

Revealing the Crucial Role and Prospect of Nano-biofertilizers for Improving Soil Health and Advancing Sustainable Crop Productivity

Die entscheidende Rolle und die Potenziale von Nanobiodüngern für die Verbesserung der Bodengesundheit und die Steigerung der nachhaltigen Pflanzenproduktivität

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Summary

In recent years, the agriculture practices have seen a growing interest in innovative technologies aimed at enhancing productivity while promoting sustainability. Nano-biofertilizers, a novel approach to crop nutrition, have emerged as a potential game-changer. This study is aimed comprehensively to uncover the potential and current utilization status of nano-biofertilizers in soil health improvement and sustainable enhancement of crop productivity. The methodology used in this study involved the application of systematic literature review (SLR) methods in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The review focused on scientific literature published from 2013 to 2023, utilizing databases such as ScienceDirect, Scopus, and PubMed. A total of 631 articles were identified through this process. Out of this pool, 10 articles were chosen based on their relevance and topic and they underwent a comprehensive and detailed review. The results showed that use of nano-biofertilizers improves the soil health, plant growth, and productivity significantly. The biological selenium nanoparticles (100 mg/mL) significantly increased the length and weight of spike, root, and shoot, grain quantity in spike, and 1000 grain weight by 5%–40% compared to control. *Comamonas testosteroni* biofertilizer combined with silver nanoparticles (AgNPs) could alleviate the salinity threatening plant growth. Nano-biofertilizers enhance plant growth, elevate their nutritional value, improve productivity, extend shelf life, and bolster their defenses against biotic and abiotic stress factors.

Keywords: Nanoparticle, Biofertilizer, Soil Quality, Crop Production, Sustainable Agriculture

Zusammenfassung

In den letzten Jahren hat das Interesse an innovativen Technologien zur Steigerung der Produktivität und Nachhaltigkeit in der Landwirtschaft zugenommen. Nanobiodünger, ein neuartiger Ansatz zur Pflanzenernährung, gelten als potenzielle Gamechanger. Diese Studie untersucht umfassend das Potenzial und die aktuelle Anwendung von Nanobiodüngern zur Verbesserung der Bodengesundheit und nachhaltigen Steigerung der Ernteerträge. Die Methodik umfasst eine systematische Literaturrecherche (SLR) nach PRISMA-Richtlinien, mit Fokus auf Literatur von 2013 bis 2023. Von den identifizierten 631 Artikeln wurden 10 für eine detaillierte Überprüfung ausgewählt. Die Ergebnisse zeigen, dass Nanobiodünger signifikante Verbesserungen in Bodengesundheit, Pflanzenwachstum und Produktivität bewirken. Bio-SeNPs (100 mg/mL) zeigten besonders positive Effekte in Länge und Gewicht von Ähren, Wurzeln und Sprossen, Kornmenge in der Ähre sowie Tausendkorngewicht im Vergleich zur Kontrolle. *Comamonas testosteroni*-Biofertilizer in Kombination mit Silbernanopartikeln (AgNPs) deutete darauf hin, dass sie die durch Salzbelastung bedrohte Pflanzenentwicklung lindern können. Nanobiodünger fördern Pflanzenwachstum, Nährwert, Produktivität und Resilienz gegen Stressfaktoren.

Schlagwörter: Nanopartikel, Biodünger, Bodenqualität, pflanzliche Produktion, nachhaltige Landwirtschaft

1. Introduction

Agriculture practices, especially overuse of chemical fertilizer or agrochemicals, are forced to supply more food to fulfill the high demands of a rapidly growing human population. Therefore, both soil and environment quality are constantly degrading. However, extensive farming techniques and heavy use of pesticides degrade soil fertility, contaminate the environment, destroy biodiversity, increase the pest resistance, and reduce crop yields (Chaudhary et al., 2021; Tripathi et al., 2017). The extensive and continuing use of chemical fertilizers in agricultural systems to increase yields raises several dangers to human health and the environment. Therefore, there is an urgent need to establish an opportunity technology that may improve agricultural productivity while also ensuring environmental sustainability.

