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REVIEW

Nano-biofertilizer: An Emerging Eco-friendly Approach for Sustainable Agriculture

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Abstract In this review, the authors focused on the applicability of nano-biotechnology in fertilizer development to improve the nutrition dynamics of the soil–plant system for sustainable crop management. Indiscriminate uses of chemical fertilizers have caused serious degradation of soil fertility, environmental pollution, pest resistivity, loss of biodiversity and economic losses. Hence, researchers and scientists have shifted their attention to a safer and productive means of fertilization for agricultural practices. Nano-biotechnology, with the potential properties of nanomaterial and biofertilizer, helps for the development of novel, low-cost, eco-friendly nano-biofertilizer. The literature on the role of nano-biofertilizer in plant and soil systems demonstrated that it acts efficiently for enhancement of agricultural productivity. They act synergistically providing higher retention of soil moisture and essential plant nutrients due to nanomaterial coating as well as microbial revitalization due to the bioorganic component containing plant growth promoters through direct and indirect interactions like biofertilization, rhizoremediation, disease resistance, etc. A review on nanotechnology-based biofertilizer formulation for sustainable agriculture development is discussed in this paper. The authors focus on the literature-based evidences and outstanding concerns of nano-biotechnological researches on the role of nanoformulated organic manures with key nutrients on crop growth and management. Literature-based evidences showed the profound role of nano-biofertilizer in benefitting crop growth and soil quality. The present review summarized various soil- or field-based studies with nano-biofertilizers and its significance over biofertilizer. It is anticipated that the development and validation of nano-biofertilizer that are non-disruptive to existing bulk nanofertilizer production systems will motivate the industry's involvement in nano-biofertilizer.

Keywords Nano-biofertilizer · Soil nutrient status · Plant growth · Eco-sustainable approach

Significance Statement Nanotechnological approach for sustainable agriculture production has been reviewed. An integrated approach of nano- and biofertilizer suggested as a better alternative against chemical fertilization. Nano-biofertilizer acts beneficially in maximizing nutrient uptake, retaining water by plant and soil system. Nano-biofertilizer contributes significantly to promote crop yield and quality. It may be preferred to get rid of chemical fertilizer deposition in soil and eutrophication into the water system.

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Introduction

Chemical fertilizers play a vital role in increasing global agricultural production to satisfy the uprising food demand of the world overgrowing population [1]. The three major types of commercial fertilizer used mostly are nitrogen (N), phosphate (P) and potash (K). It is reported that world ammonia consumption for agricultural and industrial uses grew consistently over the past 10 years at a compound annual growth rate of 2.0 percent. Phosphorus (P_2O_5) demands also increased very high, which reported amount of 39 $\times$ 10^5 tons increase during the year 2014–2018 [1]. Though the amount of total P in the soil is relatively high, its availability to plants is often low [2]. Even though inorganic fertilizers are key factors to increase the crop yield and productivity, it is less recommended for future agriculture perspectives due to its low nutrient assimilation

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efficiency and high nutrient loss percentage through soil and water runoff which causes environmental pollution, lesser crop yield, emergence of pests, disease and pathogens and loss of biodiversity [3]. Low utilization efficiency of commercial fertilizers toward plants is due to imbalanced fertilization, low nutrient use efficiency (i.e., 20–50% for Nitrogen, 0–25 percent for Phosphorus), high mineral leaching, low nutrient assimilation potency, low organic matter content and low intensities of multi-micronutrients in soil [4, 5]. Due to these critical challenges faced, chemical fertilizers contribute less toward plant growth and more toward its deposition in soil and eutrophication into the water system [6]. Scientific and agricultural reports mentioned that too much dependence on chemical fertilizers, i.e., ammonia, urea, nitrate or phosphate compounds in agricultural practices, inevitably leads to severe damage to both environmental ecology and human health [7].

