Review Article

NanoBiofertilizer and its Application in Sustainable Agriculture, Crop Specific Nutrients Delivery and Environmental Sustainability: A Review

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Abstract
Probiotic bacteria are increasingly in demand in the food and feed industries. A growing population and finite resources require efficient ways to maximize yields. Probiotic bacteria are gaining popularity in the food and feed industries due to their unique combination of benefits and values, which include consumer health interests, sustainability values, food innovation, and potential business opportunities. The use of conventional fertilizers can increase crop production but can also cause runoff and toxicity issues. A nanobiofertilizer offers improved crop nutrition and reduces application rates. Slow-release properties minimize environmental losses while nanoscale particle size enhances nutrient absorption. If nanobiofertilizers are closely regulated, they can boost yields without destroying the soil and aquatic ecosystems. In recent years, nanobiofertilizers have received considerable attention. Plant extracts and microbes are used in green synthesis to produce eco-friendly nanoparticles. Crop-specific nutrient release can be tailored using modified nanoparticle surfaces. Controlled nutrient delivery is achieved by smart nanocarrier systems that adapt to changing soil moisture, pH, and microbial activity. Combined applications of plant growth-promoting rhizobacteria have been reported that they can enhance crop growth in synergy. This review presents an overview of the most recent studies on nanobiofertilizers, as well as the issues connected with their environmental implications, safety, and regulation, presenting a roadmap for the responsible use of nanobiofertilizers, which aims to enhance food security while protecting the environment for future generations.

Keywords: Crop yield, Environmental quality, Nanobiofertilizer, Nanotechnology, Nutrient delivery system, Soil fertility

1 Introduction

Agriculture is essential to the global economy and is seen as a key component of industrialized and developed countries. Consequently, the utilization of fertilizers to enhance crop yields in developing African countries is indispensable. However, continuous overuse of chemical fertilizers has been identified to pose significant environmental problems and by extension deplete human health. In recent years, Africa has witnessed a substantial surge in crop production and productivity. This growth has been attributed to a deliberate increase in the use of chemical fertilizers, which is on the rise in tandem with the adoption of fertilizer-sensitive crop varieties [1]–[3]. Similarly, doses have increased as a result of chemical fertilizers' poor performance. Agrochemical use over long periods may be harmful to the soil. A large portion of synthetic fertilizers are reportedly lost from fields and absorbed by water resources rather than being taken up by plants. When these agrochemical fertilizers get into water bodies, they cause a variety of consequences such as eutrophication, reduced agricultural biodiversity, nutrient deficiencies, soil erosion, educed soil fertility and water-holding capacity [4], [5]. Subramanian *et al*., noted that the increase in crop production costs is at a higher rate as a result of the leaching and volatilization of contaminated fertilizers [6]. DeRosa *et al*., reported that Nitrogen is lost to the environment at an estimated rate of 50–70% through fertilizer overutilization [7]. Also, Mason *et al*., [8] and Khan *et al*., noted that soil salinity and heavy metal contamination were caused by the uncontrolled use of agrochemicals containing heavy metals [9].

The development of sustainable agriculture methods that increase the yield of crops while promoting environmental sustainability must be the greatest concern. Food must be produced using sustainable farming methods that conserve water and reduce the use of chemical fertilizers and pesticides [10]. While the use of chemical fertilizers cannot completely jettisoned, other agricultural strategies can be integrated into them to have a positive impact and reduce the negative impact. As plants undergo various stresses that reduce their growth and yield in their natural habitats, environmentally friendly strategies are needed to reduce stress and increase crop yields [11], [12]. Both expanding the area under cultivation and raising agricultural output can help achieve this. The earlier approach, which uses biofertilizers, is more appropriate. Biofertilizers not only enhance the quality of the soil but also release polysaccharides and plant hormones that promote better plant growth. They can impede the development and proliferation of several plant-pathogenic bacteria. Plant growth-promoting rhizobacteria (PGPR) are thought to promote plant growth, as one of the most appropriate and environmentally friendly ways to boost crop yields when used as biofertilizers.

Plant Growth Promoting Rhizobacteria (PGPR) is essential for plant growth. PGPR produces three products: solubilizing phosphate, indole acetic acid, and amino-cyclopropane-1-carboxylate (ACC). As well as increasing resistance to adverse environmental conditions, they also help maintain a healthy environment [13]. The plants are stimulated to grow in different ways, both directly and indirectly. Nitrogen fixation, siderophore generation, phytohormones, exopolysaccharide synthesis, and phosphorus and potassium solubilization are examples of direct methods. Plants that receive their rhizosphere inoculation become either stress-resistant or stress-tolerant. Utilizing them can help reduce reliance on synthetic fertilizers [14]. Biofertilizers confer tolerance or resistance to biotic stresses in plants improving crop health and yield, while reducing the need for chemical pesticides [15]–[17]. Research by Igiehon and Babalola [18] showed that in comparison to untreated plants under drought stress, biofertilizer significantly raised fresh pod weight, pod number, and seed weight. Under abiotic stress, biofertilizers have also been shown to enhance wheat germination and morphological characteristics [19]. In addition, it has been shown that PGPR inoculation improves relative water content, decreases electrolyte leakage, and increases proline synthesis in soybean and wheat [20], [21].

Nanobiofertilizers (NBF) offer a promising solution for agricultural challenges. They enhance nutrient transfer, boost yields, and are eco-friendly compared to bulk chemical fertilizers. NBFs help plants resist stresses, and their absorption method varies based on application and particle properties. In comparison to chemical fertilizers, biofertilizers such as rhizobia bacteria that fix nitrogen, phosphate-solubilizing bacteria, and mycorrhizae that dissolve phosphate better can improve nutrient cycling, availability, and absorption [22]. Induced systemic tolerance, nitrogen fixation, and phosphorus solubilization are just some of the processes done by biofertilizers to improve soil quality [23]. Agriculture produces greenhouse gases, but biofertilizers can offset them through efficient carbon and nitrogen cycling. The adoption of these practices is crucial for regenerative agriculture and climate resilience [24].

2 Nanofertilizer

In agricultural production, various types of conventional fertilizers are used, including nitrogen fertilizers such as urea, ammonium nitrates, ammonium sulfates, and calcium ammonium nitrates. Nitrogen is essential for plant growth, so these fertilizers are widely used to replenish soil nitrogen levels [25]. Phosphate-based fertilizers can be classified into three types: superphosphates, triple superphosphates, and ammonium phosphates. Phosphorus is essential for the growth of roots, flowers, and seeds. According to Cordell and White, 75–90% of phosphate rocks are utilized in the production of fertilizers [26]. Potassium fertilizers come in three main forms: potash, sulfate of potash, and nitrate of potash. They are known to enhance drought resistance and crop quality [27]. Nanofertilizers (NFs) are intelligently applied nanoparticles (NPs) that contain macro and micronutrients and are used to supply nutrients to crops. There are three ways to supply nutrients to crops. As an alternative, the nutrient may be encapsulated as nanoscale-sized particles or emulsions, encapsulated within nanotubes or porous materials, or encapsulated in a thin layer of protective polymer film. Nano-fertilizers are believed to be more effective than polymer-coated fertilizers, which have shown little improvement over the last decade, due to their enormous surface area to volume ratio. Nanofertilizers are environmentally friendly, enhance soil fertility, increase yields, promote seed germination, and improve nutrient utilization. Therefore, nanofertilizers are considered a viable and promising replacement for synthetic fertilizers [28]. They are advantageous for crops as they improve fertilizer efficiency. In recent years, there has been an increase in interest in using nanoporous zeolites in farming due to public concerns about chemical fertilizers adversely affecting the agroecosystem [29].