Applying and improving nanotechnology seems to be a promising method. The use of nanomaterials combined with live organisms, such as nano-biofertilizers (NBFs), has been recognized as a highly successful solution for resolving agricultural challenges. NBFs effectively transfer nutrients to plant life, revealing their benefits over conventional chemical fertilizers in terms of crop production and sustainability. NBFs also improve a plant's ability to manage various stresses, whether they are biotic or abiotic in nature. Plants can absorb NBFs through their roots or leaves, depending on the application method and the characteristics of the nanoparticles (NPs). Therefore, to minimize the reliance on chemical fertilizers and enhance agricultural and environmental sustainability, NBFs offer an achievable solution.

Nanotechnologies are the methods of designing, characterizing, producing, and applying structures, technology, and techniques at the nanoscale (Soni, 2018). A novel scientific idea known as "nanotechnology" involves use of materials and equipment that could change a substance's chemical and physical characteristics at the molecular level. It combines innovative technology and another, resulting in innovations and improvements in technology, ability, removal, tools, field, and life sciences. Under changing climate conditions, nanotechnology provides a wide range of applications and advantages. It is a new paradigm that is transitioning from the experimental to the practical areas. It aims to provide significantly to the agricultural sector by detecting contaminants, plant diseases, insects, and pathogens, managing pesticide, fertilizer, nutrient, and genetic components distribution, and improving and maintaining soil structure (Usman, 2020; Usman et al., 2020). NPs function as indicators,

activating several defense mechanisms in plants under stress. This rapidly developing period has embraced a wide range of application fields, including agricultural regulatory monitoring, improved fertilizer efficiency, advanced plant growth, and consistent agrochemical disposal. Remarkably, a strategic approach based on NPs for ensuring crop sustainability has gained recognition and success in the agricultural sector due to their exceptional properties, such as high surface area, solubility, and lightweight nature, surpassing biopesticides and other fertilizers (Chandra et al., 2015).

Biofertilizers typically consist of live formulations of beneficial microorganisms, primarily plant growth-promoting rhizobacteria (PGPR) like *Rhizobium*, cyanobacteria (blue-green algae [BGA]), mycorrhizal fungi, free-living nitrogen-fixing bacteria such as *Azotobacter* and *Azospirillum*, and phosphate-solubilizing bacteria such as *Pseudomonas* spp. and *Bacillus* spp. These microorganisms enhance nutrient availability for plants, either by inhabiting the rhizosphere (e.g., *Clostridium pasteurianum*, *Azotobacter*, *Azospirillum*, *Rhodobacter*, etc.) or by establishing endosymbiotic relationships within the plant (e.g., *Rhizobium*, *Anabaena*, arbuscular mycorrhiza, etc.) (Mahapatra et al., 2022). They enhance soil aeration and organic fertilization by improving the soil's moisture retention capacity, increasing the availability of crucial nutrients (such as nitrogen and phosphorus) to plants, and fostering soil health through the enrichment of microbial communities (Kumari and Singh, 2020). Nitrogenase enzyme for biological nitrogen fixation is found in nitrogen fixing bacteria. The most important contributions to the BNF process are made by *Azotobacter* sp., *Herbaspirillum* sp., *Azoarcus* sp., *Alcaligenes*, *Azospirillum*, *Bacillus*, *Frankia*, *Trichodesmium*, *Anabaena*, *Acetobacter diazotrophicus*, *Nostoc*, *Enterobacter*, *Pseudomonas* sp., and others (Nagpal et al., 2021).

NBF is a combination of NPs and biofertilizers. It is produced by containing nanosized biofertilizers (1–100 nm) beneath a suitable nanomaterial covering (Kumari and Singh, 2020). They regulate nutrient delivery to specific locations while minimizing the effect of environmental stresses. Their unique characteristics include a decreased dependence on chemical fertilizers, increased efficiency in using nutrients, improved nutrient availability and absorption, quick mass-scale production, environmental sustainability, cost-efficiency, and renewability (Duhan et al., 2017; Thirugnanasambandan, 2019).

However, due to a lack of understanding regarding the interactions among biofertilizers, NPs, soil, and plants,

microbe-based NBFs have yet to receive significant publicity and implementation. Recent research has primarily focused on physically and chemically produced nanofertilizers (NFs). Considering this, it is important to explore and create more convenient NBFs that can be commercialized and made available to farmers. Therefore, the purpose of this paper is to completely evaluate the current state, challenges, and future prospects of NBFs in terms of soil health and sustainable crop productivity.

