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Biological Nanofertilizer for Horticultural Crops: A Diagrammatic Mini-Review

Hassan El-Ramady [1,2], József Prokisch [2], Said M. El-Bialy [1], Taha Elesawy [1], Mohammed E. El-Mahrouk [3], Alaa El-Dein Omara [4], Tamer Elsakhawy [4], Megahed Amer [5], and Eric C. Brevik [6]

[1] Soil and Water Dept., Faculty of Agriculture, Kafrelsheikh University, 33516 Kafr El-Sheikh, Egypt
[2] Institute of Animal Science, Biotechnology and Nature Conservation, Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen, 138 Böszörményi Street, 4032 Debrecen, Hungary
[3] Horticulture Dept., Faculty of Agriculture, Kafrelsheikh University, 33516 Kafr El-Sheikh, Egypt
[4] Agriculture Microbiology Department, Soil, Water and Environment Research Institute (SWERI), Sakha Agricultural Research Station, Agriculture Research Center, 33717 Kafr El-Sheikh, Egypt
[5] Soil Improvement and Conservation Dept., Water and Environment Research Institute, Agricultural Research Center, Giza, Egypt
[6] College of Agricultural, Life, and Physical Sciences, Southern Illinois University, Carbondale, IL 62901 USA

AGRICULTURE is very important for humanity as it supplies human needs ranging from food to fiber, feed for animals and energy. The production of seedlings is of great agricultural importance, especially in horticultural nurseries. Producing vigorous and healthy seedlings like banana and strawberry using biological nanofertilizers (bionanofertilizers) is presented in this mini-review. Due to their properties, bionanofertilizers have received increasing interest in agriculture, particularly during transplanting or the production of seedlings. Many studied seedlings attributes, such as the plants' antioxidants systems, nutritional status, and quality parameters of seedlings have been improved through the use of bionanofertilizers. The most important impacts of bionanofertilizers may include enhancing production of seedlings or plants under biotic and abiotic stresses through the improvement of attributes like physiological, biochemical, and molecular characteristics. This diagrammatic mini-review will focus on biological nanofertilizers and their potential uses in horticultural crop production.

Keywords: Nanonutrients, Nano-farming, Nanotoxicology, Strawberry, Banana, Transplants

1. Introduction

The agriculture sector faces several challenges that impact global food security such as climate change, environmental pollution, urbanization due to life pattern changes; non-judicious use of natural resources, etc. (Ditta and Arshad 2016; El-Ramady et al. 2022). Agriculture also is a major sector of the global economy, which can produce and provide food for humans, both directly and indirectly (Basavegowda and Baek 2021). Furthermore, rapid population growth has increased pressure on global food resources (Basavegowda and Baek 2021). After the Green Revolution, nanotechnology represents a new frontier in modern agriculture, and is anticipated to become a major tool by offering potential applications to cope with many global challenges to food security or production, sustainability, and climate change (Mishra et al. 2017). Applying nanotechnology in agriculture is considered an effective way to translate research outcomes from many fields towards environmental sustainability (Acharya and Pal 2020). One of the most important tools in agriculture is fertilizers, which are considered

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crucial in crop production. Food production can be enhanced by utilizing agro-nanotechnology to improve fertilizers. The negative side of agro-nanotechnology, such as nanopollution still needs investigation (Singh and Gurjar 2022).