Therefore, over the past decade, great efforts were done by researchers to replace chemical fertilizer with better eco-safe alternatives. Nanotechnology has emerged as the sixth most revolutionary technology after the green revolution of the 1960s and the biotechnology revolution of the 1990s. Modern agriculture is intended to infuse nanotechnology, biotechnology and other disciplines of science into agricultural sciences to transform traditional farming practices to precision agriculture that ensure food security to the growing population of the country in the cost-effective and eco-sustainable way [8]. As better alternatives, nano- and biofertilizer has gained momentum and become increasingly popular in the agricultural sector [8, 9]. It is preferred over chemical fertilization due to the increasing efficiency of resource utilization, minimum fertilizer consumption, sustained release of agrochemicals in a slow-release way, increased crop production and yield with the least disturbance to soil structure [10]. Nano-biofertilizer is a step ahead in the innovative field of agriculture, toward the joint formulation of biofertilizer and nanofertilizer into nano-biofertilizer, a more effective alternative for eco-sustainable agriculture [11]. "Nano-biofertilizer" is a hybrid combination of nano- and biofertilizer developed by the formulation of organic fertilizer (biofertilizer) to nanosize (1–100 nm) with the help of certain nanomaterial coating [12]. Though the exact definition of nano-biofertilizer is not given in the past literature, nano-biofertilizer terminology is well explained and quoted by a few researchers in the scientific publications [12–15]. On the basis of literature explanation, nano-biofertilizer can be considered as nano- and biofertilizer "cocktails" having high efficiency of both fertilizer benefits, help in providing slow release of nutrients in a controlled way at longer period of crop growth stages with improved nutrient use efficiency and ultimately help in promoted crop yield and productivity [13]. Enhanced nutrient use efficiency, low-quantity fertilizer requirement at large-scale utilization, price effective, mass-scale production within a shorter period, eco-safe perspectives and renewable fertilization are the salient features of nano-biofertilizer [11, 12]. Bio-organic components (including urea and plant growth-promoting microorganism) of nano-biofertilizer contribute diversified benefits to soil and plant system due to the stimulation of nitrogen-fixing ability, phosphate solubility and increased level of plant growth hormones generation, improving soil microbial condition [16, 17]. Nanomaterial coating of biofertilizer may help in improving the solubility and dispersion of insoluble nutrients in the soil, reduce soil absorption and fixation, increase nutrients bioavailability to soil and plant and allow its slow and sustained release with their direct internalization and uptake by crops [18]. Due to the combined advantages of both nanoparticle and biofertilizer, nano-biofertilizer is best suited for efficient release of nutrients to plants in controlled and slow-release way, providing the available nutrients to plant gradually over the longer growing period [12].