A sustainable alternative to traditional synthetic fertilization techniques has been developed by synthesizing and developing NFs [30]. Bhattacharya *et al*., suggest that a balanced application of NPK fertilizer along with other essential elements, such as S, Zn, B, and Mo can increase the pulse grain yields significantly in red and lateritic soils. This approach can prevent low yields that are often observed due to the lack of necessary nutrients [31]. After adequate application of NPK fertilization, the yield of green and black gram increased by 13% and 38%, respectively. Liu *et al*., discovered that polystyrene, an organic material intercalated in kaolinite clay layers, forms a cementing of nano- and sub-nano composites. These composites can regulate nutrient release from the fertilizer capsule [32]. Thus, nanoparticles could be employed to control nutrient delivery through membranes within cells. Subramanian *et al*., suggests significant nitrogen release from fertilizer granules can be controlled using nanofertilizers and nanocomposites. This approach can increase nutrient usage while also preventing nutrient-rich ions from being absorbed or diffused into the environment [6]. Rahale [33] recently studied the nutrient release pattern of nitrogen-carrying nanofertilizer formulations. The findings indicate that nitrogen can be released for a longer period (> 1000 h) from fertilizer formulations based on nanoclay, such as zeolite and montmorillonite, which have dimensions of 30 to 40 nm, as compared to traditional fertilizers that have a release period (< 500 h). For the plant to absorb the nutrients from the fertilizer effectively, it is important to release the nutrients only at the right time. This can be done by keeping the nutrients separate from the soil, water, and microbes. By doing so, the nutrients will not change into forms that plants cannot use. Instead, they will be released at the precise moment when the plant can readily absorb them. To increase crop yield and the effectiveness of nutrient utilization, nanofertilizers can be incorporated with nanomaterials. The use of double-hydroxide nanocomposites with layers of zinc and aluminium has allowed for the controlled release of chemicals for plant development. Fertilizers integrated into cochleate nanotubes have been shown to increase yields [34]–[36]. To increase crop productivity and improve nitrogen use efficiency (NUE), researchers have explored the use of urease enzymes embedded in nanoporous silica to regulate the release of nitrogen caused by urea hydrolysis [37]. While this approach shows promise, it lacks mechanisms to detect and adapt to changes in soil nitrogen levels and plant demands. However, the development of functional nanoscale devices and films [38] offers potential solutions to this problem.

Nanotechnology has the potential to enhance fertilizer performance in various ways, such as the addition of titanium dioxide in nanosize as a bactericidal ingredient due to its photocatalytic properties. Furthermore, titanium dioxide has the potential to enhance agricultural productivity through nitrogen gas photoreduction [39]. The latest technology for delivering mineral nutrients to crops is biosynthesized NFs. One major benefit would be precise control of particle shape through biological processes [40]. It has been discovered that certain bacteria can produce natural fertilizers called NPs or microbial inoculants as a byproduct of their metabolic processes. These biological fertilizers may have been produced unintentionally through the bacteria' metabolic activity for generating energy using anabolic and catabolic reactions. This finding sheds light on the potential benefits of using bacteria to produce natural fertilizers [41], [42]. It is important to note that a variety of microbes have been employed extensively to produce microbial inoculants and NPs.

One effective method for promoting crop yields while maintaining agro-environmental sustainability is by using nanobiofertilizers a combination of nano and biofertilizers [14]. These NBFs can help ensure the world's ever-growing population's access to food. Bio-inoculating NPs with biofertilizers can improve plant development even in challenging environmental conditions as evidenced by studies [43]. To produce nanoparticles (NPs), it is important to choose the most efficient microorganisms based on their growth rate, enzyme output, and metabolic pathways [44]. A variety of bioresources can be used for this process, including algae, yeasts, bacteria, viruses, and fungi. These microorganisms are capable of producing metallic nanoparticles (MNPs) [45]. In the synthesis of nanoparticles (NPs), various components, such as proteins, polysaccharides and enzymes are used as stabilizing and reducing agents. These components can be in their crude form, unprocessed cell preparations, unpurified microorganism-derived enzymes or whole-cell microorganisms. The bioreduction process, which involves co-enzymes like FAD, NADH, and NADPH, is the main process used to produce NPs [45]. When producing NPs, there are several processes involved. The collection of microbial biomass is the first step in the biosynthesis process which should be done carefully to avoid unwanted reactions caused by residua nutrients and metabolites. During the scaling-up process, it is crucial to optimize the production rate and product yield by adjusting factors such as production time, pH, and temperature. These factors are essential for ensuring high-quality output [9]. In the production of environmentally friendly nanobiofertilizers, extracellular enzymes found in microbes are utilized to convert the appropriate salts into nanoparticles (NPs) [46]. Furthermore, by retaining soil moisture and accumulating together soil particles and other biologically significant elements, organic polymers are essential to ecosystems [47]. The formation of biofilms, which protect cells from a harsh environment, and cell adhesion and aggregation are also dependent on extracellular polymeric substances (EPS) [48].

3 Nanotechnology Applications in Agriculture

Nanotechnology involves manipulating individual atoms, molecules, or molecular clusters to create materials and devices with entirely new or vastly different properties. This technology presents an opportunity for novel applications in agriculture, forestry, and ecology, owing to the development of new nanodevices and nanomaterials. Nanoparticles (NPs) are materials that have two dimensions and a size range of 1 to 100 nm [49], [50]. Nanotechnology can be used to deliver certain compounds, like insecticides and fertilizers, to agricultural fields. However, the efficiency of the compounds' absorption and utilization, as well as their influence on plant metabolism, varies among species. A recent study investigated the effects of chemical nanoparticles, such as Al, Ce, La, and Ti, as well as metallic nanofertilizers including Cu, Mn, Zn, and Fe, on plants [51]. Although nanotechnology has been extensively applied in the health and medical sciences, its application in agriculture and food systems is relatively new and predicted to expand quickly. Nanotechnology is the study of materials with unique properties at the nanometric level. It has the potential to revolutionize a variety of industries, such as food, energy conversion, environmental engineering, biological processes, water resources, safety and security [52]. Theoretical possibilities are increasingly being turned into practical applications. Enhancement of plant and animal genetics [53], [54] can be achieved with this technology, which also facilitates the delivery of genes and drugs to plants and animals [55]. Possible applications of nanotechnology in agriculture include precision farming, early detection of food-borne diseases and pollutants, and sustainable management of natural resources.

The advancements in molecular therapy and disease detection tools have the potential to revolutionize the food and agricultural industries. Nanotechnology can be used to optimize nutrient uptake by plants, time the delivery of nitrogen with crop uptake, and fight agricultural pathogens with the help of intelligent sensors and delivery systems. Additionally, nanostructured catalysts can make insecticides and herbicides more effective, enabling the use of smaller dosages in the future. Moreover, nanotechnology has the potential to aid in environmental conservation by reducing pollution and purifying existing contaminants using filters catalysts, and alternative energy sources [56]–[58]. Buentello *et al.*, suggest that nanotechnology can enhance agricultural production in underdeveloped nations, making it the second most crucial sector in accomplishing the Millennium Development Goals. The priority is energy conversion and storage, while water treatment is ranked third and also requires attention [59]. Smart sensors, when combined with precision farming, can significantly enhance crop productivity by giving farmers quick access to reliable information to aid in decision-making. In the future, intelligent agricultural systems might be developed through nanoscale devices with specific characteristics. These tools could detect issues with plant health before they are visible to farmers, allowing for timely corrective measures to be taken. There is a lack of scientific research on a new technology known as nano fertilizers, which can match crop requirements by improving the efficiency of conventional fertilizers. The efficiency of conventional fertilizers has remained stagnant for many decades. These nano fertilizers are made up of substrates with nanodimensions ranging from 1–100 nm and have a large surface area that can hold a lot of nutrients and release them gradually and steadily without causing any negative effects. They may be able to customize fertilizer inputs to crop requirements. The development of zeolite-based nanofertilizers is gaining economic attention due to the increased knowledge of nanofertilizers and the availability of low-cost natural zeolites worldwide. According to a study by Chuprova *et al.*, the use of zeolite fertilizers can be beneficial to the mobile humus contents of Chernozem and the biological productivity of maize [60]. In another study, a proprietary nano-composite containing mannose, amino acids, micronutrients, P, K, and N was found to improve the nutrient uptake and utilization of grain crops [61]. Table 1 displays the various types of nanomaterials used in crop cultivation. The use of nanotechnology can improve the effectiveness of both natural and supplementary nutrient sources, thereby improving agriculture. Nanotechnology is expected to become a significant economic force that benefits farmers and consumers while minimizing environmental harm. The negative impact of chemical fertilizers on agroecosystems has prompted an increasing awareness in the agricultural industry, which has led to a greater interest in nanoporous zeolites.