Nanotechnology has been investigated to improve the quality of agricultural products (mainly fruits and vegetables) and reduce post-harvest loss by using nanofertilizers, which improves their shelf life (Haris et al. 2023). Nanofertilizers (NFs) are considered alternatives to mineral or traditional fertilizers; NF are able to slow and sustained the release of nutrients and can be tailored to the specific needs of different crops (Arora et al. 2022). Nanofertilizers have several benefits, such as offering greater stress tolerance to cultivated plants, reducing groundwater pollution due to their low rates of application, and high use efficiency of nutrients (Arora et al. 2022). Among nanofertilizers, biological nanofertilizers are sustainable and non-toxic compared to chemical or physical nanofertilizers. Recent research has included applying biological nanofertilizers to enhance the growth of many crops under different stress conditions, such as heavy metals (Ahmadi‑Nouraldinvand et al. 2022; Zhu et al. 2022), salinity (El-Badri et al. 2022; Ghazi et al. 2022), biotic stress (Abou-Salem et al. 2022), as well as under non-stressful conditions (Yadav et al. 2022; Huang et al. 2023). Several crops have been investigated such as tobacco (Zsiros et al. 2019), *Chrysanthemum morifolium* (Seliem et al. 2020), lettuce (Kohatsu et al. 2021), cucumber (Shalaby et al. 2021), *Brassica chinensis* (Zhu et al. 2022), rapeseed (El-Badri et al. 2022), wheat (Sheoran et al. 2021; Ghazi et al. 2022), sugar beet (Abou-Salem et al. 2022), guar seedling (Ahmadi‑Nouraldinvand et al. 2022), banana seedlings (Shalaby et al. 2022a), and radish (Huang et al. 2023).

This mini-review focuses on biological nanofertilizers and their impact on horticultural crops production. A special focus on biological nanofertilizers of zinc is included.

2. Biological nanofertilizers and their properties

Fertilizers are defined as substances produced by industrial techniques or that occur as natural compounds and supply essential and/or beneficial nutrients for plant growth and soil fertility (Machado et al. 2022). Nanofertilizers are excellent potential tools to overcome the negative impacts of traditional mineral fertilizers (**Fig. 1;** Babu et al. 2022). Nanofertilizers (NFs) can be applied to cultivated plants through the soil, foliar applications, or seed priming. The method of plant uptake of nutrients in nanofertilizers (through apoplast or symplast) depends on the properties of the particles (size, and shape), soil properties such as organic matter content and cation exchange capacity, NFs exposure duration, and application methods (El-Ramady et al. 2022; Verma et al. 2022).

Nanofertilizers have higher nutrient use efficiency and can increase plant tolerance to biotic and abiotic stresses as compared to chemical fertilizers (Babu et al. 2022). Nanofertilizers may also protect the environment **(Fig. 2).** Nano-fertilizers represent a smart system of nutrients and may increase plant nutrient access and crop yield due to their delivery properties including submicroscopic sizes, a large surface area, encapsulated nutrients, and slow nutrient release in the rhizosphere (Madzokere et al. 2021).

The difference between biofertilizer and bionanofertilizers is the role of microbes. In case of biofertilizers the microbes are the main operator providing fertility. With bionanofertilizers, microbes produce the nanofertilizer through media supplemented with metal compounds that are converted into nano-metals (El-Ghamry et al. 2018). Many kinds of nanofertilizers can be biologically produced, including copper, selenium, silicon, and zinc. These will be presented in the following sections. The biological approach to forming nanoparticles depends on applying plant products and their isolates, extracts, and different microbes to the production system. This is suitable for NMs synthesis because it is eco-friendly, cost-effective, scalable, and eliminates toxic chemicals (Saravanan et al. 2021).

There many biosynthesized nanomaterials (NMs) that have already been adopted for several agricultural practices, especially bionanofertilizers to overcome difficulties in crop production and to boost essential nutrients density and bioavailability. The classification of bionanofertilizers mainly depends on their nature (shape and form) and size (Saha et al. 2022; García-Ovando et al. 2022). For hybrid nanomaterials, classification is based on a combination of organic/organic NMs, organic-inorganic NMs, and inorganic-inorganic NMs; as a group these are also known as composites (Saha et al. 2022).

