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Nanobiofertilizer: A Review on Environment-friendly Approach in the Field of Agriculture

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Abstract

Agriculture is the major backbone of human evolution, as it has been considered from the very early period of human civilization. The increasing demand for food has been mitigated to enhance crop productivity using chemical fertilizer. Our environment as well as crop quality have been largely affected by the abrupt use of chemical fertilizer. Biofertilizers have been introduced into the field of agriculture to overcome the hazardous side effects of chemical fertilizer. But the small shelf life and target specificity of biofertilizers lead to the development of nano-biofertilizers. The nano-biofertilizer is a successful outcome of the hybridization of nanoscience and biotechnology. The use of nano-biofertilizers has been gaining more importance nowadays because of its potential to enhance soil quality, plant growth, and crop production. Doping nanoparticles into biofertilizers increases the longevity, stability & efficiency of biofertilizers to several fold. It has been synthesized by the combination of a variety of microorganisms with nanoparticles. This review describes the present status and future prospects of the nanobiofertilizer along with its usefulness and disadvantages that motivate the future researchers to explore further in this field.

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Agriculture;
Biofertilizer;
Chemical fertilizer;
Microorganisms;
Nanoparticles.

Abbreviations

NBF	Nano-biofertilizers
MNPs	Metal Nanoparticles
SEM	Single Electron microscopy
TEM	Transmission electron microscopy
FTIR	Fourier Transform Infra-Red Spectroscopy
XRD	X-Ray Diffractometer
EPSs	Extracellular polymeric substances

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Introduction

Agriculture is one of the prime pillars of the economy all over the world. The production of agriculture should be developed to meet the urgent demand of the increased population of one country. The use of chemical fertilizer[1,2] resolves the problem to some extent. It mainly contains inorganic nitrogen, phosphorous and potassium, and promotes plant growth gradually by supplying nutrients slowly. Owing to its target-specific efficiency, cost-effectiveness and concentrated nutrient supply make it more popular among farmers within a very short period. But abrupt use of chemical fertilizer results in decreasing soil quality and texture, nutrient imbalance, human health hazards and environmental pollution.[3,4] The run-off of the chemical fertilizer into the water body gives rise to eutrophication, reduction of DO levels and, thereby, aquatic life is at stake.[5] In this alarming situation, a suitable bio-friendly approach towards sustaining the quality and quantity of agricultural products is biofertilizers. Biofertilizers[6,7] are substances containing a variety of microbes that have the capacity to enhance plant nutrient uptake by colonizing the rhizosphere and making the nutrients easily accessible to plant root hairs. A wide variety of metabolites, plant hormones and polysaccharides are released by the biofertilizers which help to promote soil quality,[8] initiate plant growth[9] and also inhibits the growth of plant pathogens and thereby increases the crop yield. But, its target specificity, short shelf-life and extreme reaction condition prohibits its activity.[10,11] In the last few years, nanotechnology has promoted wide possibilities for sustainable agriculture through the development of nanopesticides[12,13] and nanofertilizers.[14,15] Having a large surface area, high solubility and the lightness of the nanoparticles make it more appropriate for nutrient supply, enhancing plants' growth and resisting them from different diseases over chemical fertilizers and biofertilizers. Nanobiofertilizer (NBF)[16,17] is the derivative product of the fusion of nanotechnology and biotechnology that successfully overcomes the drawbacks of chemical and biofertilizers, increasing crop yield in an eco-friendly manner by maintaining food security. It has been synthesized by encapsulating biofertilizer with a nanomaterial that increase its stability, inhibits the process of bidegradation and confirms the supply of nutrients to the soil deliberately, thereby minimizes the environmental hazards. Several reports establish the fact that it promotes plant growth by successful quenching the harmful effect of abiotic stress on the environment of the plant. Nanobiofertilizer is a unique combination of bioinoculants and nanoparticles that improves the delivery of nutrients to the target plants for the better crop production. But, the scarcity of knowledge of microbe-plant interaction restricts it application in a broad way. With an aim to minimize the knowledge gap between the laboratory experiment and practical field application, this review describes the synthesis, interaction between plant and nanoparticles, applications, advantages, disadvantages, and future prospects in an elaborate manner to carry out further research to improve its efficiency. A pictorial representation of the synthesis, mode of application and usefulness of nanobiofertilizer have been summarized in Figure 1.