Table 1: Nanomaterials on crop growth as a supplement

Nutrient	Crops	Mode of Application	Nanomaterials	Results	Ref.
Mg	Peaches (*Prunus persica*)	Using an automated sprayer, ten trees per treatment received 500 kg/ha of diluted Mg to fertilize their leaves.	Magnesium particles < 900 nm	A reduction in particle size to less than 900 nm caused a decrease in the amount of Mg found in various parts of peach leaves, influencing the leaf side, front, back and petiole.	[62]
N	Lettuce plant (*Lactuca sativa*)	A mixture of bulk-size nitrogen (b-N), and (n-N) on both surface and drip irrigation use nano nitrogen.	Nano nitrogen (n-N)	In addition to improving nitrogen absorption and utilization efficiency, the use of 25% n-N foliar spraying combined with 75% n-N drip irrigation had a significant effect on yield, crude protein, and plant biomass.	[63]
Fe	Wheat crops (*Triticum aestivum*)	Foliar application of different iron sources such as FeSO4, FeEDDHA, and nZVI at a concentration of 0.2% has been studied.	nZVI	nZVI and urea were added to grains, and the content of Fe increased greatly.	[64]
K	Maize (*Zea mays*)	With foliar spraying and irrigation at 0.03 MPa, 0.60 MPa, and 1.2 MPa, PNS concentrations of 0, 100, and 200 ppm were sprayed and irrigated at 0, 100, and 200 ppm, respectively.	PNS (potassium nanosilica)	PNS increased the amount of inorganic nutrients in seeds stressed by drought. Drought stress was less severe when PNS was applied.	[65]
Cu	Cowpea (*Vigna unguiculata*)	The concentration of nano-Cu in the plants was varied daily for 65 days at 0, 125, 500, and 1000 mg/kg.	Nano-Cu of 25 or 60–80 nm	A higher absorption effect was observed for nanocopper than for control copper	[66]

Table 1: Nanomaterials on crop growth as a supplement (*Continued*)

Nutrient	Crops	Mode of Application	Nanomaterials	Results	Ref.
Fe	Common purslane (*Portulaca oleracea* L.)	A foliar application of Fe at 0.1 and 0.2% (w/v) was applied to Fe ALA3 and Fe-EDDHA.	Fe (III)-aminolevulinic acid nano chelate.	Purslane plants benefit from Fe (III)-aminolevulinic acid nanochelates capable of increasing the levels of Fe, Zn, N, Mg, Ca, and K in the foliar tissues.	[67]
Mn	Wheat (*Triticum aestivum* L)	Spraying of foliage and cultivating soil.	Nanoparticle of manganese	Branches and grains of plants exposed to leaves contained more manganese, while their soil contained less phosphorus, potassium, and manganese.	[68]
P	Lettuce (*Lactuca sativa* L.)	Greenhouse lighting is provided by natural sources. NH_4NO_3 and P per kilogram of soil provide 200 mg of basal nitrogen (from NH_4NO_3).	Nanohydroxyapatite (NHA) synthesized	Compared to H_3PO_4-P (soluble phosphorus), NHA is more beneficial for the growth of lettuce plants and can increase the dry weight of the plants.	[69]
Zn	Maize (*Zea mays* L.)	Suspension n-ZnO particles (0, 0.05 ppm, 0.5 ppm) were used, and the ZnSO4 concentration was kept constant concerning the control group.	Nanoparticles of zinc oxide	Plant dry weight increased after the application of nanozinc. The Zn content of the branches increased to 37 ppm and the plant's height increased to 59.8 cm compared with the control. The root length also increased by 1.6 times higher than the control group.	[70]
Ca	Thankan (*Citrus tankan Hayata*)	Field testing. 26% SC, 95% WP, and CK	Carbonate of calcium nanoparticles	The K content may be affected by excessive Ca spraying, when compared to the control group, Ca concentration in leaves treated with nano-Ca increased 13 times.	[71]
P	Soybean (*Glycine max*)	Fertilizing strategies include using tap water, synthetic fertilizer containing standard P, synthetic fertilizer lacking P, and synthetic fertilizer including NHA.	Synthetic nanoparticles of apatite	The growth rate and yield of soybean seeds were increased by 20.4% through synthetic apatite nanoparticles. The biomass above and below ground increased by 18.2 and 41.2% respectively.	[72]
Zn	Peanut (*Arachis hypogaea*)	Suspensions of ZnO were conducted in 400, 1000, and 2000 parts per million concentrations.	Zinc oxide on a nanoscale (ZnO).	Plants gain Zn from ZnO nanoparticles, which enhances pod yield, root length, branch dry weight, and seed germination. Plant growth is stunted by a high concentration.	[73]
N	Italian ryegrass (*Lolium multiflorum*)	Given treatment with nitrogen at rates of 0, 60, 120, and 180 kg/ha on soil that is sandy loam	Clinoptilolite-NH_4, Clinoptilolite-urea	Nitrogen uptake efficiency and yield both showed notable improvements.	[74]

Nanotechnology has made great progress and this has resulted in increased use of nanomaterials in agriculture. Precision farming, which has replaced traditional farming methods, has been made possible through the use of nanotool technology advancements. Although the use of fertilizers and pesticides in conventional farming methods has led to increased food output, the soil's fertility has significantly decreased. This is because 50–70% of traditional fertilizers and pesticides may become incorporated into the soil through processes like leaching of soluble forms, biotransformation, and mineralization of organic forms into plant-available nutrients [2], [75]. The excessive amounts that do not reach their biological targets accumulate over time in the soil, water and air. This leads to environmental contamination and public health hazards. In addition to contributing to environmental pollution, the movement and transformation of chemicals in the environment as well as their residues in living organisms can harm human health. Nonetheless, things have greatly improved with the invention of nanomaterials, especially nanopesticides and nanofertilizers. These substances improve soil quality, nutrition, and crop protection during growth, which not only boosts the effectiveness of agricultural chemicals but also increases the nutritional value of agricultural production [76]. Biofertilizers are formulations or preparations that contain microorganisms. They help to improve soil productivity in three ways: By solubilizing phosphorus, by fixing nitrogen from the atmosphere and by synthesizing chemicals that promote growth and boost plant development [77]–[79]. To enhance plant growth, nanostructures or nanoparticles are combined with biofertilizers to create nanobiofertilizers [80]. A combination of microorganisms, proteins, enzymes, and nanoparticles creates nanobiofertilizers, which can significantly reduce heavy metals which makes them ideal for producing various metal nanoparticles, and they have been widely used for this purpose. Several bacterial species have developed defense mechanisms to withstand harsh environmental conditions, including the toxicity of nanomaterials. Due to their abundance and adaptability, these bacteria are well-suited for creating nanoparticles. This has been documented in [81], [82]. Asmathunisha and Kathiresan [83] suggest that these bacteria are a viable option for nanoparticle synthesis. The development of nanobiofertilizers involves several crucial aspects, such as the interactions between microorganisms and nanoparticles, the delivery of biofertilizers, and their shelf-life. Studies have shown that the use of gold nanoparticles and rhizobacteria can have a positive effect on plant growth [84], [85]. It is not advisable to use silver nanoparticles together with biofertilizers, as they may harm microorganisms by altering their cell membrane structure and activity [46]. Biofertilizers have a limited shelf life, which reduces their effectiveness. However, we can improve their stability and usefulness by incorporating nanoparticles. Nanomaterials can help biofertilizers withstand heat, UV inactivation, and desiccation. For instance, polymeric nanoparticle coatings can be employed to produce formulations that are resistant to drying. Ultimately, this will prolong the shelf life of biofertilizers [80], [86].