2. Materials and Methods

The research employed a systematic literature review methodology, conducting journal searches in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow guidelines. PRISMA guidelines are a recognized standard for evaluating systematic reviews and meta-analyses. This methodology focuses on promoting transparent and comprehensive reporting by authors when conducting research of this nature (Sastypratiwi and Nyoto, 2020). The data sources used in this study are the databases and indexes that can be accessed on ScienceDirect. The search was conducted on October 20, 2023, with the keywords “Nano biofertilizer AND Soil Health AND Crop” used in ScienceDirect. In a Scopus search, the keyword “Nano AND Biofertilizer” was used, and in a PubMed search, the keyword “Nanoparticle AND Biofertilizer” was used. Figure 1 is a flowchart that illustrates the algorithm for searching data sources from several databases. The selection criteria used were the year of publication from 2013 to 2023 and scientific publications in the form of research articles that were selected based on the title and abstract. All screened journals that were selected using the relevant criteria had information related to NBF, soil health, plant growth, and productivity. The results of the search for journals using ScienceDirect at the beginning of the search with the manual system found 518 articles, which were then screened for the time of publication of the journal, type of article (research article), and subject areas. The type of access used was open access, resulting in 37 research articles. The search with Scopus resulted in 70 articles, which were then screened for the time of publication of the journal and the type of document (article, review, and conference paper). The type of access used was open access, and the subject areas were agricultural and biological sciences and environmental sciences, resulting in 41 research articles. The search with PubMed resulted in 43 articles, which were then screened for full text, resulting in two research articles. After

being screened for full text, 10 article titles were obtained that contained information according to the criteria.

3. Results and Discussion

The results presented in this article are based on data collected from 2013 to 2023 using PRISMA on several websites, namely ScienceDirect, Scopus, and PubMed. The results describe the components of NBFs, the formulation of NBFs, and the mechanism of NBFs in improving soil health and crop productivity.

3.1. Components of NBF

NBFs consist of two components, NPs and biofertilizers, which together form an NBF that can improve soil health and increase crop yields.

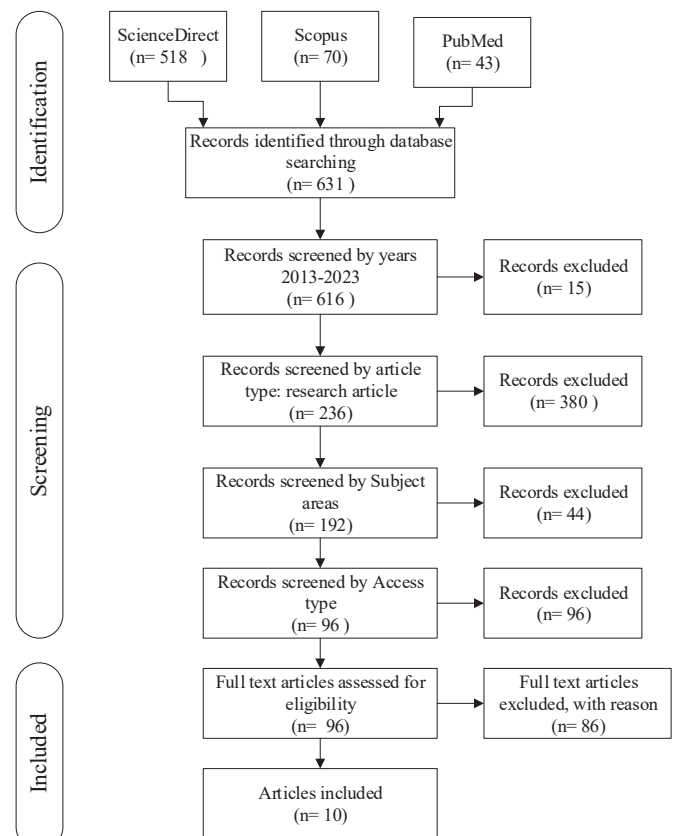


Figure 1. Flowchart showing systematic literature review: nano-biofertilizers used in the enhancement of soil health and boosting crop productivity
Abbildung 1. Flussdiagramm Systematische Literaturübersicht: Nanobio-
dünger zur Verbesserung der Bodengesundheit und Steigerung der Pflan-
zenproduktivität

