. 11. Pros and cons of nanofertilizers.

Also, the increasing adoption of NFs to enhance plant nutrient availability and boost agricultural productivity is becoming more common; however, several toxicity-related concerns persist and interact with other NPs and pollutants and NPs, especially in soils, sediments, and water. Furthermore, a lack of comprehensive research, effective monitoring, and regulatory frameworks limits the widespread use of NFs. These minute particles' safety, potential hazards, and environmental impacts remain uncertain, as they can infiltrate biological systems more profoundly and present significant risks (Elbasiouny et al., 2022; Kumar et al., 2022). The health implications of nanomaterial exposure extend beyond their cytotoxic and genotoxic effects. The small dimensions of nanoparticles enable them to penetrate cell membranes, allowing access to the cytoplasm, organelles, and even the nucleus, which can subsequently influence gene expression in animals. Their ability to spread among non-target species and enter the food chain poses potential environmental risks. These materials can impact living organisms in various ways. For example, carbon-based nanoparticles can alter the structure of DNA and gene expression in plant cells (Lahiani et al., 2015). Moreover, zinc oxide nanoparticles have been shown to interfere with the symbiotic relationship between rhizobia and legumes, negatively impacting the nitrogen fixation (Huang et al., 2014). Additionally, the presence of iron-based nanoparticles on root surfaces can lead to reduced absorption of water and vital nutrients, including calcium, magnesium, and sulfur (Chaitra et al., 2021).

Thus, concerns regarding nanotoxicity for both humans and the environment are substantial. Nanoparticles (NPs) that are generated through biological processes tend to be safer than those produced via chemical or physical methods. Furthermore, organic NPs are less detrimental to soil microorganisms when compared to metal and metal oxide NPs (Jaskulski et al., 2022). Although naturally occurring NPs are used to supply nutrients to plants, more research is needed to evaluate their toxicity thoroughly. At present, there is no effective legislation or risk management strategy in place to regulate the application of NFs for sustainable agricultural production. A significant challenge lies in the insufficient output and availability of the necessary quantities of NFs for extensive use in plant nutrition. Additionally, the higher costs associated with NFs compared to traditional fertilizers create a significant barrier to their widespread adoption across diverse pedo-climatic conditions worldwide. The lack of standardization and inconsistent formulations of these fertilizers can result in varying effects on the same plant species in different locations (Figure 12) (Nongbet et al., 2022).

