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REVIEW ARTICLE

Nanomaterials in agriculture for plant health and food safety: a comprehensive review on the current state of agro-nanoscience

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Abstract
In the modern epoch, nanotechnology took forward the agriculture and food industry with new tools that promise to increase food production sustainably. It also anticipated that it would become a driving economic force shortly. Nanotechnology has the potential to reduce agricultural inputs, enrich the soil by absorbing nutrients, manage plant diseases, and detect diseases. The aim of the present review is to cover the potential aspects of nanoscience and its trend-setting appliances in modern agriculture and food production**.** This review focuses on the impact of various nanomaterials on plant health to improve agricultural production and its cooperative approach to food production. Nanotechnology has great potential compared to conventional approaches. The appealing path of nanotrends in the farming sector raises hopes and illuminates the route of innovative technologies to overcome various diseases in plants with an enhanced yield to meet the growing global population's need for food security.

Keywords Nanomaterials · Nanosensors · Agrochemicals · Nanofertilizers · Nanopesticide · Food security

Introduction

Nanotechnology is a novel scientific approach capable of manipulating physical and chemical properties at molecular levels. On the other hand, biotechnology manages molecular, genetic, and cellular processes to develop products and services. Nanotechnology finds use in diverse fields, from medicine to agriculture, utilising the knowledge and techniques of biology (Fakruddin et al. 2012; Manjunatha et al. 2019). Agriculture, the backbone of developing countries, is the most important and stable sector because it produces and provides the raw materials for food, feed, fibres, and many other products by cultivating plants and raising livestock. Agriculture holds more than 60% of the population depending on it for their livelihood (Brock et al. 2011). The existing natural resources (production land, water, soil, etc.) may not be enough for the burgeoning population that is estimated to be 8 billion people by 2025 and 9 billion by 2050, and to accomplish the global population requirement, global agricultural production must increase. Agri-food production is one of the primary drivers of the economy. Besides, agriculture offers routes to value-added crops (Ghasemzadeh 2012; Mukhopadhyay 2014; Prasad et al. 2017; Berners-Lee et al. 2018; Mohammad Fakhrul and Karim 2020). On less available land, we have to achieve more food production, which can only be accomplished by intensifying production, in an environmentally safe manner through an ecological increase in yield per unit of area, i.e. escalating production, while meeting acceptable standards of environmental quality (Cassman 1999; Cordell and White 2013). Many believe that the intervention of plant biotechnology holds the key to producing more food. Only genetic advancement cannot fulfil the requirement, so it has to be associated with other materials such as nanofertilizer.

Nanotechnology has an impact due to the alteration of atoms and the development of magnetic power. The nanoparticles (NPs) with a smaller size possess a larger surface area and exhibit more active properties. Nanotechnology is knocking on the doors of perception shortly. In biological processes, nanomaterials play a vital role (Pokropivny et al. 2007; Prasad 2014). Nanotechnology helps in the agricultural and food industries to understand molecular

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management of diseases, rapid disease detection, enhancing the ability of plants to absorb nutrients, among others. Nanobiotechnology of various crops, on the other hand, has the potential to improve yields or nutritional values, as well as develop improved systems for monitoring environmental conditions and enhancing plants' ability to absorb nutrients or pesticides by improving our understanding of biology (Tarafdar et al. 2013). There is a significant demand for fast, reliable, and low-cost systems to detect, monitor, and diagnose biological host molecules in agricultural sectors (Vidotti et al. 2011; Sagadevan and Periasamy 2014). Nanomaterials may include synthesis from plant, bacteria, fungi system; it is considered as a green nanotechnology. Nowadays chemically synthesized nanomaterials are found to be toxic in nature (Prasad 2014). Green nanotechnology has a profound influence on the environment; it is energy efficient. It also reduces waste and greenhouse gas emissions (Prasad 2014; Prasad et al. 2016; Maksimovic and Omanovic-Miklicanin 2017; Verma et al. 2019). In the present decade, green nanotechnology implementation and its functions are still not clear. How will the environmental sustainability of green nanotechnology be achieved in the future? These risks must be mitigated in advancing green nanotechnology solutions (Kandasamy and Sorna Prema 2015). The engineered smart nanotools in modern agricultural systems can make a revolution in agricultural practices and enhance both the quality and quantity of yields (Singh Sekhon 2014; Liu and Lal 2015).