3.1.1. Nanoparticles

NPs are minuscule particles with diameters starting from 1 to 100 nm. Silicon, zinc, copper, iron, selenium, and silver are the popular NPs utilized for the creation of NBFs. The chemical content material, form, diameter, and agglomeration state of NPs have an effect on their uptake and accumulation in plants. NP translocation is in relation to their diameter, and it can also be affected by plant species, as receptors different from others. Some plants could accumulate a type of NP while excluding another. NPs function in many ways to help plants grow (Baazaoui et al., 2021; Fatima et al., 2020). Figure 2 shows the application of NPs and their internal mobility within plants. When NPs get into the rhizosphere, they can reach plant roots by endocytosis, interacting with molecules, or passing through plasmodesmata. They can also diffuse through stomata and enter the vascular bundles when applied as a foliar spray. They also move within the plant via symplast and apoplast mechanisms. The pathway of NP movement depends on the plant species and the specific type of NPs used (Anjum et al., 2019).

3.1.2. Biofertilizer

Beneficial components found in biofertilizer include PGPR, fungal mycorrhizae, BGA, and processed material from plants (Vafa et al., 2021). Microbes were first used as biofertilizers in the late 1800s (Malusà et al., 2016). Chemical

fertilizer overuse is currently negatively impacting the agroecosystem due to its extensive use. It contributes significantly to soil contamination, water pollution, and air pollution. Providing an affordable, nontoxic, and sustainable alternative to produce high crop yields with no side effects is important (Sagar et al., 2022). Biofertilizers are renewable, cheap, and sustained. They expand into plant rhizospheres and enhance plant growth through improving nutrient availability (Enrico et al., 2020).

They make nutrients, which enhance plant growth, solubilize phosphate (Ahmed et al., 2021; Sharma et al., 2013) and potassium (Baba et al., 2021), and fixate nitrogen from the atmosphere to the soil (Kusale et al., 2021). Some biofertilizers produce a siderophore that sequesters Fe (Kusale et al., 2021; Nithyapriya et al., 2021), making it unavailable to harmful microorganisms and inhibiting pathogen growth. They produce phytohormones including indole-3-acetic acid, gibberellins, cytokines, abscisic acid, and others (Hamid et al., 2021), which help in plant growth and development (Fasusi et al., 2021; Sumbul et al., 2020). However, disadvantages of biofertilizers are their high dose requirement to cover a wide area, low effectiveness in changing environments, and short shelf life (Basu et al., 2021; Kalam et al., 2020). NBFs have successfully dealt with various kinds of challenges, contributing to the improvement of agriculture through nanotechnology, increasing yields and growth of crops, while sustaining

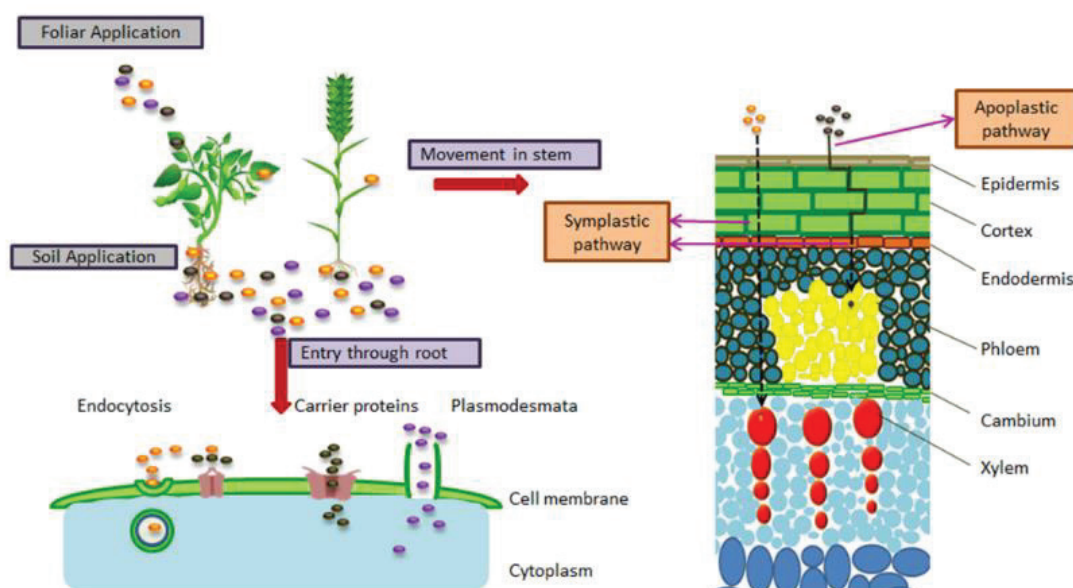


Figure 2. Uptake and movement of nanoparticles in plants (Akhtar et al., 2022).
Abbildung 2. Aufnahme und Bewegung von Nanopartikeln in Pflanzen.