Nano-biofertilizer: Progressive Evolution of Sustainable Agriculture

The use of chemical fertilizers to boost agricultural productivity is common agriculture practices for several years. However, in the past decade, scientists well concern with its associated adverse effects such as environmental toxicity and long residual action resulting from excessive use of chemical fertilizers. This prompted the urge to search for a nontoxic eco-friendly alternative to achieve the desired goal to increase the agriculture productivity without associated side problems. In recent decades, bio- and nanofertilizers have been preferred over chemical fertilizers to ensure biosafety of agriculture [19]. Biofertilizer was mainly constituted of live formulations of beneficial microorganism such as plant growth-promoting rhizobacteria, i.e., *Rhizobium*, blue-green algae (BGA), the fungal mycorrhizae, bacterium *Azotobacter*, *Azospirillum*, phosphate-solubilizing bacteria like *Pseudomonas* sp. and *Bacillus* sp., which augment the nutrient supply to crops by increasing biological nitrogen fixation and solubilization of insoluble complex organic matter to simpler form, to make them biologically available to plants. It increases soil's ability to hold moisture, enhance soil nutrient (nitrogen and phosphorus) availability to plants and keep the soil relatively healthier via enrichment of soil microbial status and helps the soil aeration and natural fertilization [20]. However, this exciting approach also comprises some major issues such as having poor shelf-life, on-field stability, performance under fluctuating environmental conditions (temperature, radiation, pH sensitive), not suitable for long term, shortage of beneficial bacterial strain, susceptible to desiccation and most importantly the high required dose for large coverage area [21]. Interestingly, nanoparticle-based formulations of biofertilizers have shown superiority in terms of confronting all these issues [8]. So, modern agriculture is embracing the innovative approach of nano-biotechnology for the development of nano-biofertilizer to combat major issues of crop production, food security, sustainability and eco-safety [22, 23]. In nano-biofertilizer formulation, biofertilizer (containing nutrients and plant growth promoter bacteria) is coated in nanoscale polymers (nanoencapsulation) [24]. Nanoencapsulation technology could be used as a versatile tool to protect biofertilizer components containing PGPR, enhance their shelf-life and dispersion in fertilizer formulation and allow the controlled release of the PGPR [25]. It may help in slow and steady release of nutrient to crop plants without any unintended loss [26]. Nano-biofertilizer acts significantly to benefit the farmers in the intensified way by improving the nutrient release characteristics and field performance and reducing economic expenses not only by cost reduction but by reducing application losses as well. It is an eco-sustainable, renewable approach, can accelerate the efficiency of nutrients utilization (N, P and K), enrich microbial population beneficial for soil, improve the activity of related enzymes system, comprehensively improve the soil fertility, facilitate the improved quality of crop products and improve the disease resistance of crops [12]. The role of nanofertilizer on enhancing plant growth and nutritional security in soil/plant system is diagrammatically presented in Fig. 1.

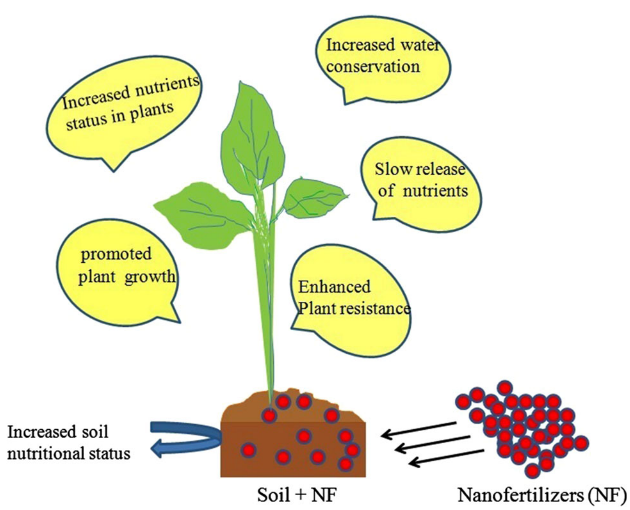

Fig. 1 Role of nanofertilizer on enhancing plant growth and nutritional security in soli/plant system

Nano-biofertilizer Applicability to Improve Crop Growth and Nutrient Status

Nano-biofertilizer promoted plant growth and nutritional quality by exerting diversified effects on soil and plant systems. Nanoencapsulation of organic nutrients using nanomaterials, i.e., chitosan, zeolite and polymers, helped in the slow and sustained release of nutrients to plants [27]. Due to surface coatings of biofertilizer by nanoparticles, the stability of nutrients increased. Increased surface area, nanosize and higher reactivity of NP-coated fertilizer could allow for enhanced interaction and active uptake of these nutrients for crop fertilization, as well as provide bioavailable nutrients supply to the plants in a sustainable way at their need at different growth stages [8]. This stability reduced the rate of dissolution of the fertilizer and allowed the slow and sustained release of nutrients by nano-biofertilizer [28]. Bioorganic components (i.e., beneficial bacterial PGPR or fungal inoculants) of nano-biofertilizer benefitted synergistically via enriching the soil nutrient status by various mechanisms such as fixation of atmospheric nitrogen by plant root via rhizobacteria, production of siderophores that chelate the metal elements and make them available to the plant root, phosphate solubilization due to the presence of phosphorus solubilizing bacterial and fungal strains, and phytohormones synthesis [29, 30].

