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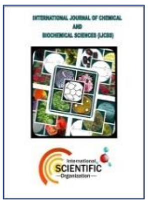

Environment friendly nanofertilizers for sustainable crop management: A review

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Abstract

Nutrient fertilization plays a key role in maintaining soil integrity and improving crop quality and productivity. The precise management of nutrients in agriculture crops is of huge concern worldwide as it depends mainly on chemical fertilizers. Indiscriminate applications of conventional chemical fertilizers have resulted in decline in soil natural fertility, environmental pollution, and biodiversity and economic losses. Therefore, researchers and scientists drew attention to safer and more efficient fertilization methods for agriculture practices. Nano-biotechnology, with the potential attributes of biofertilizer and nanomaterial, helps to develop innovative, low cost, environmentally friendly nano-biofertilizers. Literature survey on roles of nano-biofertilizers in soil and plant systems suggests that they works effectively to increase crop productivity. Nano-biofertilizers work synergistically ensuring greater retention of soil moisture and essential nutrients for plants because of nanomaterial coatings and microbial revitalization. Present review focuses on literature based evidences related to nano-biotechnology research on the roles of nano-biofertilizers in crop management. Literature based evidence has shown the intense role of nano-biofertilizer in improving soil fertility and crop yield. Various field/soil studies are discussed to highlight the significance of nano-biofertilizers over chemical fertilizers.

Key words: Nano-bio fertillizers, chemical fertillizers, nano-biotechnology, nano-coatings, sustainable agriculture, crop management

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1. Introduction

Augmentation of food production to meet the hunger of growing population applying sustainable practices is one of the biggest challenges of the world. The current global production (7000 million) is predicted to increase over time and reach around 9000 million by 2050. It has been reported that 60% to 100% more food will be required to feed the growing population [1]. To overcome this condition, the use of chemical fertilizers, disease resistant and genetically modified plant varieties has become popular in agricultural communities for past five decades. It has been observed that one-third of crop yield depends on the fertilizers and rest is attributed to the efficiency of other farming practices. However, the nutritional efficiency of conventional fertilizers (added directly to soil or foliarly applied) slightly exceeds 30 to 40%, as it depends greatly on the concentration of fertilizer finally reaching to the targeted sites [76, 80]. In true sense, very small amount that is much below the required concentration, reaches the targeted locations because of leaching loss of chemicals, hydrolysis, drift, microbial and/or photolytic degradation [81]. It was reported that in early 1970s, only 27 Kg NPK/ha was enough to produce a ton of grains, while in 2008 it was increased to 109 Kg NPK/ha to attain same yield. According to the International Fertilizer Industry Association (IFIA), global demand of conventional fertilizers was expected to reach 192.8 million tons in 2016-2017 [82]. Excessive use of conventional fertilizers results in the accumulation of toxic chemicals in the soil which may get into other compartments of the environment, causing severe environmental pollution and ultimately affect the growth of animals and plants. Therefore, in the last decade, scientists have made great efforts to replace chemical fertilizers with ecologically safe alternatives. Nanotechnology became the 6th most revolutionary technology after the green revolution in 1960s and the biotechnology revolution in the 1990s. Modern agriculture aims to introduce biotechnology, nanotechnology, and other scientific disciplines in agriculture sciences to transform conventional forming practices to precision agriculture, which guarantees food security of the growing population of the world in an economically and ecologically sustainable way. As better substitutes, nano- and biofertilizer have become increasingly popular in the agricultural communities [2-3]. They are preferred over conventional fertilizers because of enhanced resource utilization efficiency, minimum fertilizer usage, slow and sustained release of nutrients, enhanced plant growth and yield with minimal soil disruption [10]. Nano-biofertilizer is a step ahead in the revolutionary field of agriculture, toward the joint formulation of bio- and nanofertilizer into nano-biofertilizer, a more effective substitute for eco-sustainable agriculture [11]. Nano-biofertilizer is a hybrid combination of bio- and nanofertilizer developed by formulating organic (bio) fertilizer into nanosize (1 to 100nm) using some nanomaterial coatings [12]. Although the proper definition of nano-biofertilizer is not provided in previous literature, the terminology of nano-biofertilizer is well enlightened and cited by several researchers in scientific publications [12–15]. Greater nutrient use efficiency, minimal fertilizer requirement for large scale applications, effective cost, mass-scale production in a shorter time, renewable fertilization, and ecologically safe perspectives, are the main features of nano-biofertilizers [11, 12]. Bio-organic components (including urea and plant growth promoting microorganisms) 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 [16,17]. Coating of nanomaterial enhances the dispersion and solubility of insoluble nutrients in the soil, and permits their slow and sustained uptake of nutrients by decreasing soil fixation and absorption [18].

2. Nano-Biofertilizer

The use of chemical fertilizers to boost agricultural productivity is common agriculture practice 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 [4]. 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 increase 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 [2]. So, modern agriculture is embracing the innovative approach of nanobiotechnology for the development of nano-biofertilizer to combat major issues of crop production, food security, sustainability and eco-safety [5-6]. In nano-biofertilizer formulation, biofertilizer (containing nutrients and plant growth promoter bacteria) is coated in nanoscale polymers (nanoencapsulation) [7]. 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 [8]. It may help in slow and steady release of nutrient to crop plants without any unintended loss [9]. 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.

3. Utilization of Nano-biofertilizer for promoting crops growth and nutritional value

Nano-biofertilizer promoted plant growth and nutritional quality by exerting diversified effects on soil and plant systems. Nano-encapsulation of organic nutrients using nanomaterials, i.e., chitosan, zeolite and polymers, helped in the slow and sustained release of nutrients to plants [10]. Due to surface coatings of biofertilizer by nanoparticles, the stability of nutrients increased. Increased surface area, nano size 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 [10]. 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 [11-12]. 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.