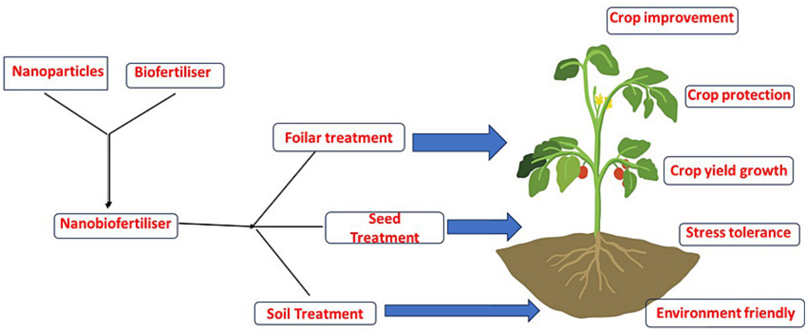

Fig. 1: Schematic diagram of the application and uses of Nanobiofertilizer.

Methodology

An extensive systematic literature survey methodology, leading to journal searches according to the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) flow guidelines. PRISMA guidelines are a well-known standard for assessing systematic reviews and meta-analyses. Database search has been carried out to assemble peer-reviewed articles, mainly emphasize on the work "nanobiofertilizer in the field of agriculture" that were published between 2017 and 2026. Data were retrieved from the articles available in Scopus, Google Scholar and Science Direct using keywords such as 'nanobiofertilizer', 'biofertilizer', 'chemical fertilizer', and 'agriculture'. The selection process followed PRISMA guidelines, as represented in Figure 2.

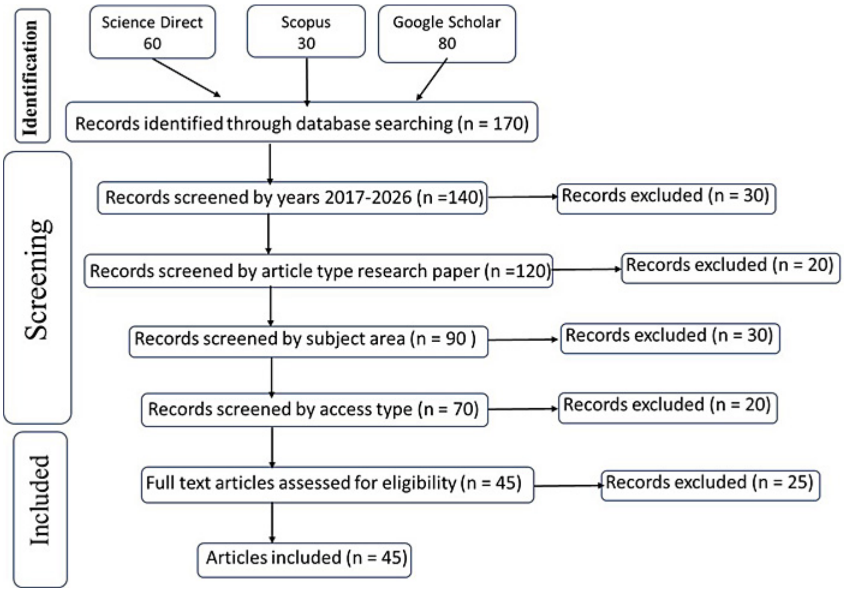

Fig. 2: Flowchart diagram of systematic literature review. All inclusions and exclusions were done manually.

Synthesis

Metal nanoparticles, biofertilizer and the encapsulating agents are the three prime ingredients for the synthesis of nanobiofertilizer. Nowadays stress has been given on the "Green" synthesis of metal nanoparticles (MNPs) apart from the conventional physical (Top-down approach)[18] and chemical methods[19] because of their environment friendliness.