Due to synergistic benefits of nanomaterial and biofertilizer component, nano-biofertilizer showed intensified response on improving crop growth, productivity, yield and quality attributes of crops as reported in several research studies. This improvement in crop growth and quality attributed by nano-biofertilizer application is due to their significant effects of these major plant traits.

To Promote Plant Morphological and Physiological Development

Application of nano-biofertilizer intensifies the growth of crops by optimizing photosynthesis, nutrients absorption efficiency, higher photosynthate accumulation and nutrients translocation to the economic parts of the plant, leading to increased plant productivity and quality. Dikshit et al. [16] studied the use of nano-biofertilizer on agricultural crops and reported that nano-biofertilizer developed by entrapping biofertilizer (including growth-promoting microorganism; *Pseudomonas fluorescens*, *Bacillus subtilis* and *Paenibacillus elgii*) within silver and gold nanoparticles was proved to be strongly effective in promoting crop growth in various agricultural crops with respect to response observed in crops when nanoparticles directly applied as fertilizer. Nanostructured fertilizer containing neem cake + PGPR also offers potential efficacy in promoting crop productivity in some leguminous crops via stimulating germination potency of crop seedlings and delivering doped nutrients to plants in an efficient way [31].

To Increase Nutritional Security in the Soil/Plant System

Continuous use of chemical fertilizers depletes soil essential soil nutrients that are naturally found in fertile soil. Excess soil acidification is a major factor for deteriorating soil fertility [31]. Low soil fertility and nutrient imbalance of soils have been the major challenges faced by farmers as the deficiencies of nutrients in soil are highly correlated with a decline in crop productivity and low food nutrition value [32]. Nano-biofertilizer provides a sustainable, low-cost and efficient integrated nutrient management in solving these drawbacks. It enhanced the nutrient absorption and assimilation by plants as well as minimized the soil nutrient losses by leaching, gasification or competition with other organisms [33]. Bioorganic components of nano-biofertilizer (PGPR) help in nitrogen-fixing, phosphate-solubilizing and restoring soil nutrient richness, and nanoparticle coating of biofertilizer helps in the slow release of nutrients in a synchronized way as per crop demand [34].

Nano-biofertilizer: Role in Crop Protection

Nano-biofertilizer acts significantly not only to promote crop productivity, nutritional quality, shelf-life and water conservation potency, but it also acts as resistance inducing agent to increase plant resistance against pest and disease pathogens. Gatahi et al. [35] examined the effects of nano-biofertilizer in tomato crops infected with bacterial wilt disease (caused by *Ralstonia solanacearum*) and examined its pest-resistant role against wilt disease. Gouda et al. [26] also studied the role of nano-biofertilizer (containing PGPR; *Pseudomonas fluorescens, Bacillus subtilis, Paenibacillus elgii and Pseudomonas putida*) against harmful fungal and bacterial pathogens within the rhizosphere of leguminous crops and reported its defensive role in protecting these crops against different pathogens. Increased adhesion of beneficial bacteria onto the roots of oilseed rape and protection of crop against harmful fungal infection were experimentally proved through titanium nanoparticle-coated nano-biofertilizer application by Mishra and Kumar [36]. Nanoclay-coated biological agent containing *Trichoderma* sp. and *Pseudomonas* sp. can be used for control of fungal–nematode disease in rabi crops and to provide crop resistance against abiotic stressed condition [37].

Current Status of Nano-biofertilizer in Research and Development (R &D)