Biofertilizers can be more effectively delivered to soil and plants through the use of nanomaterials. Research has shown that hydrophobic silica nanoparticles, when applied in a water-in-oil emulsion, can enhance product distribution and prolong shelf life by reducing desiccation [87]. This innovation resulted in better and more gradual nutrient release, leading to lower fertilizer manufacturing costs and reduced fertilizer usage for plants. The nutrients' gradual release improves the product's efficiency. To further enhance the potency of the product, biofertilizers can be encapsulated with nanomaterials. Encapsulation can be done using nanomaterials, such as zeolite, chitosan, polymers, and metallic and metal-oxide complexes, along with starch and non-toxic, such as calcium alginate. This method speeds up the growth of some bacterial strains [15], [88] and provides more information about the encapsulation process. Figure 1 shows the role of nanobiofertilizers in sustainable agriculture.

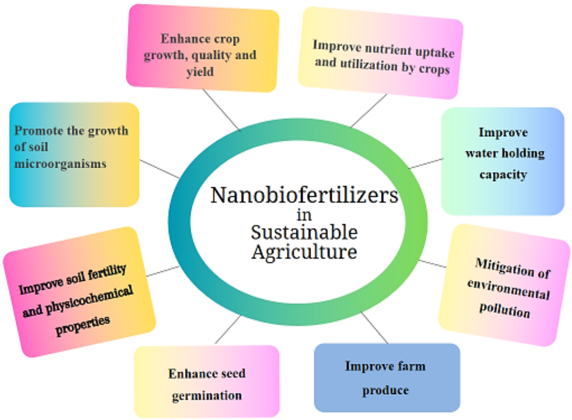

Figure 1: Potential role of nanobiofertilizers in sustainable agriculture.

5 Formulation and Production of Nanobiofertilizer

Biofertilizer containing nutrients and microorganisms that stimulate plant growth is nanoencapsulated in polymers to form nanobiofertilizers [89]. The production of nanobiofertilizers can be achieved through different methods and techniques. This depends on whether nanoparticles encapsulate biofertilizers or attach themselves to nanoparticles. However, due to the small size of nanoscale structures, the production of nanobiofertilizers poses a significant challenge. To transport more microbes from fermentation operations to plants, macroscopic filters with radially oriented carbon nanotube walls show promise [80], [90]. These filters can absorb *Escherichia coli*, making them effective [80]. There are various methods used to create nanobiofertilizers, including encapsulation, which involves enclosing microorganisms and nutrients in protective nanoparticles or capsules made of different materials, such as polysaccharides, silica, and polymers [91]. Common encapsulation methods include freeze drying, emulsion, and extrusion, which create nanosized particles to safeguard bacteria and nutrients from degradation [92]. Bioconjugation is another technique that chemically immobilizes microbes and nutrients on the surfaces of nanoparticles, such as iron, gold, silica, and titanium dioxide, by attaching them directly to their surfaces. The process of conjugating nanoparticles to surfaces is achieved through cross-linking agents [93]. Nanoparticle entrapment is another method that uses cage-like nanoparticle structures or porous nanomaterial networks synthesized using techniques, such as sol-gel trapping in silica gel to physically trap microorganisms in biofertilizers [94]. Complex coacervation is yet another technique that utilizes oppositely charged nutrient polymers/proteins to form a polymeric shell via electrostatic/hydrophobic interactions around the core biofertilizer solution [95]. It is clear that nanobiofertilizers have the potential to overcome some of the limitations in biofertilizers, but more research and development are still necessary to make this technology a reality.

To prepare nanobiofertilizers, the inoculum is combined with either a liquid or solid carrier. Solid carriers can serve a dual purpose of biologically breaking down organic pollutants and increasing the absorption of nutrients like phosphorus by plants. Additionally, the use of solid carrier materials can enhance plants' resistance to soil-borne diseases [96]. Biofertilizers can be transported using different organic and inorganic components. Some examples of these components include alginate beads, talc, press mud, vermiculite, charcoal, perlite, and peat compositions. For a biofertilizer carrier, it is recommended to have a minimum of 10 million viable cells of a particular strain per gram. However, liquid inoculants have been reported to offer several benefits such as requiring less inoculant, being easier to produce, sterilizing completely to avoid contamination, and being compatible with modern agricultural machinery. They also support more cells for a longer time, do not require a sticker material, and can even reduce stress. [97]. There are various methods of using nanobiofertilizers. Oil-dried bacteria, lyophilized microbial cultures, capsule-based carriers like contaminated spores and cells in capsules, plant waste products like composts, wheat bran, soybean meal, peanut oil, and farmyard manure, and inert materials like alginate beads, poly-acrylamide gels, vermiculite, powdered rock phosphate, and calcium sulfate are a few examples of these methods [98].

Nanobiofertilizers are a promising solution for improving crop yield and soil health. They slowly release nutrients, enhancing the plants' efficiency in using nutrients. The use of biofertilizers has been found to have long-lasting effects on the chemical, biological, and physical characteristics of soil. To further enhance their efficiency, biofertilizers can be encapsulated in nanoparticles to create a nanobiofertilizer. By using this technique, the bacterial strains are protected from mechanical stress and can release nutrients gradually. Encapsulation involves containing biofertilizer cells in a nanoparticle capsule made of non-toxic and biodegradable substances such as starch and calcium alginate. Studies have shown that using starch in the capsule effectively stimulates the growth of bacterial strains [15], [99]. The formulation of nanobiofertilizers involves three crucial steps: 1) culturing the biofertilizer, 2) encasing it in nanoparticles, and 3) assessing its quality, efficacy, purity, and shelf life [100]. To create a microcapsule form of nanobiofertilizer, a suspension of PGPR can be combined in a 2:1 ratio with 1.5% sodium alginate, 3% starch, and 4% bentonite. For the final step in the synthesis, the mixture is encapsulated with a calcium chloride solution that crosslinks between them. After that, sterile distilled water is used to clean the microcapsules that were produced [101]. The combination of salicylic acid and nanoparticles has resulted in the creation of nanobiofertilizers. This technique involves blending the biofertilizer with salicylic acid (at 1.5 mM concentration), ZnONPs (at 1 μg/mL concentration), and sodium alginate (at 2% concentration). After that, a 3% calcium chloride solution was applied to the solution which resulted in the formation of 1-mm beads. These beads are air-dried and kept in an incubator at 4 °C [100]. Figure 2 illustrates the process of formulating nanobiofertilizer. The reports suggest that mixing organic waste with nanoparticles can produce an effective nanobiofertilizer that enhances the fertility of the soil. Organic wastes, such as kitchen scraps, flowers, and cow manure,