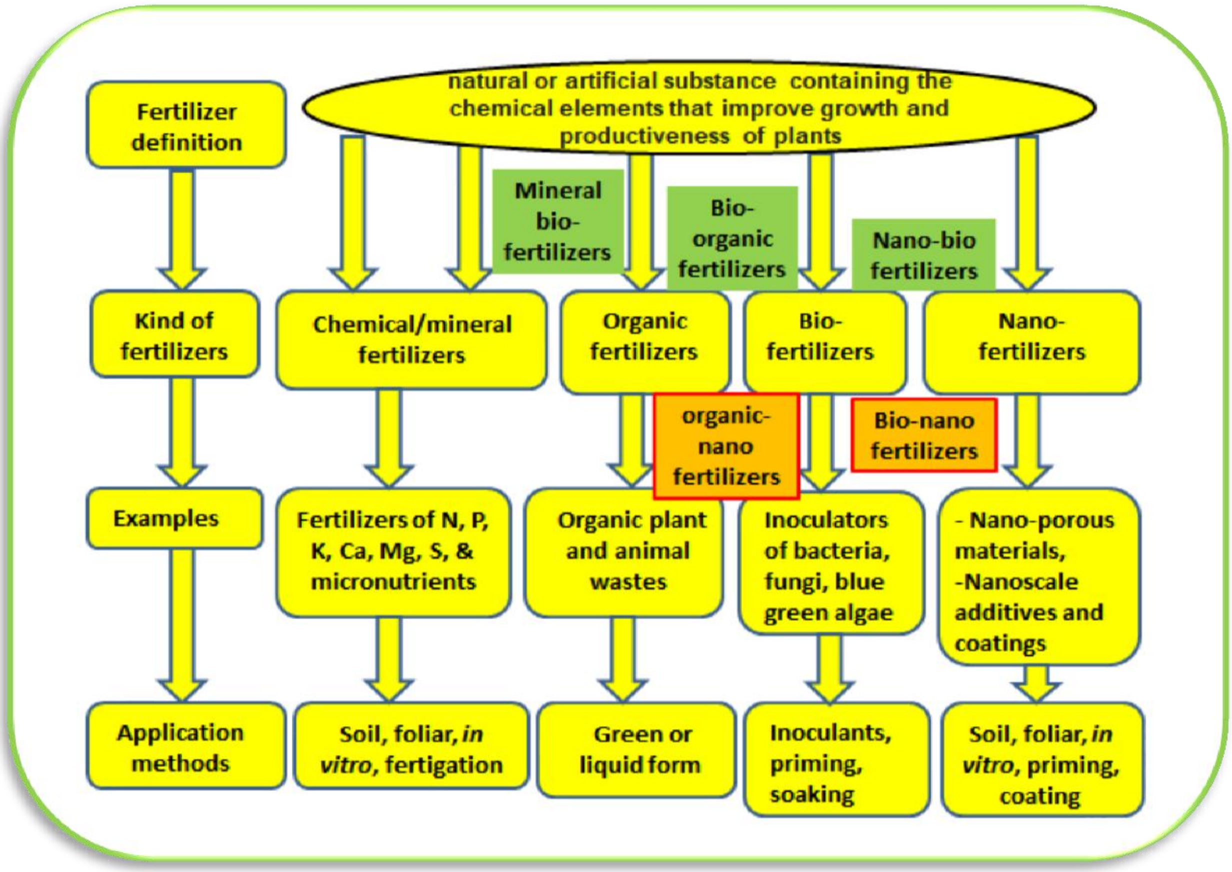

Fig. 1. Different kinds of fertilizers, examples for each group, and their application methods (adapted from different sources).