International Status

Scientists around the world are focusing on the potential role of nano- and biofertilizer for agricultural aspects. However, the past literature showed that few studies conducted on the role of nanoformulated biofertilizer (nano-biofertilizer) to improve the agriculture productivity. Most of the studies on environmentally sustainable nano-biofertilizer development have been reported by Iranian researchers till date [14, 15, 38–40]. Mardalipour et al. [15] from Iran studied the crop plant spring wheat variety and reported that foliar application of Biozar® as nano-biofertilizer significantly increased the crop growth, seed yield and yield components of the wheat crop. It also efficiently improves the nutrient absorption capacity of wheat plants. Farnia and Omidi [14] from Iran studied on the *Zea mays* crop and found the significant increase (approx 1 + 1/2 fold) of grain yield, at 7-day treatment of crop with nano-biofertilizer (nano-Zn + biofertilizer). Jakienė et al. [41] from Lithuania studied on the sugar beet plants and reported a great potential of nano-biofertilizer for optimizing sugar beet development via improving morphological and physiological parameters, i.e., leaf area (19.6%), root biomass (42.6%), net photosynthetic productivity (15.8%), sucrose content 1.03%, resulting in 19.2% increase in the yield of white sugar. Safaei et al. [39] studied on the applicability of nano-biofertilizer (nanopharmax + humic acid) in black cumin (*Nigella. sativa*) and reported the increased level of nutritional ingredients in *N. sativa* by this nano-biofertilizer. Sabir et al. [42] from Turkey experimented on the efficiency of nanofertilizer alone or nanofertilizer + biofertilizer (*Ascophyllum nodosum*) on grapevine plant and revealed that nano-biofertilizer in combined state had particularly high contribution to improvement of vine growth, yield, berry quality attributes and leaf nutrient level in grapevines (cv. "Narince") grown under alkaline soil condition with respect to nanofertilizer alone. Mir et al. [43] analyzed the effect of nano-biofertilizer (azetobarvar + phosphorbarvar + chelated nanofertilizers) on nutrients, carbohydrate and pigments content on different plants and evaluated that it significantly improved plant nutrient status, chlorophyll content and carbohydrate on agricultural crop forage sorghum (Speed Feed hybrid).

In India

Researchers in India also prompted interest in the nanoformulation of commercial fertilizers into high-efficient nano-biofertilizer by fabricating the biocompatible nontoxic nanomaterial with bioorganic components. Kumari et al. [44, 45] experimented on the biogenic synthesis of silver nanoparticle (AgNP) in legume crop *Vigna radiata* as well as the extracellular synthesis of AgNP using metabolites from bacterial strain *Pseudomonas aeruginosa*. Kumari and Singh [46] presented a review on applicability of silver nanoparticles in agriculture and pointed out that silver nanoparticles can itself be used as nanofertilizer or used as a nanoencapsulating agent for the formulation of fertilizer into nanofertilizer. Barsaiya and Singh [47] studied on the biogenic synthesis of zinc nanoparticle using microorganism *Pseudomonas aeruginosa* and reported that ZnONP has broad-spectrum antimicrobial property. Due to broad-spectrum antimicrobial characteristics, ZnONPs can be better exploited in agriculture farming for the crop resistance. Shukla et al. [13] from Allahabad University documented the technical report to Ministry of Agriculture on prospects of Nano-biofertilizer in Horticultural Crops of Fabaceae family and reported a significant increase in crop yield and nutritional value in crops by intensifying the efficacy of biofertilizer by introducing nanoparticle leading toward the development of nano-biofertilizer. They reported that in India, under limited availability of land and water resources use of nanomaterials such as silver and gold nanoparticles could be more effective for nanofertilizer development. But the use of these nanomaterials alone as a fertilizer may not be preferred for fertilization due to some side effects. However, when these nanoparticles are used in combination with biofertilizer containing *Pseudomonas fluorescens, Bacillus subtilis* and *Paenibacillus elgii,* they act as good plant growth promoter. Mukhopadhyay and De [37] studied the role of nanoclay-coated biofertilizer (containing *Trichoderma* and *Pseudomonas* species) on crops and reported its positive role in enhancing water retention capacity and nutrient use efficiency in rainfed Rabi crops resulting in a significant increase in crop productivity. Celsia and Mala [48] from Tamilnadu fabricated the nanostructured NPK fertilizer system associated with neem cake and plant growth-promoting rhizobacteria (PGPR) and reported its significant role in increasing seed germination potency in *Vigna radiata* plant. Further, Mala et al. [31] extended this experimentation and reported that this nano-biofertilizer treatment acts positively in improving yield attributes of *Vigna* crop by stimulating the biochemical reactions associated with. They stated that PGPR helps in nutrients solubilization and neem cake (NC) acts as an organic carrier/vehicle for efficient transport of insoluble nanofertilizers and PGPR. Rajak et al. [49] experimented on a combination of biofertilizer (*Piriformospora indica;* plant growth-promoting fungus) + copper nanoparticle (CuNPs) on leguminous crop *Cajanus cajan* and showed that combined treatment of nano + biofertilizer (nano-biofertilizer) could promote plant growth and vitality more efficiently. Few reports on national and international studies on nano-biofertilizer response on plant growth and yield attributes of different crops are summarized in Table 1.