Green Synthesis of Metal-nanoparticles (MNPs)

Synthesis of nanobiofertilizer (NBF) primarily involves the "Green Synthesis" of MNPs because of its environment friendly manner and less hazardousness. Moreover, it is highly beneficial over the conventional method as the NPs produce having the perfect combination of size and stability. A wide variety of microorganisms like algae, fungi, bacteria, and different parts of plants such as leaves, petals, stalk, fruits, seeds, roots are used for this biosynthesis. They are so chosen as they have the potential to absorb the metal ions from their surroundings. This type of synthesis includes two major categories that are described below:

Microorganisms Aided Synthesis

Intracellular and extracellular are the two major pathways for the microorganism's aided synthesis of MNPs.[20] The negatively charged cell wall of the microorganisms plays an important role in the intracellular method. The positively charged metal ions are deposited on the negatively charged cell wall through electrostatic interaction followed by the reduction of the metal ion by nitrate reductase enzyme via metabolic reactions to synthesise the MNPs. The extracellular method involves the conversion of metal ions to their respective MNPs, via nitrate reductase enzyme method. The extracellular method is more advantageous over the intracellular one, as the former does not require any kind of follow-up steps to recover the intercellular nanoparticles, which make it less time-consuming and more cost-effective. This method has become more popular as it needs optimum external conditions like pressure, temperature, pH etc to develop the MNPs and its growth rate is also very high. A wide variety of microorganisms like yeast, bacteria, fungi, algae have been proven to be more challenging to execute both intracellular and extracellular method. Recently, myconanotechnology[21] has emerged a new area to synthesize MNPs using fungi like *Aspergillus sp., Fusarium oxysporum* etc., which found to be more effective because of it widespread availability than other microorganisms. Some microorganisms aided syntheses of nanoparticles used in the formation of nanobiofertilizer are tabulated in Table 1.

Table 1: Microorganisms aided syntheses of nanoparticles for nanobiofertilizer

Microorganisms	Nanoparticles	Effect on plant
Microalgal extract	Iron oxide nanoparticles	Promote the growth of plants[22]
Acidophilus, Lactobacillus casei, and *Bifdobacterium sp.*	Cu nanoparticles	Enhance the plant immunity against the different types of diseases[23]
Microalgae	Ag nanoparticles	Having antioxidant property[24]

Plant Facilitated Synthesis

Plant is the most commonly available natural resources to prepare MNPs. The extracts obtained from different parts of the plant contain flavonoids, ketones, aldehydes, terpenoids, quinones act as electron donors to reduce metal ions to MNPs from the aqueous solution. The reducing agent also serves as capping agent to stabilize the MNPs. Table 2 depicts the plant prompted synthesis of nanoparticles for nanobiofertilizer.

Table 2: Plant facilitated syntheses of nanoparticles for nanobiofertilizer

Plant Extract	Nanoparticles	Effect on plant
Clove buds	Zn nanoparticles	Improve the yield and growth of *Pisum sativum* L.[25]
Leaf extract of *Parthenium hysterophorus* L	ZnO nanoparticles	Enhance the germination of seeds and vegetative growth of *Sesamum indicum* L[26]
Fruit extracts of *Cornus mas* L	Iron oxide nanoparticles	Root and shoot biomass have been stimulated[27]
Leaf extract of Aloe *barbadensis* Mill	ZnO nanoparticles	Act as rich nutrient source to the plant[28]

Metal nanoparticles so far synthesized combines with plant growth promoting Rhizobacteria (PGPR) like Azotobacter, Azospirillum, Pseudomonas sp., Bacillus sp., Mycorrhizal fungi, Blue-green algae, and then encapsulated with chitosan, starch, alginate solution to form nanobiofertilizer. Systematic stepwise synthesis of nanobiofertilizer has been depicted in Figure 3.

Characterization of Nanobiobertilizer

Nanobiofertilizers have been synthesized so far and are characterized[29] by examining the activity of their nanoscale components, followed by assessing the interaction between plants and the biological components and evaluating their performances through UV-Vis spectroscopy, Single Electron microscopy (SEM), Transmission electron microscopy (TEM), Fourier Transform Infra Red Spectroscopy (FTIR), X-Ray Diffractometer (XRD), Zeta Potential Analysis etc.