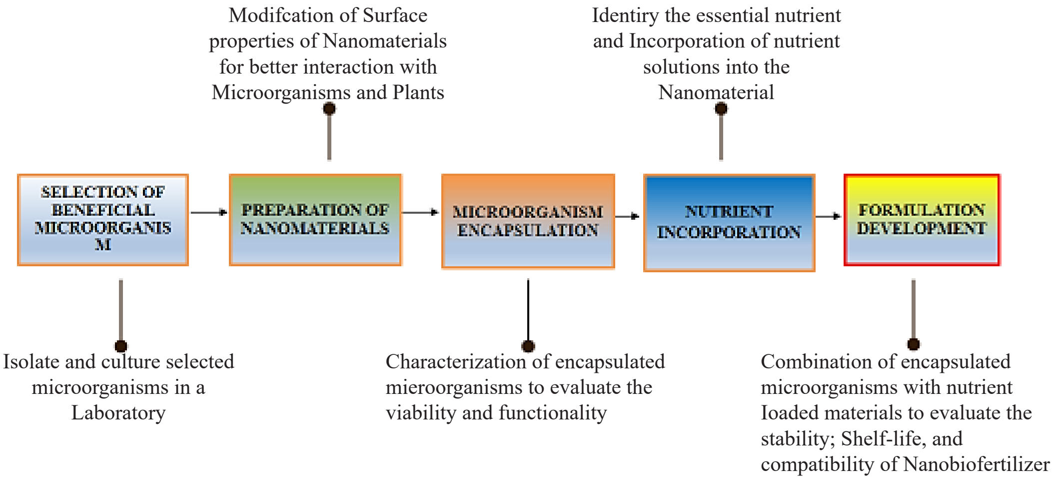

Figure 2: Formulation process in the production of Nanobiofertilizer.

were broken into small pieces, soaked in water to remove impurities, and then subjected to pyrolysis or decomposition to produce nanobiofertilizer. Following that, the waste that had partially decomposed or been pyrolyzed was combined with nanoparticles. This process results in the production of a substance that can be utilized to improve soil fertility [102].

6 Nanobiofertilizers Mode of Operation

Nanobiofertilizers could be a possible solution to the current issues of nutritional and environmental safety. These functional nanoparticles are biologically generated, encapsulated, water-soluble fungal proteins that can enter plant tissues through the stomata or vascular systems. It is believed that the stomata pathway is particularly effective due to its large size exclusion limit and high transit velocity [103]. These nanoparticles are environmentally friendly, water-soluble, reasonably stable, and easy to handle downstream [104]. They have the potential to enhance metabolic processes, leading to increased crop yield. Microorganisms can be used to create biofertilizers and nanobiofertilizers. Research into the synthesis of nanoparticles using biological systems is also ongoing, as these particles have potential applications in nanomedicine [30]. When nanobiofertilizers are injected into the rhizosphere, they enter the vascular tissue through the apoplastic route, allowing them to reach the center and core of the root. To bypass the Casparian strip barrier, the symplastic route is used. Alternatively, when applied to the phyllosphere, nano-biofertilizers follow the phloem translocation route. The use of silicon nanocomposites enlarges the chloroplast and grana size, as well as the amount of chlorophyll, which helps to improve the photosynthetic capacity of plants [43]. Stress, whether caused by living organisms (biotic) or non-living factors (abiotic), can have a detrimental impact on plant growth. This is because it causes damage to the DNA by increasing the generation of reactive oxygen species (ROS) and reducing the chlorophyll content. The use of nanobiofertilizers is a promising solution as they mimic the actions of antioxidant enzymes, such as nanoenzymes, which can help to eliminate oxidative stress. Additionally, these particles can interact with harmful heavy metals, reducing their impact based on factors, such as surface charge, area, and size [105].

Nanobiofertilizers are a combination of biofertilizers and nanofertilizers that offer various advantages and applications. However, a higher concentration of nanomaterial can be harmful to plants, leading to phytotoxicity. To avoid this, it's important to consider the use of certain PGPRs that can help mitigate these negative effects and protect against the continuing presence of nanoparticles in the rhizosphere, Azotobacter salinestris [106]. Microorganisms, for instance, produce extracellular polymeric substances (EPS) that facilitate the efficient transport of nanoparticles and the formation of metal-EPS complexes [107]. As a result, these EPSs play a crucial role in reducing the harmful effects associated with high concentrations of certain

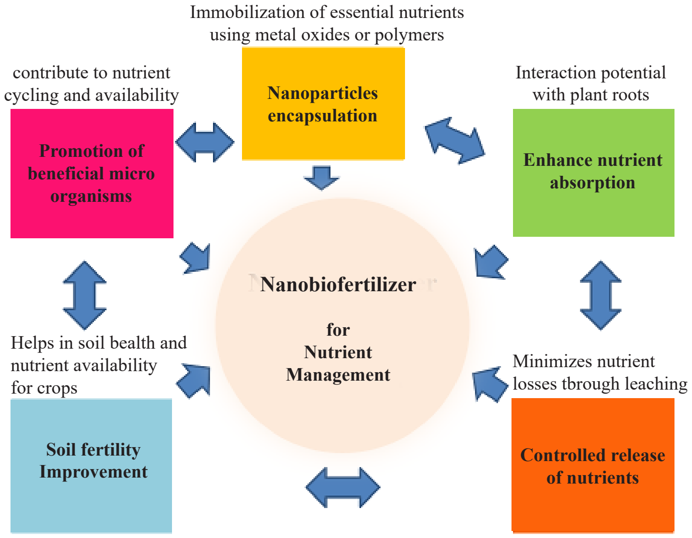

Figure 3: Mode of operation of nanobiofertilizer for a nutrient cycle.

nanoparticles. Figure 3 illustrates the benefits of using nanobiofertilizers for nutrient cycling. To optimize the advantages of nanobiofertilizers, it is possible to enhance their plant growth-promoting qualities, increase their bioavailability, and improve nutrient use efficiency. Additionally, nanobiofertilizers can boost the synthesis of PGP compounds and secondary metabolites, enhance cell viability, prolong shelf life, and protect microbial inoculants from dehydration.

7 Improving Nanobiofertilizer Delivery Methods

To improve the use of fertilizers and prevent soil damage caused by excessive fertilizer application in agriculture, researchers are looking for ways to enhance plant growth-promoting fertilizers. Although traditional methods of applying fertilizer are still not very effective and result in a lot of wastage, the use of nanomaterials has shown to be more efficient. However, the use of nanomaterials needs to be limited to avoid negative impacts on the environment and public health [108]. To address this issue, a combination of PGPR and nanomaterials has been developed to create a nanobiofertilizer that gradually delivers customized nutrients to crops [109]. The lack of comprehensive knowledge about the interactions between nanoparticles, biofertilizer microflora, and plant systems has been hindering the large-scale development and implementation of nanobiofertilizer formulations [108]. There are two ways of applying nanofertilizers to crop plants: either together as a nano-biofertilizer or separately as individual nanofertilizers and biofertilizers [109]. When used on their own, nanoparticles can enhance various aspects of plant growth such as photosynthesis, carbon sequestration, seed germination, enzyme activity, and nitrogen fixation [110], [111]. For example, CuNPs and multiwalled carbon nanotubes have been utilized to improve plant development in crops like pigeon peas, soybeans, corn, and tomatoes [112]. Nanoparticles have been shown to enhance microbial growth when used at optimal concentrations, in addition to their direct effects. The improved growth rate and cell viability in harsh environments can be attributed to the induction of molecules and enzyme secretion from microbes, which reduces abiotic stress, increases surface area, promotes nodule development, and protects inoculants from dehydration. The application of ZnO-NPs resulted in a dose-dependent increase in the synthesis of PGPR siderophores, whereas the application of CuNPs increased the production of IAA [113]. These studies provide evidence of the impact of nanoparticles on microorganisms.