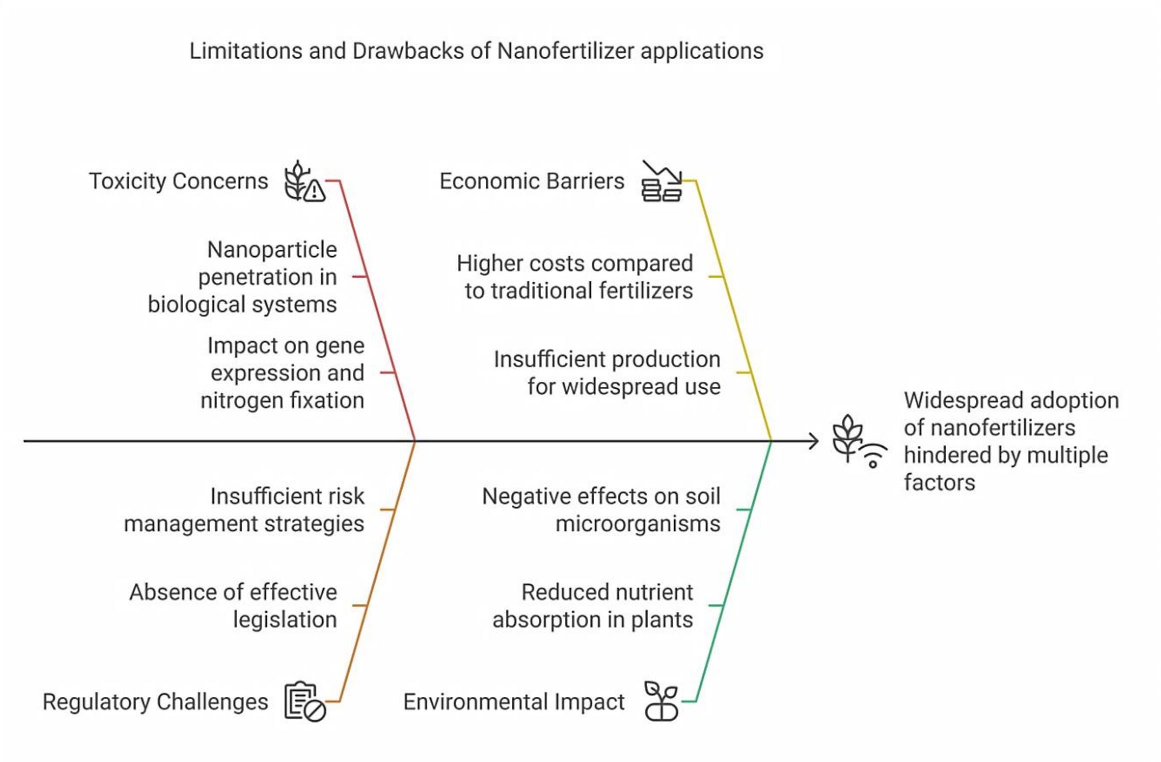

Fig. 12. Limitations and drawbacks of nanofertilizers application.

5.6. The prospects of nanofertilizer applications

Future research on NFs should explore several key avenues: (a) The focus on N- and P-NFs may increase due to their high application rates and challenges related to availability; (b) For micronutrients, a comprehensive investigation is warranted to understand the factors influencing their availability in agricultural settings. Additionally, comparing the efficacy of these micronutrients with commercially available fertilizers in biofortification and application methods, such as fertigation, presents another valuable research direction. Given the concerns surrounding nanotoxicity, it is essential to identify the optimal dosages for various crops to avoid negative impacts; and (c) Currently, there is a lack of conclusive evidence supporting the notion that fertilizers utilizing nanocarrier technology enhance nutrient absorption by plant tissues or mitigate the environmental risks associated with traditional fertilizers (Nongbet et al., 2022).

5.7. Nanobiofertilizers

As highlighted earlier, nanomaterials (NMs) serve as fertilizers that effectively provide essential nutrients, both macro, and micro, due to their advantages, such as increased surface area, the ability to penetrate plant tissues, and greater reactivity with other substances. Moreover, these materials are extensively employed in the remediation of environmental toxins. However, careful application of nanomaterials in agriculture is essential, as high concentrations may induce plant stress (Elbasiouny et al., 2022). Nanotechnology has permeated various fields of science and technology, particularly in its recent applications aimed at enhancing crop yields and maintaining the environmental integrity of agricultural lands. Although it still needs more research, there is growing momentum towards the creation of advanced smart nano-fertilizers, which encompass innovative formulations of traditional fertilizers and adsorbed or encapsulated nano-nutrients. The concerns regarding the phyto- and eco-toxicity associated with these new nano-scale fertilizers have intensified the demand for alternatives that can mitigate the adverse effects linked to the use of nano-fertilizers on their own (Kalia and Kaur, 2019). Biofertilizers are plant-derived carriers that contain advantageous microbial cells (Akhtar et al., 2022). BFs mainly comprise live cultures of advantageous microorganisms, including Rhizobium species, that enhance plant development. They also contain phosphate-solubilizing bacteria like Rhizobia, along with blue-green algae (BGA), mycorrhizal fungi, and bacteria such as Azotobacter, Azospirillum, and Pseudomonas species (Somna et al., 2024). Nano-biofertilizers (NBFs) represent a combination of nanoparticles (NPs) and biofertilizers (BFs) (or reducing the size of BF to nano size) with the aid of encapsulating BFs that have been reduced to nanoscale within an appropriate nanomaterial coating. This innovative cocktail approach enhances nutrient delivery to targeted areas and mitigates the effects of environmental stress (Ali et al., 2021a; Sharma et al., 2023; Zafar et al., 2024). Thus, NBFs incorporate NPs such as silver (Ag), zinc (Zn), iron (Fe), zinc oxide (ZnO), titanium dioxide (TiO2), silicon dioxide (SiO2), and magnesium oxide (MgO) can play a crucial role in crop protection. Meanwhile, algal species, including Chlorella spp., Arthrospira spp., and Dunaliella spp. are recognized as effective biostimulants and biofertilizers. Furthermore, microorganisms that promote plant growth, such as Azotobacter, Azospirillum, Rhizobium, Pseudomonas, Bacillus, and Trichoderma, along with synthetic strigolactones like GR 24, enhance crop yield and improve resilience to stress (Chattaraj et al., 2025).