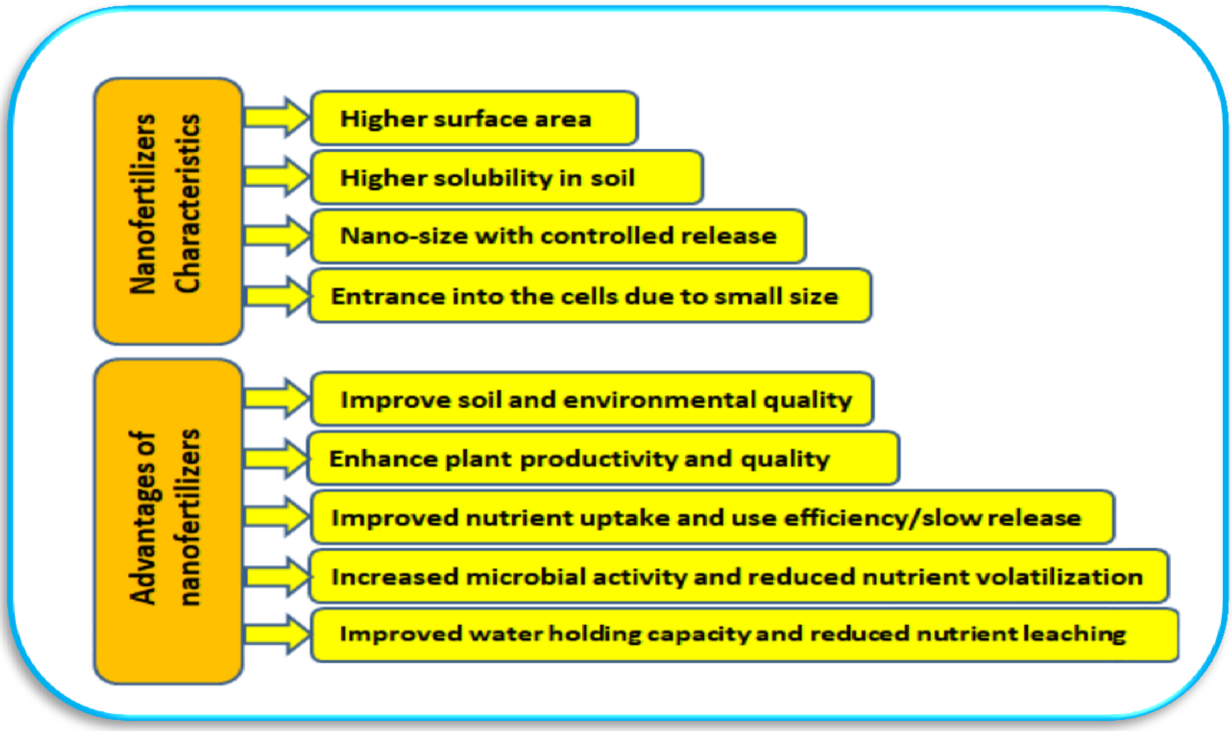

Fig. 2. The main characteristics and advantages of nanofertilizers (adapted from Ditta and Arshad 2016; Jakhar et al. 2022; Verma et al. 2022).

Bionanofertilizers are produced by plants (i.e., root, leaf, flower, and fruit extracts) or microbes (e.g., bacteria, fungi, algae, and actinomycetes). Important distinguishing properties include their size (1-100 nm), shape, and surface properties, as well as their mechanical, thermal and electrical properties, which combine to control the release of nutrients (García-Ovando et al. 2022). Biosynthesis of NMs is considered one of the most environmentally friendly methods of NMs synthesis (**Fig. 3**). It is a complex multi-step synthesis approach, which is mainly regulated by catalytic enzymes (Maťátková et al. 2022; Nguyen et al. 2022). Biopolymers (cellulose, chitosan) represent eco-friendly alternatives to traditional polymers for the delivery of nutrients and as green materials are characterized by renewability, availability, biodegradability, and low ecosystem toxicity (Machado et al. 2022). Over 18,000 studies were published from 2013–2023 on biosynthesis to create NMs (García-Ovando et al. 2022). These studies confirmed the promising possibilities of green synthesis to generate metallic, metallic oxide, and composite-NMs for applications including environmental remediation, agriculture, and medicine (García-Ovando et al. 2022).