Table 1. The role of nano-biofertilizer in improving soil health, plant growth, and productivity
Tabelle 1. Die Rolle von Nanobiodünger bei der Verbesserung der Bodengesundheit, des Pflanzenwachstums und der Produktivität

Nano-biofertilizer	Crop	Plants' responses	References
Zinc sulfide nanoparticles, <i>Acinetobacter pittii</i> and <i>Bacillus velezensis</i>	Tomato (<i>Solanum lycopersicum</i> L.)	• Increase in plant fresh and dry biomass • Improve total soluble protein, sugar, and phenolic contents • Improve the tomato plant nutrition [silicon (Si), magnesium (Mg), calcium (Ca), and potassium (K)]	Shah et al., 2023
Biological selenium nanoparticles (Bio-SeNPs) synthesized by <i>Lactobacillus acidophilus</i> ML14	Wheat grains <i>Triticum</i> spp. (Masr1)	• Enhance plant growth, improve wheat grain quantity and quality by 5%–40% • In addition, they boost photosynthetic pigments and gas exchange characteristics • Enhance their tolerance to drought and heat stress, and increase their growth and productivity	El-Saadony et al., 2021
<i>Pseudomonas gessardi</i> and <i>Pseudomonas azotoformans</i> + cerium oxide nanoparticle	Fenugreek plant	• Increases the shoot and root length of fenugreek plant with only 75 ppm of CeO₂ in the nanocomposite • Prevents bioaccumulation	Sonali et al., 2022
Zinc-oxide nanoparticles (ZnO-NPs) and PGPR contain phosphorus- and potassium-solubilizing, nitrogen-fixing siderophore activity performing PGPR	Maize (<i>Zea mays</i> L.)	• Increase relative water content by 43%–50% and plant biomass • Utilizing rhizobacteria-infused biofertilizer alongside ZnO-NPs has the potential to be a highly efficient bioresource for enhancing the growth of maize plants in the presence of arsenic stress	Khan et al., 2022
ZnO nanoparticles in combination with Zn biofertilizer	Wheat (<i>Triticum aestivum</i>)	• With the application of ZnO-NPs and biofertilizer, there was a substantial improvement in various plant growth indicators: total length, fresh weight, dry weight, chlorophyll content, and carotenoid content increased by 14.6%, 37.5%, 40%, 30.9%, and 31.7%, respectively • Protein levels, grain yield, and zinc content in the grain experienced significant boosts, with increases of 30.7%, 8.8%, and 66.3%, respectively • The populations of total aerobic bacteria, fungi, nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and zinc-solubilizing bacteria showed remarkable growth, with increments of 99%, 34%, 31%, 166%, and 1400%, respectively	Salceem et al., 2023
Nano-zeolite-loaded nitrogen and biofertilizers (HNB)	Caraway (<i>Carum carvi</i> L.)	• Significant improvement over control in both growing seasons	Mahmoud et al., 2017
Combination of application of TiO ₂ nanoparticles and arbuscular mycorrhizal fungi	Sage (<i>Salvia officinalis</i> L.)	• In comparison to the unfertilized treatment, the combination of TiO₂ and Arbuscular Mycorrhizal Fungi led to a 35% increase in dry matter yield and a 35% improvement in water usage efficiency • 50% maximum allowable depletion fertilized with TiO₂ + AMF exhibited the highest content of essential oil (EO) at 1.48%, the highest yield at 2.52 g/m², and the highest concentration of <i>cis</i>-thujone at 35.84%, which is the primary ingredient in sage essential oil	Ostadi et al., 2022
Application of iron oxide nanoparticles + <i>Rhizobium pusense</i>	Green gram [(<i>Vigna radiata</i> (L.) Wilczek]	• The effects of iron oxide nanoparticles and <i>R. pusense</i> on the increase and improvement of green gram plant life, either single or a combination of both, varied substantially • Plant life cultivated with IONPs and <i>R. pusense</i>, each on its own and in mixture, had appreciably higher seed germination rates, duration, and dry biomass of plant organs and seed additives than controls	Saleem et al., 2023
Chitosan nanoparticles and arbuscular mycorrhizal fungi	Thyme (<i>Thymus vulgaris</i> L.)	• Combined application of AMF + Chitosan NPs increased thyme dry yield by 21.7% when compared to the control	Amani Machiani et al., 2023
<i>Comamonas testosteroni</i> and silver nanoparticles (AgNPs)	Linseed (<i>Linum usitatissimum</i> L.)	• AgNPs and <i>C. testosteroni</i> have the potential to serve as biofertilizers for enhancing the growth of flax crops in the presence of salinity stress	Khalofah et al., 2021