4. To intensify physiological and morphological development of plant

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. A study investigated the use of nano-biofertilizer and found that fertilizer developed by the entrapping the bio-fertilizer such as growth promoting microbes (*Pseudomonas fluorescens*, *Bacillus subtilis*, *Paenibacillus elgii*) within gold and silver nano-particles was effective in promoting growth of various agricultural crops [13]. Nanostructured fertilizer containing neem cake and plant growth promoting rhizobacteria (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 [14].

5. To improve nutritional security in the Plant/soil 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 [14]. 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 [15]. 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 [16]. 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 [17].

6. 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. A study 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 [18]. Researchers also investigated the role of fertilizer containing plant growth regulating rhizobacteria (*Pseudomonas fluorescens*, *Pseudomonas putida*, *Paenibacillus elgii*, and *Bacillus subtilis*) against pathogenic bacterial and fungal strains in rhizosphere of legumes and reported its defensive role in protecting these crops from pathogens [9]. 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 [19]. 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 [20].

7. Current Status of Nano-biofertilizer in Research and Development

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 (nanobiofertilizer) to improve the agriculture productivity. Most of the studies on environmentally sustainable nanobiofertilizer development have been reported by Iranian researchers [21-23]. Iranian researchers examined a crop variety of wheat and found that foliar application of Biozar as nano-biofertilizer significantly improved the crop growth, and seed yield. Moreover, the nutrient absorption ability of investigated plants was also enhanced [21]. Another group of researchers studying Zea mays crops found a significant increase (about 1 to ½ fold) in grain yield after seven day treatment of nanobiofertilizer (nano-Zn and biofertilizer) [24]. Lithuanian researchers studied sugar beet crop and reported a huge potential of nano-biofertilizer for optimizing sugar beet development by improving physiological and morphological 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 [25]. Application of nano-biofertilizer (humic acid and nanopharmax) in *Nigella sativa* (black cumin) increased nutritional status of plant [26]. Scientists from Turkey experimented on the effectiveness of nanofertilizer and nano-biofertilizer (*Ascophyllum nodosum*) on grapevine crop and revealed that nano-biofertilizer in combined state had a particularly large contribution to improving vine growth, yield, berry quality characteristics and leaf nutrient level in crops grown under alkaline soils with respect to nanofertilizer alone [27]. Another study analyzed the impact of nano-biofertilizer (azetobarvar plus phosphorbarvar and chelated nanofertilizers) on contents of nutrients, carbohydrates, and pigments in various agriculture crops and assessed that this significantly improved the nutritional status, chlorophyll, and carbohydrate contents in sorghum crop [28]. Few reports on studies on nano-biofertilizer response on growth and yield characteristics of various crops are enlisted in Table 1.

Table 1 Effects of nano-biofertilizers on growth and productivity of various agriculture crops

Nano-biofertilizer	Experimental plant	Responses	Ref.
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	[22]
Nanofertilizer + humic acid	*Nigella sativa* L.	Combination of this fertilizer improves due to having nutritional ingredients and different physiological effects improve N. sativa performance	[29]
Nanotitanium + biofertilizer containing azorhizobium	Triticosecale	In triticale, grain yield, grain weight, leaf Cd, seed Cd and chlorophyll content increase approx 1 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	[30]
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	[21]
Nano-Zn + biofertilizer	*Zea maize* L.	Increased production of maize grain yield, after 7-day application of nano-biofertilizer	[31]
Biofertilizers (azetobarvar 1 + phosphorbarvar 2) + chelated nanofertilizers	Forage sorghum (Speedfeed hybrid)	The highest chlorophyll a, chlorophyll b, carotenoid and carbohydrate were achieved from combined biofertilizers	[32]
Biological nanofertilizer containing bacteria	Ornamental plant Buxus hyrcana Pojark	1.80 g/pot drench +2.00 g/l spray of bionanofertilizer specially for ornamental plants introduced as a good treatment for proliferation of Buxus hyrcana Pojark	[33]
Bioorganic nanofertilizer ‘‘Nagro’’	*Beta vulgaris* L.	Showing great potential for optimization of sugar beet development, productivity and quality parameters	[25]
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	[27]
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	[18]
Bio-based polyurethane-coated fertilizer + nanosilica	*Lycopersicum esculentum* L.	Acts as superhydrophobic controlled released fertilizer and significantly improves the controlled release characteristics of fertilizer	[34]

Gold nanoparticles + rhizobacteria This nano-biofertilizer	Some horticultural crops of Fabaceae	Shows very good growth promotion in vitro studies	[35]
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	[12]
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	[20]
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	[36]
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	[37]
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	[38]

8. Future Direction

To achieve nutritional security with limited resources, the prospect of a new approach to biotechnology and nanotechnology for sustainable crop management will always be appreciated. Biofertilizer encapsulated in nanoparticles can bring long-term benefits to soil and crops. However, the negative perceptions and risks associated with the use of nano-biofertilizers cannot be overlooked and can be taken seriously. Keeping in mind the both positive and negative attributes of nano-technological interventions, great efforts are needed to improve future research to overcome the risks of using nano-biofertilizers. Results of Lab-scale experiments could not be considered the complete assurance of nano-biofertilizer strategy in real agricultural practices. Hence, testing of nano-biofertilizer should be done in natural habitats by selecting an appropriate experimental design to provide an accurate description of its environmental effects. 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 bio-magnification transfer effects of nano-biofertilizer applications is necessary for comprehensive study of its toxic effects.

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