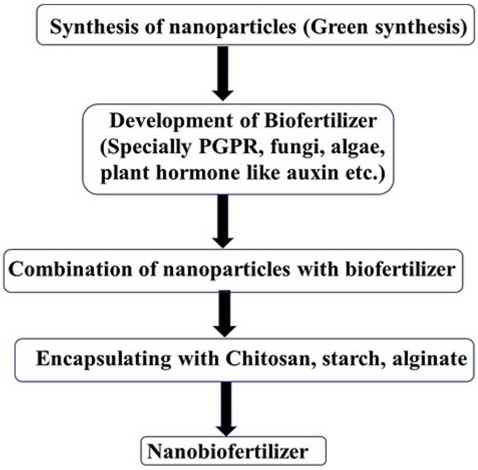

Fig. 3: Stepwise representation of synthesis of nanobiofertilizer.

Mode of Application and Interaction of Nanobiofertilizer with Plants

The suitable method of application of nanobiofertilizer has played a crucial role in the growth of plants. The choice depends on the soil quality, weather type and nutrient accessibility. Concerning these facts, suitable selection of the mode of application of nanobiofertilizer makes it more useful in modern agriculture. Three primary methods[30] that have been employed for the application of nano-biofertilizers are foliar application, seed nanopriming and soil treatment. A foliar application[31] involves the spraying of a nanobiofertilizer onto the leaf's surface, leading to its direct absorption through stomata, and further penetrate into vascular bundles and spread throughout the plant body following symplastic and apoplastic pathways. Cuticle on the surface area of the leaf hinders the absorption of nutrients through stomata which has further overcome by the formation of nanobiofertilizer. The treatment of seeds with nanobiofertilizer before planting is the major concern of the seed priming method.[32] This mode of application increases the rate of germination of the seed along with specific delivery of nutrients in minimum concentration to avoid its toxic effect on plants. The application of nanobiofertilizer to the soil in the required amount during planting is included in the soil treatment mode[32] of application. The applied nutrients have been absorbed by the root of the plants through endocytosis method and then carried out throughout the whole plant body by symplastic and apoplastic pathways. This method has several beneficial aspects, like application feasibility, controlled release of nutrients, thereby minimizing the loss of nutrients and improving plant growth. Some methods like root dipping, main field application etc. have also been applied by farmers to get a better effect from it. A systematic representation of the mode of interaction of the nanobiofertilizer with the target plants has been shown in Figure 4.

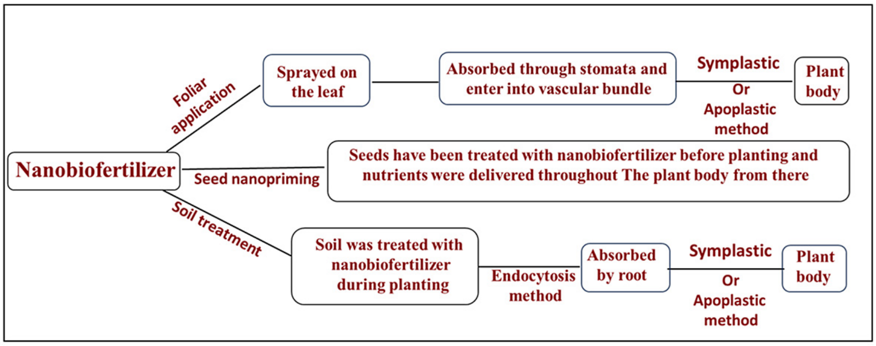

Fig. 4: Schematic representation of the interaction of nanobiofertilizer with plant.

Usefulness of Nanobiofertilizer

Nanobiofertilizer improves the plant growth and nutrition uptake by imparting different qualities to the soil and plant. The nanoencapsulation of biofertilizer with nanoparticles enhance its stability thereby minimize the rate of dissolution of fertiliser as well as increased surface area of nanobiofertilizer results in its higher activity and greater interaction with plant, thereby slow release of nutrients to plant. Bioorganic part of nanobiofertiliser synergistically maximizing the soil nutrient capacity through various mechanisms like fixation of atmospheric nitrogen into the plant roots by *Rhizobacteria*, synthesis of siderophores which can bind the essential metal ions into the plant root via chelate formation and solubulization of phosphate due to the presence of different bacteria and fungi. Owing to the combined effect of nanomaterials and biofertilizer, nanobiofertiliser shows an intense effect on the improvement of plant growth, crop yield and quality in the near future.