the natural environment. They enable the controlled release of fertilizer while preserving its quality. Biofertilizers provide an environmentally friendly alternative that decreases use of chemical fertilizers, while also providing long-term benefits to the soil (Du et al., 2018).

4. Formulation of NBF

NBF is a product that combines NPs and biofertilizers. It improves plant nutrient usage efficiency by slowly releasing nutrients. It has the capability to improve soil properties by having long-term effects on the physical, chemical, and biological components of the soil. NBF production process involves the encapsulation of NPs within biofertilizer. This serves to protect the bacterial strains from mechanical stress and enhances the delayed nutrient release, thereby boosting the product's efficacy. This encapsulation method, which protects biofertilizer cells in a nanomaterial capsule, is also known as encapsulation. It uses biodegradable, non-toxic ingredients such as calcium alginate and starch. Bacterial strains show enhanced development when mixed with starch (Du et al., 2018, Vafa et al., 2021).

5. NBF in Improving Soil Health and Crop Productivity

Extensive and uncontrolled use of chemical fertilizers nowadays has side effects including soil structure disruption, water source contamination, pollution, soil toxicity, and nutrient leaching, all of which impact the ecosystem and human health. It is important to prioritize soil health management for productive and sustainable agriculture. Proper soil nutrient management is essential to meet the agricultural demands while sustaining the health of the environment (Janmohammadi et al., 2016; Mahapatra et al., 2022). Table 1 is a summary of several research results showing improvements in soil health and increased crop yields after NBF application.

5.1. NBF Improves Soil Health

Comamonas testosteroni was selected to alleviate the salinity threatening plant growth because it was previously used as a salinity challenger up to 3% concentration, the application of *C. testosteroni* biofertilizer paired with silver NPs (AgNPs) ought to alleviate the salinity threatening plant

growth. Salinity impacts photosynthesis by reducing stomatal conductance, altering pigment awareness, and affecting the chloroplast ultrastructure. These findings suggest that salinity causes chlorophyll loss resulting in reduced photosynthesis, while AgNPs and *C. testosteroni* may want to improve plant improvement controllers or boost plant nutrient consumption (Khalofah et al., 2021).

Furthermore, using NBFs can increase soil biological qualities, such as boosting the overall number of microorganisms in the soil. The use of ZnO NPs in conjunction with Zn biofertilizer resulted in greater populations of total aerobic bacteria than the control, with Zn-NBF achieving 99% days after sowing and the control achieving 69% DAS. The population of phosphate-solubilizing bacteria increased by 166% on Pikovskaya's agar and by 40% on Zn-NBF after 120 days. Similarly, when Zn-NBF was used, the population of Zn-solubilizing bacteria grew up to 1400% compared to 47% in the control (Saleem et al., 2023).

5.2. NBF Advancing Plant Growth and Productivity

NBF enhances the solubility of the applied fertilizer and minimizes the leaching of the fertilizer into the soil (Ali et al., 2021). Furthermore, it improves the crop quality by increasing the production of secondary metabolites, which encompass both nonenzymatic (phenols and flavonoids) and enzymatic (catalase, superoxide dismutase, and peroxidase) compounds. These metabolites not only extend the shelf life of fruits and vegetables, but also offer health benefits (Paschalidis et al., 2021). When applied to plants, the collaborative mechanism of action between biofertilizers and NPs leads to enhanced responses. It triggers various plant systems responsible for promoting plant growth and productivity. In addition, it mitigates the adverse effects of harmful substances and restricts or inhibits the growth of pathogens in the plant rhizospheres.