Approaches

Multiple literature searches in Google Scholar, PubMed, and Scopus using the terms nanomaterials, agrochemicals, nanofertilizers, food security, and safety, as well as hand-searching recent reviews, were conducted to determine the efficacy of nano-resources in agriculture and food. We included only studies that were published in English and excluded those that were only available in abstract form. Literature search and study selection criteria in order to investigate the efficacy of nanomaterials, multiple literature searches were performed in PubMed, Google Scholar, and Scopus using the terms nanomaterials, agrochemicals; nanofertilizers, food security, and safety, as well as hand searching recent reviews. Only studies published in English were included, and those only available in abstract form were excluded. For observational studies, searches were made for reports of nanomaterials' apparent consequences on crop production and their amicable attitude toward quality food fabrication. What are the requirements for research organisations to use natural solutions to improve the growth and health potential of plants? Aside from minimising the use of hazardous chemicals for short-term benefits, it is also critical that the ecosystem's strength be improved to bring long-term benefits to agricultural commodities. The critical appraisal of nanomaterials in the path of the review was discussed below, including an analysis of the potential preconceptions of its implications in agriculture and food supplementation.

Insight seascape of nanomaterials for sustainable plant growth and development

Improved agronomic and bioenergy crop production can fulfil the world's rising food and vitality demands through emerging scientific attention and the use of nanomaterials in fertilizers (Boutchuen et al. 2019). Agricultural innovations are crucial for the explosion of the worldwide population through the use of natural and manmade assets. In particular, multiple agriculture-related problems can be solved with the help of nanotechnology (Fig. 1). NPs provide pronounced scientific attention to link the gap between bulk constituents and minute atomic or molecular structures (Prasad et al. 2017; Shang et al. 2019). NPs-based fertilizers are to be used effectively to transport essential nutrients for plants while reducing fertilizer input into the environment (Guo et al. 2018; Boutchuen et al. 2019). The properties of the NPs are important because they influence the morphological and physiological properties of cells during their interaction with plants (Fig. 1; Siddiqui et al. 2015a). Both optimistic and adverse effects on plant growth and development by the use of NPs have been already reviewed by many researchers from their finding (Nowack and Mueller 2008; Handy et al. 2008; Ju-Nam and Lead 2008; Monica and Cremonini 2009; Stampoulis et al. 2009; Kahru and Dubourguier 2010; Ma et al. 2010, 2013; Nair et al. 2010; Menard et al. 2011; Peralta-Videa et al. 2011; Khot et al. 2012; Pan and Xing 2012; Smita et al. 2012; Aslani et al. 2014; Deng et al. 2014; Gardea-Torresdey et al. 2014; Aliofkhazraei 2015; Siddiqui et al. 2015a, b; Chichiriccò and Poma 2015; Huang et al. 2015; Abd-Alla et al. 2016; Le Van et al. 2016; Wen et al. 2016; Gil-Díaz et al. 2016). Engineered NPs have an impact on a plant's system depending on their composition, concentration, size, physical and chemical properties, and also on the plant's species.

Impact of nanoparticles on plant health

Nano-silicon dioxide (SiO_2) in the seed germination

The role of NPs in plant seed germination, growth (shoot and root biomass), and photosynthesis have been illustrated to some extent in many plants. The emblems of plant growth