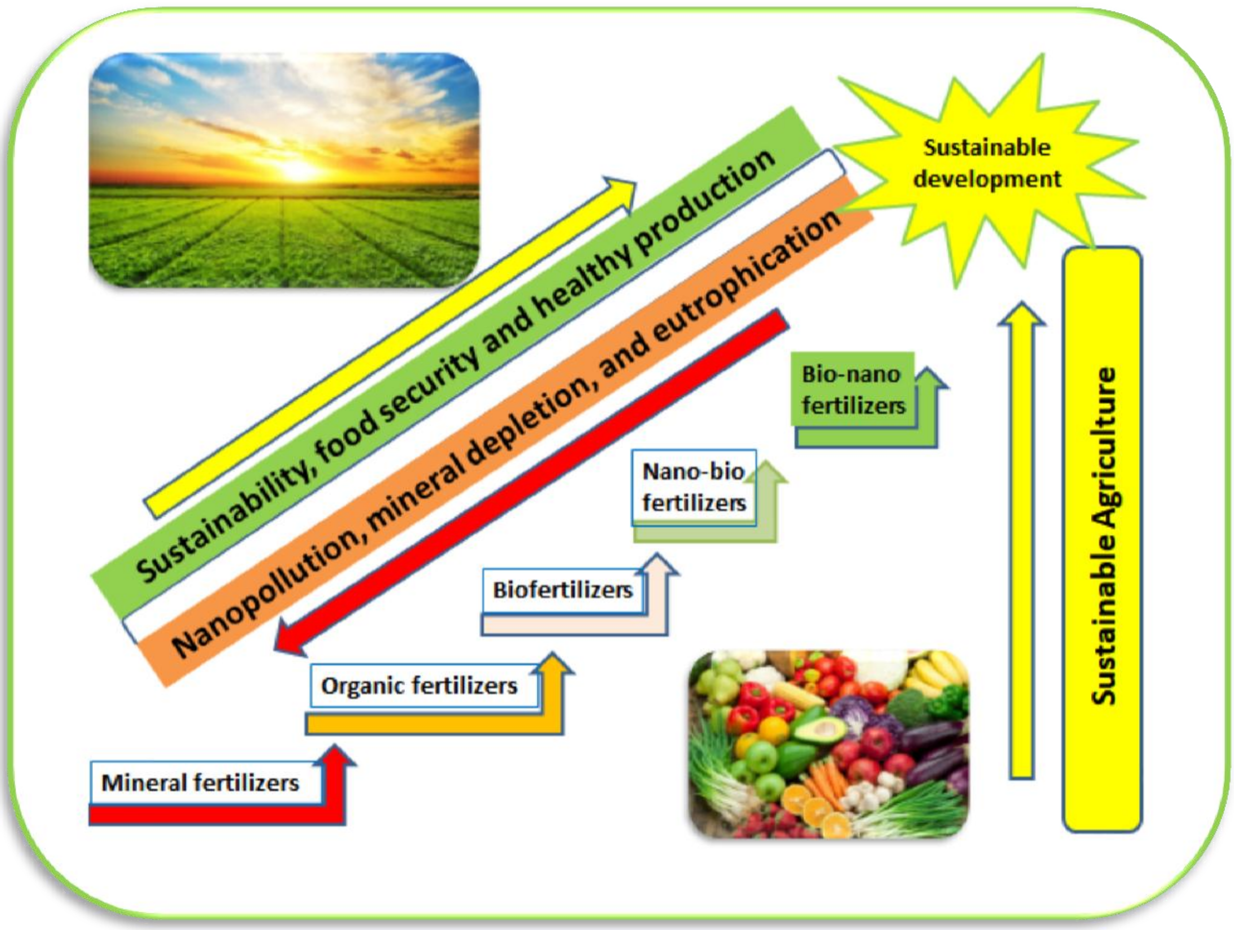

Fig. 3. Major steps in the historical development of the fertilizer industry and their relationship to environmental pollution and agroecosystem sustainability. Note that mineral or chemical fertilizers have led to many ecological problems, whereas bio-nanofertilizers may allow much more environmentally sustainable food production (adapted from Dhlamini et al. 2022).

Zinc is an essential micro-nutrient for both plants and humans and has crucial functions in over 300 enzymes and hormones (Sandeep et al. 2019; Brevik et al., 2020; Almendros et al. 2022). Zn-deficiency in humans is mainly associated with Zn-deficient soil, which is strongly linked with diet quality. This was confirmed by FAO/WHO, which reported that Zn-deficiency is the most common micro-nutrient deficiency worldwide and its availability depends on the types of soils in which crops are grown (FAO 2017).

Zn-deficiency in plants may cause physiological stress and problems in plants including significant decrease in growth and crop yield due to the fundamental role of Zn in many metabolic processes (Obrador et al. 2022). Zn-fertilizers, including mineral and/or nanofertilizers, are crucial to address Zn-deficiency in the human diet. The effects of biological Zn-nanofertilizers have been investigated for a wide range of crops (**Table 1)**.

Table 1. A brief review of some published articles on Zn-nanofertilizers and their impacts on plants.