The Bio-SeNPs (100 mg/mL) significantly increased spike, root and shoot's length and weight, grain quantity in spike, and 1000 grain weight by 5–40% compared to control with a relative increase of about 20% over Che-SeNPs (100 mg/mL) (El-Saadony et al., 2021). The alterations in the overall length, fresh weight, and dry weight of *Triticum aestivum* were assessed after treatment with a combination of Zn-biofertilizer and ZnO-NPs. When amended with ZnO-NPs the total length, fresh weight, and dry weight of the wheat plant increased significantly by 14.6 %, 37.5 %, and 40 %, respectively compared to the control. The spikelet per spike, spike length, grains per spike, and grain yield increased by

8.9 %, 10.7 %, 3.4 %, and 3.5 %, respectively when amended with bulk ZnO. While, an increase of 25 %, 32 %, 9.7 %, and 8.9 % in spikelet per spike, spike length, grains per spike, and grain yield, respectively was observed compared to control when ZnO NPs were used (Saleem et al., 2023).

Figure 3 shows how plant cells respond to water stress and the impact of applying NPs and biofertilizers. When subjected to these treatments, the plants activate their antioxidant systems, protecting the cell membrane and organelles from the harmful effects of stress. In addition, there is an elevation in the production of growth hormones like indole acetic acid and cytokinin, coupled with a reduction in stress hormones such as abscisic acid. These alterations contribute to the plant's enhanced ability to withstand stress, increasing the likelihood of successful crop establishment in demanding environmental conditions (Bibi et al., 2022).

Figure 4 shows the manufacturing flow and benefits of NBF in making agriculture sustainable. NBFs offer a multitude of benefits and present novel opportunities for advancing sustainable agriculture and addressing climate change. NFs refer to NPs containing both macronutrients and micronutrients, which are applied to crops in a controlled and intelligent manner because they are environmentally secure and boost seed germination, soil fertility, nutrient usage efficiency, and

yield. NFs appear to be an incredible and promising alternative to artificial fertilizers (Ali et al., 2021). The synthesis and development of NFs is planned for a long time, with the goal of overcoming the problem of inorganic fertilization, which is expensive and environmentally harmful (Chugh et al. 2021). Biosynthesized NFs represent the most recent and technologically advanced methods for delivering mineral nutrients to plants. The ability of a biological process to intricately control the shape of the particles is a significant advantage (Jakhar et al., 2022).

6. Challenges and Future Perspectives of NBFs

NBFs represent a significant breakthrough in the endeavor to enhance soil health and promote sustainable agricultural crop productivity. However, focus on research about them has not yet reached the level of practical implementation by farmers. This includes aspects such as NBF formulation, soil health improvement, crop enhancement percentages, challenges faced by NBFs, and their prospects, which are still in the research phase and have not yet been applied at the community or farmer level. Despite these challenges, continuous research and innovation hold the promise of creating a more