Recommendation and Future Perspectives

To achieve nutritional security in the limited land and resources, the perspective of the novel approach of biotechnology and nanotechnology for sustainable crop management will always be appreciated. Nanotrapped fertilizer loaded with biological agents can go long-term benefits of crops. However, simultaneously risk and negative perception of nanotechnological interventions in the agricultural sector may not be overlooked and can be seriously taken. Keeping both positive and negative aspects of nano-biofertilizers in mind, there is dire need to make extensive efforts toward improving the futuristic researches to overcompensate the risk factors associated with nanoparticles and bioorganic usage.

- Laboratory-based experimentation only could not contribute to the complete acceptance of the nano-biofertilizer strategy in realistic practice and implementation in the agricultural sector. Hence, an experimental design must be set in a natural environment to give a precise depiction of the environmental impact of nanoparticles.
- Scientific and government-based safety assessment should be undertaken for validating the permissible and safety limit of nanoparticles dose, and managing the shortcomings of organic waste used needs to be explored and clarified based on realistic natural field conditions.
- An understanding of the biodegradability and biomagnification transfer effects of nano-biofertilizer applications on plants must be included to gain comprehensive knowledge of its toxicity.

Conclusion

The excessive use of fertilizers in the agriculture sector to increase the crop production resulted in distorted soil fertility by altering soil physicochemical integrity, affecting plant nutritional quality and led to other non-desirable

Table 1 Several national and international studies on nano-biofertilizer response on plant growth and yield attributes in different agricultural crops

S. no.	Nano-biofertilizer	Experimental plant	Response	References	Country
1.	Nanosilver and nitroxin biofertilizer	*Solanum tuberosum* L.	Application of nanosilver and nitroxin biofertilizer in combination can reduce the amount of mineral nitrogen fertilizer to half, while producing higher tuber yield to these treatments alone	[38]	Iran
2	Nanofertilizer + humic acid	*Nigella sativa* L.	Combination of this fertilizer improves due to having nutritional ingredients and different physiological effects improve *N. sativa* performance	[39]	Iran
3.	Nanotitanium + biofertilizer containing azorhizobium	*Tritico secale*	In triticale, grain yield, grain weight, leaf Cd, seed Cd and chlorophyll content increase approx 1 + ½ to 2 times more at nTiO$_2$ + azorhizobium treatment in responsive nTiO$_2$ alone in cadmium (Cd)-stressed triticale, revealing a significant mitigating effect against Cd stress	[40]	Iran
4.	Nanofertilizers of Fe, Zn and Mn + biofertilizers containing *Azotobacter* and *Pseudomonas bacteria*	*Triticum aestivum* L.	Nano-biofertilizer increased spike length, spike number, seed number, seed number in spike, seed weight and growing period length, leading to high growth and plant yield	[15]	Iran
5.	Nano-Zn + biofertilizer	*Zea maize* L.	Increased production of maize grain yield, after 7-day application of nano-biofertilizer	[14]	Iran
6.	Biofertilizers (azetobarvar 1 + phosphorbarvar 2) + chelated nanofertilizers	Forage sorghum (*Speedfeed hybrid*)	The highest chlorophyll a, chl.b, carotenoid and carbohydrate were achieved from combined biofertilizers	[43]	Iran
7.	Biological nanofertilizer containing bacteria	Ornamental plant *Buxus hyrcana* Pojark	1.80 g/pot drench + 2.00 g/l spray of bio-nanofertilizer specially for ornamental plants introduced as a good treatment for proliferation of *Buxus hyrcana* Pojark	[50]	Iran
8.	Bioorganic nanofertilizer "Nagro"	*Beta vulgaris* L.	Showing great potential for optimization of sugar beet development, productivity and quality parameters	[41]	Lithuania
9.	Nanofertilizer + sea weed (Ascophyllum nodosum)	*Vitis vinifera* L.	Nano-Ca based fertilizer had a significant role on vine growth, yield, berry quality attributes and leaf nutrient and would be recommended to use for alleviating the adverse effects of abiotic stress for sustainable grape production	[42]	Turkey
10.	Chitosan immobilized silica nanocomposites + Biocontrol agents (*Bacillus subtilis, Gomus mossease, Trichoderma viridae*)	*Lycopersicum esculentum* L.	Increasing resistance of tomato variety against tomato bacterial wilt caused by *Ralstonia solanacearum*	[35]	Kenya
11.	Bio-based polyurethane-coated fertilizer + nanosilica	–	Acts as superhydrophobic controlled released fertilizer and significantly improves the controlled release characteristics of fertilizer	[51]	China
12.	Gold nanoparticles + rhizobacteria	Some horticultural crops of *Fabaceae*	This nano-biofertilizer shows very good growth promotion in vitro studies	[12]	India
13.	Nanophosphate and potash fertilizer + neem cake and PGPR	*Vigna raidata* L.	This nano-biofertilizer treatment stimulated germination and biochemical characteristics in *Vigna radiata* leading to increased yield and yield attributes of *Vigna* crop	[30]	India