Nanofertilizer type	Plant species	The main agronomic findings of the study	Refs.
Chemical ZnO-NPs (0.12 g pot^{-1})	Wheat (*Trilicum aestivum* L.) variety Gemmieza	ZnO-NPs improved chlorophyll contents, physical parameters, and wheat yield under salt stress (10 dS m^{-1})	Adil et al. (2022)
Chemical nano-Zn-fertilizer (40, 80, 120 and 160 mg/kg)	Maize (*Zea mays* L.)	ZnO- nano-fertilizer foliar and soil applications improved growth, photosynthetic pigments, and antioxidant system of maize	Azam et al. (2022)
Bio-synthesized ZnO-NPs at 1, 50, and 100 ppm	Tomato (*Lycopersicon esculentum* L.)	ZnO-NPs improved the photosynthetic system and vegetative growth, protein and sugar content were enhanced	Azim et al. (2022)
Chemical ZnO-NPs at 3, 20, and 225 ppm	Cherry tomato (*Solanum lycopersicum* L. var. cerasiforme)	Mn uptake decreased with ZnO-NPs application in both acidic and calcareous soils. Effect of ZnO-NPs depended on soil characteristics; ZnO-NPs can be used in Zn-biofortification.	Almendros et al. (2022)
Spraying nano-Zn at 20, 50 and 80 mg L^{-1}	Wheat (*Triticum aestivum* L.)	Applied nano-Zn increased plant growth under irrigated saline water (EC = 6.3 dS m^{-1}) by stimulating formation of osmolytes, total soluble sugars, proline, and nutrient uptake	Lalarukh et al. (2022)
Bio-Zn-NPs at 5, 15, and 25 ppm	*Brassica napus* L.	Exposure to bio-Zn-NPs, upregulated response to oxidative stress in *B. napus* and photosynthesis	Sohail et al. (2022)
ZnO-NPs at levels from 0 to 500 ppm	Soybean (*Glycine max* [L.] Merr.)	ZnO-NPs improved root architecture in soybean up to 200 ppm; Zn bio-uptake followed the order: root > seed > leaf > stem	Yusefi-Tanha et al. (2022)
Nano-ZnO-NP at 5, 10 and 15 mg Zn L^{-1}	Maize (*Zea mays* L.)	ZnO-NPs> Zn-EDTA> $ZnSO_4$ for maize growth under nutrient deficiency stress in soil	Abbas et al. (2021)
Chemical ZnO nano-priming	Rapeseed (*Brassica napus* L.)	ZnO nano-priming enhanced seedling growth, biosynthesis of pigments, osmotic protection, reduced ROS accumulation, regulated antioxidant enzymes, enhanced economic yield under saline conditions (150 mM NaCl)	El-Badri et al. (2021)
ZnO-NPs at 10, 50 and 100 ppm	Tomato (*Lycopersicon esculentum* Mill.)	ZnO-NPs induced salt tolerance (150 mM) in tomato by improving antioxidative enzyme activity and enhanced protein content	Faizan et al. (2021a)
ZnO-NPs at 10, 50 and 100 ppm	Tomato (*Lycopersicon esculentum* Mill.)	ZnO-NPs alleviated Cu toxicity (100 ppm) in tomato by enhancing leaf gas exchange parameters, activity of carbonic anhydrase, and protein content	Faizan et al. (2021b)
Bio-nano-ZnO at 40, 80, and 120 ppm	Wheat (*Triticum aestivum* L.)	Growth and yield of wheat was enhanced using Zn bio-nanofertilizer with less harmful impact on the environment	Sheoran et al. (2021)
ZnO-NPs at 100, 200 and 500 ppm	Wheat (*Triticum aestivum* L.)	Foliar applied ZnO-NP at 100 ppm improved total chlorophyll, grain Zn-contents, and sustained production in Zn-deficient alkaline soil	Singh et al. (2021)
ZnO-NPs at 40, 80, 160, and 400 ppm	Soybean (*Glycine Max* Cv. Kowsar).	ZnO-NPs promoted seed yield up to 160 ppm; spherical 38 nm ZnO-NPs elicited the least oxidative stress except at 400 mg Zn/kg	Yusefi-Tanha et al. (2020)