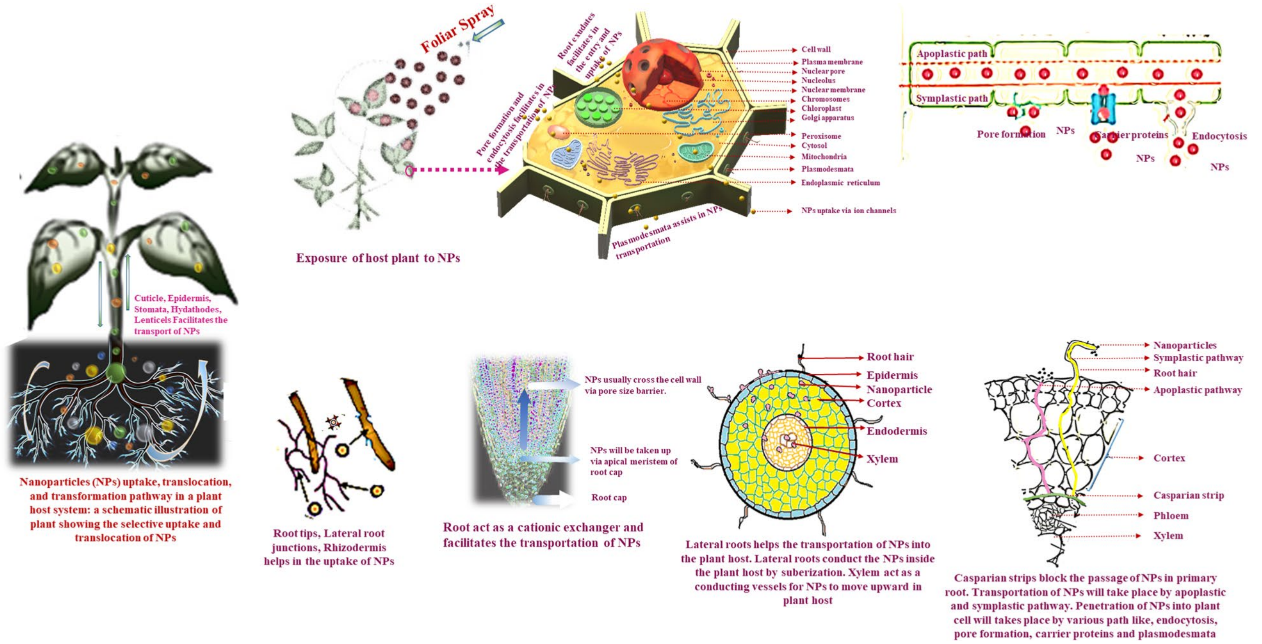

Fig. 1 Transverse section of the plant cell/root absorption zone showing the nanoparticle entry and interaction in the host plant

and development start with seed germination, followed by elongation of root and shoot development. Concerning plant growth and development, reports are available on the effect of the concentration-dependent effect of NPs on seed germination (Fig. 1). Nano-SiO_2, with its lower concentration, improves seed germination parameters in tomatoes (Siddiqui and Al-Whaibi 2014). Suriyaprabha et al. (2012) illustrated the influence of nano-SiO_2 with enhanced seed germination in maize seeds by providing restored nutrient availability, pH, and good conductivity to the growth medium. Further, $nSiO_2$ significantly enhanced the potential of seed germination, average germination time, seed germination and seed vigour index, fresh seedling weight, and dry weight. Nano-SiO_2 application is beneficial for plant growth and enhanced yield. According to Bao-Shan et al. (2004), nano-SiO_2 has a positive effect on *Larix olgensis* seedlings. Nano-SiO_2 improves seedling growth quality parameters, with enriched mean plant height, increased root collar width, increased primary root length, and an amplified number of lateral roots, and also elicits the synthesis of chlorophyll in the host plant. According to Haghighi and Teixeira Da Silva (2014), nano-SiO_2 improves seed germination under abiotic stress. In tomato, Siddiqui and Al-Whaibi (2014) demonstrated that nano-SiO_2 improves seed germination and elicited the antioxidant activity in squash under NaCl stress conditions. Shah and Belozerova (2009) and Frenk et al. (2013) tested gold (Au), silica (Si), palladium (Pd) and copper (Cu) NPs and observed that all these NPs significantly impact seeds and their growth. Also, in soybean, the exogenous application of nano-titanium dioxide (nano-TiO_2) and nano-SiO_2 increases seed germination by improving nitrate reductase (Maity et al. 2018; Acharya et al. 2020; Shinde et al. 2020) and enhances the seeds ability to absorb water and nutrients in spinach, it increases chlorophyll content and seed germination. Under salinity stress, nano-SiO_2 recovers leaf fresh and dry weight, chlorophyll content, and proline accumulation, demonstrating that quantum dots (QDs)-coated silica promotes root growth in rice significantly (Haghighi and Teixeira Da Silva 2014; Karimi and Mohsenzadeh 2015; Rastogi et al. 2019). Nano-SiO_2 promotes plant growth and development by increasing photosynthetic net rate, transpiration frequency, stomatal conductivity, PSII potential action, active photochemical efficacy, profound photochemical proficiency, electron transport rate, and photochemical quench (Siddiqui and Al-Whaibi 2014; Felix Alvarez et al. 2018; Pushpa and Lohani 2018; Zhu et al. 2019; Madany et al. 2020).