8 Nanobiofertilizer in Sustainable Agricultural Practices

The use of chemical fertilizers has been a common practice in agriculture for many years, but its excessive use has led to environmental toxicity and long residual action. To address this concern, scientists have been searching for a non-toxic, eco-friendly alternative to increase agricultural productivity without causing harmful side effects. Biofertilizers and nanofertilizers have become more popular than chemical fertilizers in recent years due to their safer impact on the environment [114]. Biofertilizers contain live, beneficial microorganisms, like phosphate-solubilizing bacteria, blue-green algae, Mycorrhizae, Azotobacter and Azospirillum. The microorganisms present in biofertilizers enhance the soil's microbial status, increase soil nutrient availability, and improve crop nutrient delivery, which in turn improves soil health, aeration, and biological nitrogen fixation [115]. Biofertilizers have some drawbacks, including short shelf life, high dose requirement for wide coverage, and vulnerability to desiccation [116]. Nanoparticle-based biofertilizer formulations have proven to be effective in solving various agricultural issues [42]. These formulations cover biofertilizers with nanoscale polymers containing nutrients and bacteria that promote plant growth, improving their shelf life and dispersion. Additionally, nanobiofertilizers release nutrients gradually and steadily without causing any unintentional loss, thus reducing application losses and financial costs. Using renewable and eco-friendly processes, they can enhance soil microbial populations, increase enzyme systems' activity, improve crop quality, and boost soil fertility. Furthermore, they can improve crop resistance to disease. The innovative approach of nano biotechnology is revolutionizing modern agriculture and contributing to the development of sustainable farming practices, ensuring food security, and promoting eco-safety [117], [118]. Nanoencapsulation technology could be a promising method for safeguarding biofertilizer components, such as PGPR, in enhancing their shelf life. This technique may also facilitate the controlled release of PGPR [119], gradually and consistently delivering nutrients to plants while avoiding unintentional wastage [109]. Nanobiofertilizer is an eco-sustainable and renewable method that has a major positive impact on farmers. It enhances nutrient release characteristics, and field performance, and lowers costs through cost reduction and application loss reduction. This method boosts the efficient utilization of macronutrients like N, P, and K, enhances the population of beneficial microorganisms in the soil, improves soil fertility, increases the activity of associated enzyme systems, makes it easier to produce higher-quality crop products, and increases crop resistance to diseases [120].

8.1 *Nanobiofertilizer role in enhancing crop growth and nutrient Status*

Nanobiofertilizers offer many benefits for soil and plant systems. To promote growth, the nutrients are supplied gradually and steadily to improve the nutritional quality of plants. To protect and deliver organic nutrients, they are enclosed in nanomaterials such as polymers, zeolite, and chitosan [121]. Adding nanoparticles to biofertilizer surfaces improves the stability of the nutrients, allowing for better interaction and active uptake by crops during various phases of growth [42]. This stability produces a gradual and consistent release of nutrients, which slows down the rate of fertilizer dissolution [122]. The bioorganic components of nanobiofertilizers, such as beneficial bacterial PGPR or fungal inoculants, enhance soil nutrient status through various mechanisms. Several mechanisms help plants absorb nutrients from the soil. These include the use of rhizobacteria to convert nitrogen from the air into a form that plants can use, the production of siderophores to make metal elements more easily available to plant roots, the solubilization of phosphorus through the production of phytohormones and the existence of specific bacterial and fungal strains [123], [124]. The combination of nanomaterial and biofertilizer enhances crop growth and quality attributes, according to research studies. Table 2 shows the effect of different nanobiofertilizers on different crops and the corresponding response on the crop. The use of nanobiofertilizer improves crop growth and quality due to its effects on plant features.

8.2 *Nanobiofertilizer for protecting crops*

Nanobiofertilizer not only enhances crop yield, nutritional value, shelf life, and water conservation but also acts as a resistance-inducing agent for strengthening plant defense against pests and diseases. A study conducted by Gatahi *et al.*, [125] revealed that nanobiofertilizer fought bacterial wilt disease caused by Ralstonia solanacearum in a pest-resistant manner in tomato crops. Similarly, Gouda *et al.*, investigated

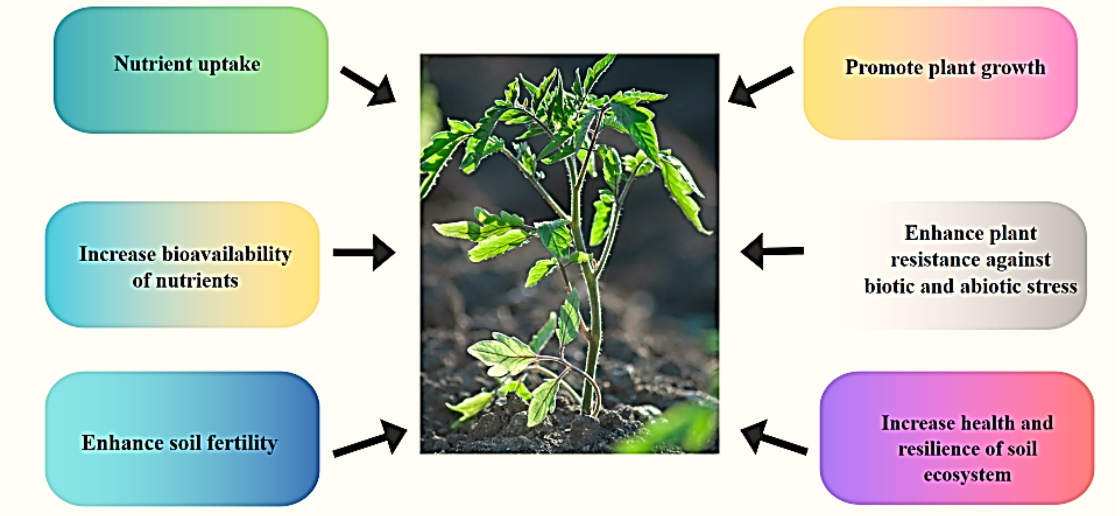

Figure 4: Nanobiofertilizer impact on enhancing plant growth and nutri-response observed in crops when applied.

the protective role of nanobiofertilizer containing PGPR (*Pseudomonas putida*, *Bacillus subtilis*, *Paenibacillus elgii*, and *Pseudomonas fluorescens*) against bacterial and fungal diseases in leguminous crops. They found that it played a protective role in defending these crops from various diseases [109]. Mishra and Kumar [126] conducted experiments to demonstrate that applying titanium nanoparticle-coated nanobiofertilizer increased the adhesion of beneficial bacteria to the roots of oilseed rape, which in turn protected the crop from harmful fungal infections. Additionally, Mukhopadhyay and De [127] found that using nanoclay coated biological agents containing Pseudomonas and Trichoderma spp. can help protect crops from abiotic stressors and manage fungal-nematode diseases in rabi crops.

8.3 *To improve the plant/soil system's nutritional quality*

Frequent use of chemical fertilizers can deplete the vital nutrients that are naturally present in rich soil. One of the main reasons for declining soil fertility is excessive soil acidity [128]. Low soil fertility and nutrient imbalance in crops can lead to reduced crop productivity and low food nutrition value, which farmers have to deal with daily [129]. Using nanobiofertilizer is an effective, affordable and sustainable way to deal with soil nutrient loss due to leaching, gasification, or competition with other species. It helps plants to better absorb and assimilate nutrients [130]. The nanoparticle coating of the biofertilizer releases nutrients slowly and synchronously according to crop demand. Additionally, Plant Growth Promoting Rhizobacteria (PGPR), a bioorganic component of the biofertilizer, aids in nitrogen-fixing, phosphate solubilizing, and restoring soil nutrient richness [131].

8.4 *To contribute to the morphological and physiological development of plants*

The use of nanobiofertilizers can significantly enhance crop development by promoting photosynthesis, increasing nutrient translocation to valuable parts of the plant, and improving nutrient absorption efficiency. This results in higher plant productivity and better-quality harvests. In a study by Dikshit *et al.*, [132], a nanobiofertilizer that encapsulated growth-promoting microorganisms such as Bacillus subtilis, Paenibacillus elgii, and Pseudomonas fluorescens within silver and gold nanoparticles was found to be highly effective in promoting crop growth in various crops. Additionally, a fertilizer containing neem cake and PGPR in a nanostructure was reported to increase germination potency and effectively supply nutrients to plants, thus improving agricultural productivity in leguminous crops [128]. Figure 4 shows the impact of nanobiofertilizers on crop yield and nutrient response.