Table 1 continued

S. no.	Nano-biofertilizer	Experimental plant	Response	References	Country
14.	Nanoclay polymer composite + biological agents *Trichoderma harzianum*	In rabi crops	Helps significantly in promotion of rainfed agriculture via increasing water retention capacity, nutrient use efficiency, productivity and control of fungal–nematode disease	[37]	India
15.	Nano-NPK fertilizer + neem cake, plant growth-promoting rhizobacteria	*Vigna raidata* L.	Accelerated the enzyme activity during germination and responsible for the observed an increase in seed vigor index	[48]	India
16.	Copper nanoparticles and plant growth-promoting fungus (*Piriformospora indica*)	*Cajanus cajan* L.	Copper nanoparticles in combination with *P. indica* enhanced the vitality, growth and productivity of *C. cajan* with respect to Cu nanoparticle alone	[49]	India
17.	Chitosan nanocomposite + chicken feather as bioorganic compound	*Solanum lycopersicum* L. *Brassica junceae* L., *Trigonella foenumgraecum* L.	These nano-biocomposites in small amount could provide better nutrients for the plant growth	[52]	India

environmental and ecological consequences. A strategy should be designed to develop an eco-sustainable way to improve agricultural productivity with least ill effects. The advanced nano-biotechnology tools and techniques can improve the way of sustainable agriculture management and have a promising future in the upcoming age of agricultural mechanization. Nanoparticles loaded with organic fertilizers have a great potential as "nutrient booster" allowing the slow and sustained release of nutrients to plants to achieve the nutritional supply to plant throughout the growth period. Wherever possible, organic manures and other organic materials should be used in an integrated fashion with nano-based fertilizers to ensure efficient and effective nutrient use as well as better soil health. Nano-biofertilizer could promote several benefits to plants, i.e., slow-release characteristics, enhanced stability of functional ingredients, use of small dose, limited nutrients loss by degradation and leaching, masking soil nutrient depletion and improving crop yield attributes. Hence, the future of the nano-based agriculture improvement is very bright and it may be proven not only an eco-friendly approach but also an economical method for sustainable agriculture development.

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Compliance with Ethical Standards

Conflict of interest The authors have no conflict of interest to publish this manuscript.

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