Promote Plant Growth

Research exhibits that some nanoparticles such as silicon, copper, silver, chitosan etc. facilitate the production of phytohormones like auxin, gibberellic acid etc. that are helpful to increase plant growth and stress tolerance ability. Nanoparticles, coated with biofertilizers, increase the efficiency of biofertilizers and release nanoparticles in a controlled manner into the plant's rhizosphere for sustainable agriculture. Owing to small size of the nanoparticles it easily gets absorbed onto the root and then spread throughout the whole plant. Nanoparticles enhance the water solubility of biofertilizers in NBF, thereby reducing its loss by leaching.[33] NBF also helps to produce secondary metabolites such as catalase and peroxidase and nonenzymatic oxidants like phenols and flavonoids that improve the crop quality by enhancing the shelf life of the crops, which is also beneficial to our health.[34] The synergistic action of nanoparticles and biofertilizers stimulate a variety of pathways within the plant body that are responsible for the better development of plants. NBF helps to upgrade the genes that are accountable for producing antioxidants and osmolytes, thereby minimizing the harmful effect of Reactive Oxygen Substrate (ROS) on plants during stressed conditions and also preserving the cell's structure along with its functions. NBF promotes the secretion of growth hormones like indole acetic acid, cytokinin and suppresses the production of stress-related hormones like abscisic acid,[35] which in turn improves stress tolerance of the plant and also maintains the crop yield even under unfavourable environmental conditions. Moreover, nanoparticles regulate the release of hormones and thereby, enhancing its sensitivity, and coating of hormone with the nanoparticles prevents it degradation and improving the stability and availability. The rate of photosynthetic activity, growth of the seedlings has been highly affected by nanoparticles that also improve the crop yield and quality.

To Increase Soil Fertility

Abrupt use of chemical fertiliser reduces the naturally found nutrients in the soil; thereby decreasing soil inherent fertility. Additionally, acidification of soil is the prime factor that is responsible for diminishing the soil fertility. Loss of soil fertility and nutrients imbalance are the two major factors that deteriorate the crop productivity and its nutrition value. Nanobiofertilizer, plays an important role to minimize these limitations in an efficient manner. Nanoparticle part of the nanobiofertiliser helps the plant to absorption the nutrients slowly and prevent the loss of nutrients from the soil by leaching, gasification36 etc.; its biofertiliser component provides the scope for assimilation of nutrients into the soil and on the various parts of the plants through various mechanisms. Apart from this, biofertilizer coated with nanoparticles enables to improve the microbial action in the soil, results in the better cycling of nutrients.[36] The synchronization of the functions of the two components of nanobiofertiliser provides a wide scope to enrich the soil fertility.

To Improve the Crop Security Against Pest and Pathogens

Nanobiofertilizer also provides resistance to the plants against the diseases caused by the pests and pathogens. Nanoparticles have been designed judiciously so that it can interact with different types of microorganisms specifically to ensure the plant protection which also effect the crop security. There are several evidences on the action of nanobiofertilizer against bacteria, fungi and pesticidal effect. The organic part of the nano biofertilizer protects the leguminous plants from bacterial infections as is evident from the study of S. Gouda et al.,[37] Silver nanoparticles coated biofertilizers prevents the bacterial growth on the targeted plants and thereby reduces the loss of crops.[38] Metal oxides nanoparticles encapsulated nanobiofertilizer directly attack the plant pathogens to prevent them from this biotic stress.[39]

Environmental Impact

Nanobiofertlizer can lessen the nutrients loss by leaching and run-off, which thereby regulate the water pollution and eutrophication. Due to target-specificity of nano biofertilizer, it can directly apply to the root of the plant, thereby optimize the nutrient uptake, and minimize the amount of requirement of nutrients.[40]