Table 2: An overview of the impacts of several nanobiofertilizers

Country	Types of Crop	NanoBiofertilizers	Results	Ref.
Spain	*Triticum aestivum*	FeNPs and *Bacillus aryabhattai* RSO25	FeNPs alone efficiently increased wheat Fe biofortification via Fe spike accumulation	[133]
Iran and Russia	*Pistacia vera*	SiO_2 and Carbon nanotubes, *Bacillus velezensis* encapsulated in gelatin and sodium alginate microcapsules	Nano formulations act as biocontrol agents, protecting PGPRs from adverse environmental conditions	[134]
India	*Vigna unguiculata*	*Pseudomonas monteilii* in the rhizosphere and chitosan nanoparticles	Increased fresh weight, leaf count, and shoot length	[135]
Egypt	*Zea mays Linn*	PGPR and SiNPs	Increased maize yield and nutrients.	[136]
China	*Oryza sativa, Zea mays, Brassica nigra, Vigna radiata, Citrullus lanatus*	Fe_3O_4-NPs and *Chlorella* K01	Fe_3O_4 nanoparticles boosted the germination, growth and resistance of watermelon, rice, corn, mustard, and green grams against fungal pathogens.	[137]
Pakistan	*Oryza sativa*	Magnetite nanoparticles MNPs made of magnetite and *Bacillus sp.* MR-1/2	Rice cultivated in low-water conditions undergoes less oxidative stress due to higher N uptake.	[138]
Egypt and Saudi Arabia	*Zea mays*: maize hybrid 'Pioneer SC 30N11'	Nanopotassium fertilizer, compost manure and humic acid	Improved quality and yield of maize.	[139]
Iran	*Zea mays*	Iron nanooxide, *Pseudomonas* and *Mycorrhiza*	Both under normal circumstances and during drought stress, a biofertilizer containing *Pseudomonas* and *Mycorrhiza* enhanced yield. Iron nanooxide had no noticeable benefit.	[140]
India	*Zea mays*	AgNPs and *Bacillus cereus* LPR2	Enhanced growth of plants and LPR2 significantly suppressed the growth of harmful fungal pathogens.	[141]
India	Some horticultural crops of *Fabaceae*	Au nanoparticles + rhizobacteria	Tests conducted in vitro showed excellent growth stimulation with this nanobiofertilizer.	[120]
India	*Cajanus cajan*	*Piriformospora indica* and CuNPs	Optimal health and energy for seedlings.	[142]
India	*Cicer arietinum*	AgNPs utilizing the BHU-S7 strain of *Stenotrophomonas*	Severely affected pathogenic propagules, reducing the germination of conidia and sclerotia.	[116]
Iran	*Tritico secale*	Nano titanium + biofertilizer containing *Azorhizobium*	Application of $nTiO_2$ + *azorhizobium* to cadmium (Cd)-stressed triticale increased: grain yield, grain weight, chlorophyll content, leaf and seed Cd, and responsive $nTiO_2$ alone. An effective mitigating effect against Cd stress.	[143]
China	*Triticum aestivum*	Bio-based fertilizer with a polyurethane coating containing nanosilica	Greatly enhances controlled-release qualities by acting as a superhydrophobic controlled-release fertilizer.	[144]
India	*Vigna raidata* L.	Neem cake, PGPR, potash fertilizer and nano phosphate	The application of nanobiofertilizer improved Vigna radiata's germination and biochemical characteristics, which promoted crop yield and quality.	[124]
India	*Vigna raidata* L.	Nano-NPK fertilizer + neem cake, plant growth promoting rhizobacteria	Enhanced seed vigor index through accelerated germination-related enzyme activity.	[145]

Table 2: An overview of the impacts of several nanobiofertilizers (*Continued*)

Country	Types of Crop	NanoBiofertilizers	Results	Ref.
India	*Cajanus cajan* L.	Copper nanoparticles and plant growth-promoting fungus (*Piriformospora indica*)	Cu nanoparticles + *P. indica* improved the vitality and growth of *C. cajan* more than Cu alone.	[142]
India	*Solanum lycopersicum* L., *Brassica junceae* L., *Trigonella foenumgraecum* L.	Chitosan nanocomposite + chicken feather as bioorganic compound	Adding small amounts of these nano-biocomposites can improve the plant's nutrient intake	[146]
Iran	Ornamental plant Buxus *hyrcana* Pojark	Bacteria-containing biological nanofertilizer	2.00 g/l bionanofertilizer sprayed directly on ornamental plants and a 1.80 g/pot drench was developed as an effective treatment for Buxus hyrcana Pojark proliferation.	[147]
Iran	Forage sorghum (Speed feed hybrid)	Biofertilizers (azetobarvar 1 + phosphorbarvar 2) + chelated nano fertilizers	Chlorophyll a, b, carotenoids, and carbohydrates were found in the highest concentrations through the use of combined biofertilizers.	[148]
Iran	*Zea maize* L.	Nano-Zn + biofertilizer	Increased maize grain yield production after 7 day application of nanobiofertilizer.	[149]
Lithuania	*Beta vulgaris* L.	Bioorganic nanofertilizer “Nagro”	Development, productivity, and quality factors for sugar beets can be significantly optimized.	[150]
Kenya	*Lycopersicum esculentum* L.	Chitosan immobilized silica nanocomposites + Biocontrol agents (*Bacillus subtilis*, *Gomus mossease*, *Trichoderma viride*)	Increase tomato varieties' resistance to *Ralstonia solanacearum*-induced bacterial wilt.	[125]
Sweden	*Brassica napus*	Titania nanoparticles and *Bacillus amyloliquefaciens* UCMB5113	Protection against infection and *Bacillus amyloliquefaciens* UCMB5113's root adhesion was improved.	[151]
India	*Rabi crops*	Nanoclay polymer composite + biological agents *Trichoderma harzianum*	Significantly promotes rainfed agriculture by improving water retention, nutrient use efficiency, productivity, and disease control.	[127]
Turkey	*Vitis vinifera* L.	Nanofertilizer + sea weed (Ascophyllum nodosum)	A nano-Ca-based fertilizer had a significant impact on vine development, yield, berry quality characteristics, and leaf nutrients, and it would be recommended for use in minimizing the adverse effects of abiotic stress for long-term grape production.	[152]
Iran	*Triticum aestivum* L.	Nanofertilizers of Fe, Zn and Mn + biofertilizers containing Azotobacter and *Pseudomonas* bacteria	Nanobiofertilizers boost crop growth and yield by increasing spike and seed metrics, as well as growing period length.	[153]
Iran	*Solanum tuberosum* L.	Nanosilver and nitroxin biofertilizer	By combining nitroxin biofertilizer with nanosilver, tuber output can be increased while mineral nitrogen fertilizer usage is reduced to half.	[154]
Iran	*Nigella sativa* L.	Nanofertilizer + humic acid	The performance of N. sativa is improved by mixing these fertilizers with the nutrient content and physiological impacts.	[155]
India	*V. mungo*	Nano-Zn, Nano Cu + Azospirillum	Enhance 50% in grain yield	[156]
China	*Pisum sativum*	Nanorods ZnO +fulvic acid (FA) and ammonium phosphate	Induced strong roots and improved yield. 119% increase of Pisum sativum, uptake of seedling increase of P and Zn by 54 and 400% respectively.	[157]

Table 2: An overview of the impacts of several nanobiofertilizers (*Continued*)