The synthesis of NBFs involves three key stages: (1) cultivation of BF culture, (2) encapsulation with NPs, and (3) evaluation of effectiveness, purity, quality, and shelf life (Figure 13). NBFs can be prepared as microcapsules by mixing plant growth-promoting rhizobacteria (PGPR) with 1.5% sodium alginate, 3% starch, and 4% bentonite in a 2:1 ratio. This mixture is coated with calcium chloride solution, washed, and sterilized. Another method involves combining BF with sodium alginate (2%), zinc oxide NPs (1 µg mL^{-1}), and salicylic acid (1.5 mM). The solution is coated with 3% CaCl2, forming 1-mm beads that are air-dried and stored at 4°C. Additionally, organic waste (e.g., flowers, cow dung, and kitchen scraps) can be combined with NPs to create NBFs. The waste is washed, chopped, and partially decomposed or pyrolyzed before being mixed with NPs to create NBFs (Akhtar et al., 2022). Some authors didn't use this technique and combined NPs and microbes without encapsulation, such as (Saleem and Khan, 2022; Karunakaran et al., 2024). The term NBF, also called the NPs, emerged from natural materials such as plant waste as described by Batool et al. (2024), who called NBF the fertilizer created from the chelation of minerals complex from pomegranate peels with citric acid. Behl et al. (2024) also stated that biofertilizers are increasingly recognized as essential components of contemporary agriculture due to their affordability, sustainability, and environmentally friendly Nature. In recent years, understanding the interactions between plants and soil microorganisms has evolved, leading to a broader interpretation of BFs. This term now encompasses a variety of eco-friendly options, including green manure, seaweed extracts, plant extracts, and microbial blends.

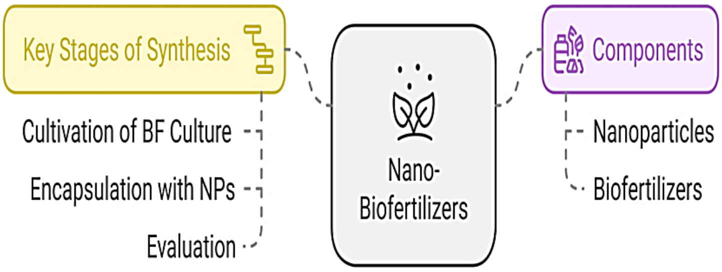

Fig. 13. Synthesis and components of nano-biofertilizers.

Thus, key advantages of NBFs include a decreased reliance on chemical fertilizers, enhanced nutrient use efficiency, improved nutrient availability and absorption, rapid mass production, environmental sustainability, cost-effectiveness, and the potential for renewable fertilization. Research indicates that NPs can influence plant-microbe interactions directly and indirectly; direct effects involve nutrient availability in the rhizosphere, while indirect effects include the stimulation of microbial activity (Sharma et al., 2023). The enhancement of N fixation capabilities, increased phosphate solubility, and elevated hormone levels that promote plant growth, along with the improvement of soil microbial conditions and other bioorganic elements found in NBFs (such as urea and growth-promoting microorganisms), provide numerous advantages to both soil and plant systems (Zafar et al., 2024). The bio-organic components of NBFs positively affect various soil and plant characteristics, such as promoting nitrogen fixation, solubilizing phosphates, increasing the secretion of plant growth hormones, and enhancing the soil microbiome. A significant attribute of NBFs is their ability to penetrate plant tissues, whether applied as soil amendments, seed treatments, or foliar sprays. The nanomaterials, whether used as coatings or immobilization substrates for biofertilizers, can enhance the dissolution and availability of insoluble nutrients in the soil, reduce nutrient absorption and fixation, and facilitate the gradual release of nutrients for plant uptake. This controlled nutrient release ensures that plants receive essential nutrients throughout their growth cycle.