Disadvantages

Though nanobiofertilizers seem to be beneficial for sustainable agriculture, their effect on the environment and on human health should have to be thoroughly studied. The major disadvantage of nanobifertilizers is the potential toxicity that they can impose on the plant and other organisms if not properly designed and employed. Nanoparticles, owing to its small size, can easily accumulate in the food chain and enter the human body through the consumption of food.[41] The improper treatment of nanobifertilizers can affect the environment, especially the water, due to nutrient run-off from the field.[42] A detailed trial and error investigation should be carried out by researchers to control the dose of nanobiofertilizer to minimize its harmful effect on the environment as well as on human health. The living microorganisms used as biofertilizer in NBF, will possess a very poor shelf life and is unsuitable for the soil having inadequate mineral content. Moreover, the production cost of nanobiofertilzer is quite higher than that of the traditional fertilizer, owing to specialized manufacturing processes and special equipment techniques. The long-term effect of nanobifertilizers on the soil for their prolonged use is still a big question. Furthermore, the farmers in our country have poor knowledge of the method of application and beneficial aspects of nanobiofertilizers. Addressing the issues, a comprehensive research work along with an exhaustive campaign should urgently be required to promote the use of nanobiofertilizer for the development of eco-friendly and sustainable agriculture.

Table 3: Present scenario of nanobiofertilizer for sustainable agriculture

Nanobiofertilizer	Target plants	Response
Plant-promoted bacteria with iron oxide nanoparticles	Soyabean seedling	Improve the growth of the seedlings[43]
Chelation of minerals from plant extract with citric acid	Common bean plant	Antifungal activity[44]
Graphene + plant growth promoting bacteria	*Hordeum vulgare*	Improve the germination of seeds[45]
Zinc oxide nanoparticles + *Azospirillum*	*Mung bean (Vigna radiata)*	Improve plant growth[46]
Silver nanoparticle coated *Bacillus cereus* LPR2	*Zea mays*	Improve plant growth and also exhibit antifungal activity[47]
Iron nano-oxide and Pseudomonas and Mycorrhiza	*Zea mays*	Improve plant growth even under drought situation[48]
Gold nanoparticles and rhizospheric *Pseudomonas monteilii*	*Vigna unguiculata*	Improve the length of shoot, leaf number and weight of the plant[49]

Zinc nanoparticles blended with Rhizobactor and organic fertilizer	*Phaseolus vulgaris* L	Enhance the plant growth, number of leaves, nutrient uptake and protein, carbohydrate content in pod[50]
Titanium nanoparticle combined with *Azospirillum brasilense, A. caulinodans* and *Azotobacter chroococcum*	*Triticum secale*	Increased chlorophyll content, moisture hold, crop yield of the target plant[51]
Nanozeolite mixed with *Bacillus spp.*	Any targeted plant	Increases the biomass and chlorophyll content, antioxidants, and yield of the plant[52]
Onion silver nanobiofertlizer	Brinjal and tomato plants	Enhance leaf area and leaf nutrient content and improve crop quality[53]
Mesoporous silica NPS + Bacillus sp.	Black wheat	Increase plant growth, chlorophyll content, proline level, nitrogen content[54]
Plant Growth Promoting Rhizobacteria + Silicon NPs	Sugar Beet	Highly improve plant growth and crop yield under soil salinity and saline water irrigation[55]
Staphylococcus aureus + Fe Nanoparticles (Applied under chromium stressed condition)	Rice plants	Reduce the chromium uptake by plants and also lessen the harmful[56]
Nanozinc-chelate + biofertlizer	Maize plants	Improve the maize yield by shortening the irrigation perod[57]

Present Status of Nanobiofertlizer

All over the world, researchers have focused on the potentiality of the nanobiofertilizer in crop production. Some current work on nanobiofertlizer has been summarized in Table 3.