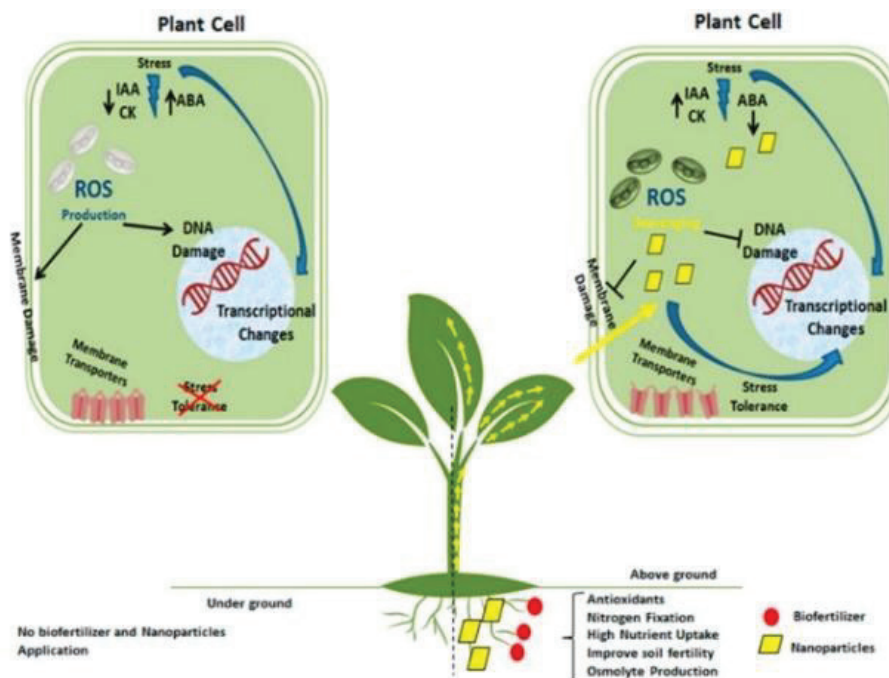


Figure 3. The response of plant cells under water stress and the effect of the application of nanoparticles and biofertilizers (Akhtar et al., 2022)

Abbildung 3. Die Reaktion von Pflanzenzellen unter Wasserstress und die Auswirkungen der Anwendung von Nanopartikeln und Biodüngern

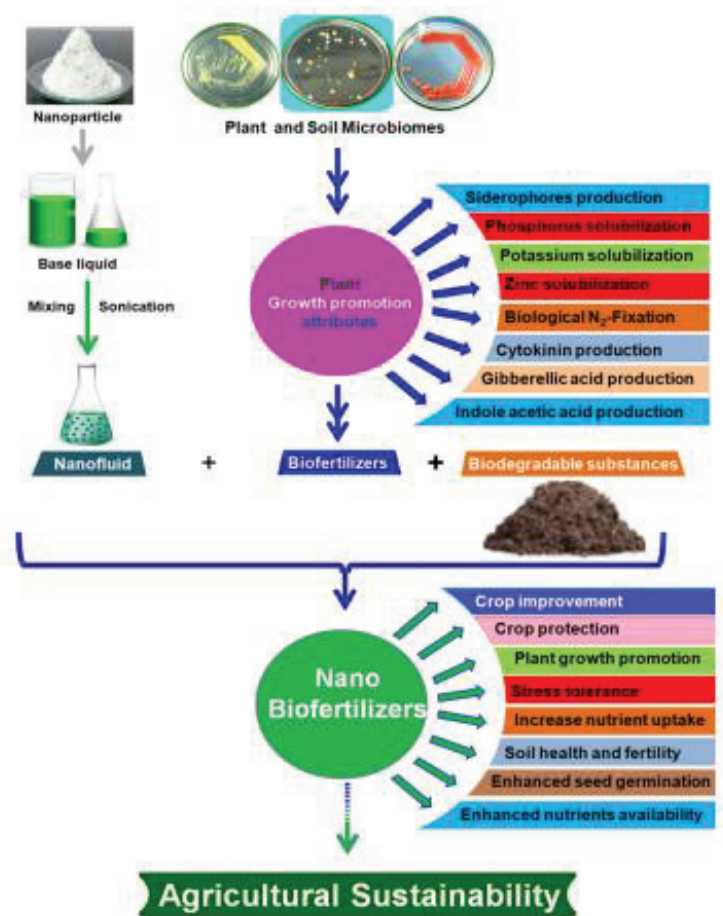


Figure 4. Nano-biofertilizers for agricultural sustainability (Yadav et al., 2023)

Abbildung 4. Nano-Biodünger für eine nachhaltige Landwirtschaft

sustainable and productive agricultural sector. Looking further, the use of NBFs has the potential to lead to a more sustainable and healthy future for global agriculture. The findings show that NBFs' chances for improving the sustainability of food crops are strongly dependent on their capacity to efficiently distribute nutrients, promote a better soil ecology, and increase crop yields. This indicates the important part they can play in determining the future of agriculture.

7. Conclusion

The utilization of chemical fertilizers disrupts the ecosystem and has adverse effects on human health. In contrast,

NBFs enhance plant growth, improve nutritional quality, boost productivity, prolong shelf life, and enhance resistance mechanisms against both biotic and abiotic stressors. Through the activation of various mechanisms, NBFs contribute to maintaining nutrient levels in the soil, thereby promoting better crop development and increasing the yield.

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