Information regarding weather and soil conditions also enables farmers to optimize their operations. For instance, nano-devices could detect crop health issues before they become visible to farmers, allowing for timely interventions and effective management strategies. NBFs, being minute particles, can easily infiltrate plant tissues, enhancing their overall efficacy (Sharma et al., 2023). Thus, NBFs hold significant potential for tackling contemporary agricultural challenges (Biswal, 2024). NBFs have the potential to significantly contribute to solving the global food security issue while reducing the environmental footprints of farming practices (Chand et al., 2025). The data is still rare in this field. However, some examples of the effect of NBF on soil fertility and plant growth are presented in Table (3) and Figure 14.

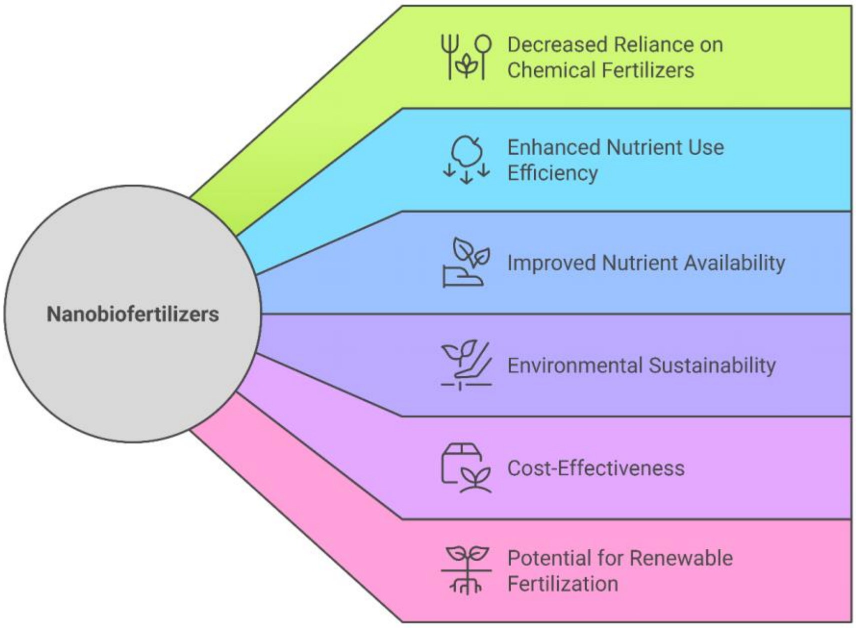

Fig. 14. Key advantages of nanobiofertilizers.

Table 3. The effect of NBFs on soil fertility and plant growth.