Nano-ZnO has distinctive properties including functioning as fungicidal, antibacterial, and photochemical agents, and catalysis, for these reasons they are used extensively in industry (Azim et al. 2022). ZnO-NPs have been applied as a nanofertilizer in the agricultural sector, especially in Zn-deficient regions (Munir et al. 2018). Azim et al. (2022) reported on root uptake of Zn from Zn-nanofertilizers. After penetration of Zn-nanofertilizer inside the roots, it transfers into the cortex and invades the vascular system along with the gaps in the casparian strips at the orientation of the primary and lateral root junction. The reason for ZnO-NPs translocation in the shoot may relate to the decomposition and biotransformation of nano-ZnO into $ZnPO_4$ inside the plant (Azim et al. 2022).

3. Biological nanofertilizers for horticultural crops

Horticulture is a branch of agriculture that includes study of the growth and productivity of vegetables, fruits, and ornamental or medicinal crops (Jiménez-Rosado et al. 2022). Global horticulture production in 2020 was 329.86 million tons, which represents an increase of nearly 2.93% compared with 2019 (FAOStat 2022). This production is still not enough to feed all people globally, and this is a major challenge as global population continues to increase and many environmental changes are occurring worldwide. Therefore, progress in increasing the productivity and/or sustainability of horticultural crops is an urgent goal for researchers (Zulfiqar 2021). Production starts with selecting the right seeds or/and seedlings, followed by the proper horticultural practices, which mainly include fertilization and irrigation programs. The horticulture sector is very important to society, as it can provide us with healthy foods, needed vitamins and minerals, and recreational activities (Xu 2022). On the commercial level horticulture is very diverse in terms of crops grown, its available cultivars, growing media, propagation of planting materials, production systems, crop protection, and postharvest management and processing and demands intensive labor input (Xu 2022).

Horticultural applications of nanotechnology include nano-nutrition, nano-pesticides, food nano-processing, nano-packaging, nano-safety, and nano-nutraceuticals. However, these applications have the potential to cause problems and risks for the environment and human health (Feregrino-Perez et al. 2018; El-Badri et al. 2021). The promising applications of nanotechnology in raising horticultural seedlings may include nanofertilizers, nano-encapsulated nutrients, or nano-pesticides that promote seed germination and seedling growth (**Fig. 4**) (Feregrino-Perez et al. 2018). Depending on the kind of nanofertilizers and the applied dose, impacts may either inhibit or activate enzymes, which control the uptake of water by seedlings or seeds, level of gibberellin, and production of abscisic acid (Feregrino-Perez et al. 2018). Other physiological, biochemical and antioxidant properties of horticultural crops have been enhanced after application of nanofertilizers (mainly biological ones) such as bionano-Se and -Cu on banana (Shalaby et al. 2022a) and tomato (Saffan et al. 2022) and bionano-Se on radish (Huang et al. 2023). Therefore, the applications of nanotechnology in agriculture, and particularly horticulture, may provide sustainable solutions for many problems facing this sector (Bala et al. 2022; Nongbet et al. 2022).

4. Conclusions and researchable priorities

Nanotechnology has become a crucial sector that may offer solutions to many problems in agriculture. Nanotechnology offers potential benefits to all stages of crop growth, from the sowing a seeds to mature plants, with benefits extending into harvest and postharvest. Nano-biofertilizer is a technically advanced, eco-friendly, cost-effective to provide a sustained, slow delivery of nutrients to plants to enhance their growth, productivity, and quality parameters, increase nutrient use efficiency, minimize nutrient leaching and volatilization, and reduce soil and water pollution. On the other hand, application of nanofertilizers may cause problems for plants (phytotoxicity), soil macro-fauna and microflora, and risks for human health. The nanofertilizer industry needs to carefully investigate both the potential benefits and drawbacks of nanofertilizers. The main problems to the immediate expansion of nanofertilizer use include toxicity-related risks, gaps in research related to the legislation and regulation of their use, and sufficient monitoring. However, the potential for a more sustainable and environmentally friendly option to provide plant nutrients during agricultural production makes it worth investigating these issues.

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Mango

Banana

Strawberry

Fig. 4. Selected horticultural seedlings (mano, banana, and strawberry). Photos by El-Bialy.

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