The current state of nanobiofertilizer application has shown that it is an environmentally beneficial synchronizing effect of biotechnology and nanotechnology that not only effectively improves plant growth, crop yield, and crop protection but also imparts soil fertility, water restoration, seed germination, chlorophyll content, and stress tolerance capability. According to recent research, the best candidates for nanobiofertilizer formulation are Plant Growth Promoting Rhizobacteria (PGPR) like Azotobacter, Azospirillum, and Rhizobium, as well as fungi (mycorrhizae) and algae in combination with zinc oxide (ZnO), silicon (Si/SiO_2), iron (Fe/Fe_2O_3), and silver (Ag) nanoparticles. These nanoparticles are so chosen that they can improve plant growth, nutrient uptake and stress tolerance when combine with biofertilizer. Among organic nanoparticles, chitosan is seemed to be appropriate owing to their biodegradability and efficiency in encapsulating the biofertilizer. Recently, nanobiofertilizer capsules[58] have been synthesized and characterized by loading necessary agro-nutrients in nanoscale level and beneficial microorganisms like Pseudomonas Fluorescence for slow release of nutrients. Furthermore, neem cake blended with plant growth promoting rhizobacteria increase the crop yield and rate of germination of seedlings of a specific leguminus plant.[59]

Future Prospect

Concerning the nutrient supplier, plant growth, and safety regulations, nanobiofertilizers, a combination of nano- and biotechnology, are an appropriate approach towards the development of sustainable agriculture. Along with its beneficial aspects, there are some limitations and toxic effects which cannot be overlooked as such. Despite having several advantages, the present scenario reveals that the worldwide application of it has still been restricted. Future researchers should give stress on the following points for the better application of nanobio-fertilizers towards green and sustainable agriculture.[60]

- Nanoparticles of nanobifertilizers should be designed carefully to optimize their size, dimensions, and surface properties to enhance their stability, dispersibility and nutrient release, so that plants can absorb them properly. The small size and large surface area of the nanoparticles help the fertilizer to deliver the nutrients slowly, thereby minimizing the loss of nutrients.
- Compatibility studies of the nanoparticles with the selected biofertilizers should be made carefully to increase their usefulness.
- Nanobiofertilizers cannot get full acceptance among farmers only based on laboratory-based experimentation. A similar set-up should be developed in the natural environment to make it more popular.
- The impact of nano-biofertilizer on soil texture and plant ecology for it prolong use should be assessed primarily, to examine its long-term effect.
- The government should undertake a thorough safety regulation program to evaluate the toxic effect of the nanobiofertilizer due to the inclusion of nanoparticles and restrict the permissible dose to get better results.
- Users should have a deep understanding of the biodegradation and transformation of nanobiofertilizers on plants to get insight into their toxic effect on the environment.
- Investigations should be carried out to find out the most suitable way to get more crop yield in a more economical way using nanobiofertilizer.

Conclusion

In summary, nano biofertilizer, an innovative approach of nanobiotechnology incorporating nanoparticles into bio-fertilizers, has become promising nowadays as a part of eco-friendly green sustainable agriculture. It has several advantageous aspects that include a small dose of application, increasing the stability of the functional ingredients, minimizing the loss of nutrients either through leaching or biodegradation, which all help to improve the crop yield and soil quality. Besides having several beneficial aspects, it has some toxic effects on the soil because of the presence of nanoparticles. Some microrganisms act as biofertilizer of nanobiofertilizer enables to form an extracellular polymeric substances (EPSs) that can effectively encapsulate the nanomaterials and minimize the toxic effect of overconcentrated nanoparticles. Moreover, the formation of biofertilizer itself in the nanoscale form in place of combining nanoparticles and biofertilizers expected to give better results and partly resolve the toxic effect of nanoparticles; algal nanobiofertilizer is one of the most developing areas in this aspect. In recent times, researchers have actively been engaged in developing nanobi0fertilizers by using hybrid nanomaterials and bio nanocomposites to make them more acceptable. Moreover, the design and synthesis of multi-nutrient delivery nano biofertilizers shows a new horizon in the field of green agriculture. This is a fertilizer that supplies multiple nutrients to the plants simultaneously, in a controlled manner that can improve the soil quality as well as plant health. This review also opens scope for upcoming researchers for the proper implementation of the hybridization of nanotechnology and biotechnology towards a sustainable and eco-friendly approach in the field of agriculture in the coming future. It also suggests achieving a thorough insight into the interaction between the nanoparticles with the plant body, which will help future researchers to be involved in interdisciplinary collaborative research between nanotechnology and agriculture for the betterment of humanity.

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Data Availability Statement

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Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

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Not Applicable

Author Contributions

The sole author was responsible for the conceptualization, methodology, data collection, analysis, writing, and final approval of the manuscript

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