Country	Types of Crop	NanoBiofertilizers	Results	Ref.
Egypt	*Hordeum vulgare*	Nanophosphozink + Acinetobacter baumannii	Increase the yield of barley.	[158]
India	*Triticosecale*	NanoFe + methylpofrom, *Pseudomonas* putida, Azotobacter crocococcus	Enhance yield and improve photosynthetic pigments. 0.806 chlorophyll a and 0.275 and 0.224 mg g FW-1 chlorophyll b was obtained.	[159]
India	*Paspalum scrobiculatum*	Fe_2SO_4 + Azotobacter	Increase both weight and yield of grain	[160]
India	*Vigna unguculata*	Nanohyroxyapatite (nHA) particles + Burkholderia seminalis	Improve growth of endophytic root nodules	[161]
Ecuador	*Lupinus mutabilis*	ZnO_MnO-NPs + fulvic acid (FA) and ammonium phosphate	Promote photosynthetic pigments and enhance root size. 6% increase in height, 19% in root size, 3.5% in Chlorophyll content and 300% in leaf area.	[162]
Iraq	*Avena sativa*	NanoCu + Acinetobacter baumannii	Increase the yield of Oats. 22% increase in harvest index, 1000 grain weight, 5.85 and 26.52 ton ha^{-1} for yield and biological yield respectively.	[163]
Slovak Republic	*Setaria italica*	ZnONPs + Azotobacter	Improve the nutritional properties of millet	[164]
Egypt	*Phaseolus vulgaris*	ZnO, MnO_2 and MoO_3 + Azospirillum	Improvement in flower number and vegetative yield	[165]

9 Nanomaterials Fate in Soil

The interaction between nanomaterials and organic and natural minerals in the soil can cause the separation of the aqueous and solid phases of the soil system. Despite research mostly focusing on these topics in water systems, little information is available on the behavior and fate of nanomaterials in soil systems [166]. Depending on the type of soil and how it interacts with nanoparticles, various processes can affect the stability, reactivity, toxicity, and mobility of nano materials. These processes can lead to chemical, physical, and biological transformations [167]. The rhizosphere, the area surrounding plant roots, is a place where bacteria, animals, soil, and roots interact intensively. Soil inoculation can be done using both liquid and solid formulations, but the solid formulation requires more inoculants. Using microorganisms that solubilize phosphorus can help increase plant nutrient availability, particularly phosphorus, and ultimately improve resistance to soil diseases [168]. When nanoparticles are released into the environment, their natural tendency to aggregate reduces their surface area and alters their reactivity [169]. Aggregation can result from both homogeneous and heterogeneous aggregates making it possible for nanomaterials and other environmental particles [170]. Overuse of chemical fertilizers can lead to the depletion of vital nutrients present in fertile soil [128], [129]. This can cause the soil to become acidic, which subsequently reduces crop output and the nutritional value of food. However, nanobiofertilizers offer an effective, affordable and long-lasting solution for managing soil nutrients. By reducing the amount of nutrients lost due to gasification, leaching, or competing with other species, they help improve plants' ability to absorb and assimilate nutrients [130]. The bioorganic elements present in nanobiofertilizers, such as PGPR, aid in nitrogen fixation, phosphate solubilization, and replenishment of soil nutrients. Furthermore, biofertilizers with nanoparticle coatings can gradually release nutrients in coordination with crop requirements [131].

10 Challenges and Acceptability of Nanobiofertilizers

To make informed decisions, it is imperative to understand agricultural practices and technologies, including biofertilizers, nanobiofertilizers, and pseudonano biofertilizers. Biofertilizers, particularly nano biofertilizers, have attracted attention because of their potential to boost sustainable agriculture and improve soil fertility. However, they are also limited and challenged, as with any technology. Nanobiofertilizers are environmentally friendly fertilizers made with particles as small as 100 nanometers, which are thought to revolutionize sustainable agriculture. These tiny particles, which come from both organic and inorganic sources, are very powerful even at low concentrations despite their tiny size. By strengthening their tolerance to biotic and abiotic stressors, plants gain from these nutrients. They are thus more effective than conventional fertilizers [171]. Nanobiofertilizers do have certain restrictions, though. Both plants and animals may be at risk for poisoning due to their high levels of reactivity. As a result, this new sector has a lot of potential, but to realize it and address the difficulties that come with it, more study and research are needed [172]. Ensuring the effectiveness of nanobiofertilizers in agriculture is a major challenge. These fertilizers have gained popularity and a substantial contribution can be made to sustainable agriculture through these products. However, most of the products available in the market today are of poor quality. This has led to reduced confidence among farmers in their efficiency. Biofertilizer production is a multistep process that involves combining an appropriate carrier with one or more strains of microorganisms. It is essential to have this carrier to ensure microbe survival, proper installation in the soil, and protection from severe storage conditions. A quality control process is essential during all stages of formulation development and production. There must be rigorous scrutiny at every step of the production process to ensure dependability and efficacy [173]. However, nanobiofertilizers minimize some of the key causes of nutrient runoff while no fertilizer source eliminates it. Compared to conventional soluble fertilizers, these fertilizers are comparatively efficient, have a low application rate, and are stabilized. Achieving major benefits with fewer tradeoffs is possible if their use is optimized. To maintain a balance between delivering essential nutrition to plants and keeping the ecosystems healthy, research must continue. Despite this, the present study indicates that nanobiofertilizers can be an important component of a sustainable agriculture approach if they are used appropriately. Moreover, excessive nutrients can cause problems such as eutrophication in aquatic bodies [174]. Critics often argue that biofertilizers are more expensive than traditional fertilizers, particularly in terms of immediate productivity gains [42]. Concerns about quality control and regulations are also prevalent. It can be difficult to maintain the consistency and quality of biofertilizer products, which raises questions about their reliability [175]. Nanobiofertilizers have evolved from a mere research project to a practical solution in agriculture. They possess the ability to revolutionize the farming industry by increasing crop yields and minimizing harm to the environment. Current research is focused on improving their composition, maximizing nutrient release, and exploring their potential for specific crops and soil types. The market offers various types of biofertilizers and nanofertilizers, each with unique microorganisms and nanoparticles.

11 Conclusions

The agricultural industry has been using fertilizers persistently to increase crop yields, which has resulted in the distortion of soil fertility by altering the physicochemical parameters of the soil. Plant nutrition has declined as a result of this and undesirable effects on the environment and ecology. An incorporation plan should aim to achieve increased agricultural productivity in an environmentally sustainable way with minimal negative impacts. Advanced tools and techniques in nanobiotechnology can make a huge difference when it comes to improving agricultural management's sustainability and ushering in a new era of agricultural mechanization. The use of organic fertilizer-loaded nanoparticles as "nutrient boosters" holds enormous potential. These particles can release nutrients gradually and continuously, providing plants with the necessary nutrition to thrive throughout the growing season. For farmers looking to improve soil health, combining the use of organic manures and other organic materials with nanotechnology-based fertilizers is the way to go. This combination ensures the efficient and effective use of nutrients. The use of nanobiofertilizers can benefit plants in multiple ways, such as by providing slow-release properties, improving the stability of functional components, and allowing for the usage of small doses. By improving crop productivity, hiding soil nutrient deficiencies, and reducing leaching and degradation of nutrients, we can maximize crop productivity. Therefore, the development of nanotechnology-based agriculture seems like a promising and environmentally friendly approach for the advancement of sustainable agriculture. It is evident that by developing better fertilizer products, nanotechnology can greatly contribute to the transformation of the energy industry, the economy, and the environment. Investigating new ways to integrate nanotechnologies into fertilizers is crucial, while also being mindful of potential hazards that harm the environment and human health. By collaborating, governments and academic researchers can develop agriproducts that are enabled by nanotechnology, which we believe will bring about a revolution in this industry.

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Author Contributions

O. M.: investigation, conceptualization, topic organization, writing an original draft; K. O.: writing, reviewing, and editing; A. A.: writing, reviewing, and editing; M. F.: writing, reviewing, and editing; D. A: writing, reviewing, editing, and supervision. All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflicts of Interest

The authors declare no conflict of interest.

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