BF	Nanocomposite and carrier	Plant	Findings	Ref.	Note
Pseudomonas azotoformans and *Pseudomonas gessard*	Cerium oxide (CeO2) carried on Soya chunks	Fenugreek	Increase in the length of the shoot and the root	Sonali et al., 2022	
Azospirillum brasilense, Azotobacter chroococcum, Bacillus subtilis, Lactobacillus plantarum, Saccharomyces cerevisiae, Rhodopseudomonas palustris, Pseudomonas putida.	Chitosan based-nanocarrier	Banana, cassava, and local herbs	Increasing the yields of banana and cassava, improving the indicators of soil health such as soil organic matter and beneficial microbial populations, and increasing nutrient availability (P and K).	Serroune & Inthasak, 2025	
-	Minerals complex from ripe Pomegranate waste with citric acid	Bean	Effective uptake and translocation of N, P, K, Zn, Mn, Fe, Ca, Mg, Cu, and Se from the NBF. The decline of amino acid proline indicated that it alleviates the stress caused by nutrient deficiency.	Batool et al., 2024	The complex in this ref. called NBF that created from natural material without including any microbe
Rhizobium pusense	Iron oxide NPs	Greengram	A significant increase in seed germination rate, plant growth, length, plant dry biomass and seed, greater protein and chlorophyll content	Saleem and Khan, 2022	
Bacillus subtilis and *Bacillus sp*	Mesoporous silica NPs, zinc oxide NPs, and copper oxide NPs	Wheat	Zinc oxide NPs and Bacillus sp showed the most favorable results regarding plant growth and properties.	Karunakaran et al., 2024	

The emerging domain of microbial-derived metal NPs presents significant potential for tackling urgent societal and environmental issues while promoting advancements in nanotechnology. However, obstacles such as scalability, reproducibility, and standardization persist, highlighting the need for continued research and development initiatives (Dash et al., 2025). Thus, comprehensive research is essential to elucidate the interactions between microbes, nanoparticles, plants, and the soil conditions the environment influences before these NBFs can be widely distributed (Figure 15) (Biswal, 2024).

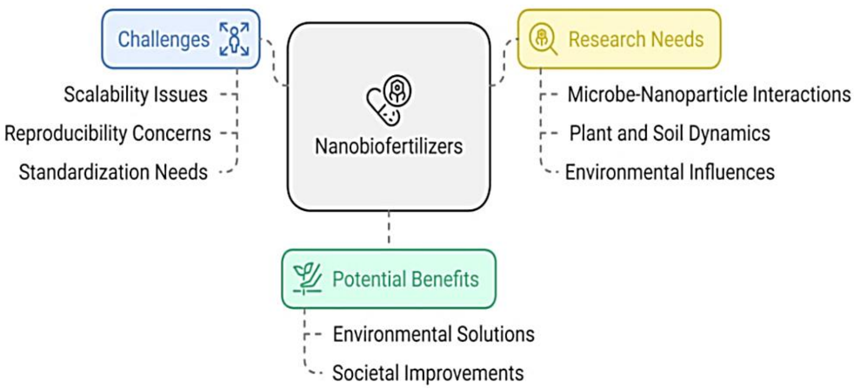

Fig. 15. Challenges, benefits, and research needs in nanobiofertilizers.

6. Conclusion

The increasing demand for sustainable agricultural practices necessitates the adoption of eco-friendly soil amendments such as biochar, nanobiochar, vermicompost, and nanobiofertilzers. These nature-based fertilizers enhance soil fertility, improve nutrient availability, and promote microbial activity while mitigating the negative impacts of traditional chemical fertilizers and thus promote environmental health. Biochar and nanobiochar contribute to soil carbon sequestration, enhance soil structure, and optimize nutrient retention, making them valuable tools for climate change resilience. However, there are some challenges in utilizing nanobiochar. On the other hand, vermicompost accelerates organic matter decomposition, enriches soil biodiversity, and enhances plant health by releasing essential nutrients in bioavailable forms.

Despite their promising benefits, the large-scale implementation of biochar, nanobiocahr, and vermicompost presents challenges such as production costs, variability in feedstock composition, and long-term soil interactions that require further research. Future studies should focus on their application rates, assessing environmental trade-offs, and integrating these fertilizers into holistic soil management strategies. By advancing research and promoting sustainable policies, nature-based fertilizers can play a pivotal role in addressing food security, climate change adaptation, and environmental sustainability in global agricultural systems.

List of abbreviations:

BC: Biochar; NBC: Nanobiochar; VC: Vermicompost; NBFs: Nanobiofertilizer; NBSs: Nature-based solutions; NFs: Nanofertilizers

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

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