Iron nanoparticle

Iron (Fe) is a vital nutrient for all living beings (Zuo and Zhang 2011). Recently, it has been illustrated that iron oxide (Fe_2O_3) NPs have the potency to be an ideal substitution for the traditional Fe fertilizer (Rui et al. 2016). Zero-valent iron NPs (nZVI) elements can penetrate into the peanut seed coats, which improves the uptake of water and fuels the germination of seeds. The growth rate experiments indicated that at higher concentrations, it shows phytotoxicity, while at lower concentrations it stimulates the plant's growth and root development (Li et al. 2015; Li and Lan 2017).

Another study shows that Fe_2O_3 NPs stimulated the growth of peanuts by regulating phytohormone contents, antioxidant enzyme activity, and other parameters also. Accordingly, the likely replacement of the Fe fertilizer with NPs is possible (Rui et al. 2016). The effect of copper (Cu), zinc (Zn), manganese (Mn), and FeO NPs on *Lactuca sativa* reveals that CuO NPs were slightly more toxic than Cu ions, whereas zinc oxide (ZnO NPs) was similar to that of Zn ions. MnOx NPs and FeOx NPs were less toxic than their ionic forms and also significantly activated the growth of lettuce plant seedlings by 12–54%. It also showed that synthetic NPs were not always more toxic than other chemical types containing the same elements. Mn or Fe NPs can significantly improve the growth of the plant and can be effective nanofertilizers for increasing agronomic productivity (Liu et al. 2016; Zia-ur-Rehman et al. 2018; Rizwan et al. 2019). However, further advancement in this direction is still required to know its possible threat to the environment and to food safety.

Zinc oxide nanoparticles

Zinc (Zn) has a foremost role as a biotic micronutrient in plant health systems, and it plays significant roles in metal-protein complexes (Sturikova et al. 2018). Prasad et al. (2012) investigated the pivotal role of ZnO NPs in plant growth and development. Lower concentrations of ZnO NPs were found to have a positive effect on seed germination, seedling vigour, plant growth, flowering, chlorophyll content, root length, and pod yield in *Brassica nigra* (Sedghi et al. 2013), onion (Raskar and Laware 2014), and wheat (Ramesh et al. 2014). At higher concentrations of ZnO NPs, they significantly inhibit the germination of seeds. The NP influence on seed germination depends on the concentrations of NPs and differs from plant to plant. Studies on the various concentrations of ZnO NPs in alfalfa, cucumber, and tomato plants found that only cucumber plant seed germination was effectively boosted (de la Rosa et al. 2013). Tarafdar et al. (2013) reported that ZnO NPs significantly improve *Cyamopsis tetragonoloba* plant shoot and root growth, biomass, root area, protein and chlorophyll synthesis, rhizospheric microbial population, alkaline phosphatase, acid phosphatase, and phytase activity in the cluster bean rhizosphere region. It is also apparent by the scanning microscope, correlative light, and inductively coupled plasma/atomic emission spectroscopy analysis, that ZnO NPs on the roots of *Vigna radiata* and *Cicer arietinum* absorption, stimulated the shoot and root lengths and their biomass (Dhoke et al. 2011; Burman et al. 2013). Also in three Solanaceae crops, e.g., *Solanum melongena*, *Lycopersicon esculentum*, and *Capsicum annum,* enhanced germination rates and shoot–root biomass were recorded (Younes et al. 2020). Under in vitro conditions, the Nano ZnO supplemented with Murashige and Skoog (MS) media encouraged shooting, somatic embryogenesis, regeneration of plantlets, elucidated proline synthesis, superoxide dismutase activity, catalase, and peroxidase, thereby inducing resistance to biotic stress (Murashige and Skoog 1962; Elizabath et al. 2017; Ahmad et al. 2020). ZnO NPs show significant influence at varied concentrations on germination, vigour, and premature growth of *Capsicum annuum* plantlets and also show a better increase of phenolic composites and antioxidant activity in the radicle. ZnO-NPs can elicit the production of desirable secondary metabolites (Garciá-López et al. 2018). ZnO NPs were tested on wheat (*Triticum aestivum*) grown in hydroponic media. At 50 mg/l, the NP positively affects seed germination rate, the number of roots, plant biomass, and the total growth factors of shoots, roots, and leaves (Awasthi et al. 2017). The development of multiple antioxidant defence biomarkers during the lifecycle of soil-grown soybean (*Glycine max* cv. *Kowsar*) and the maximum oxidative stress responses (H_2O_2 synthesis, catalase (CAT), peroxidase (POD), and superoxide dismutase (SOD)) under these NPs treatment was observed. ZnO NPs have the potential to be used as a nanofertilizer for crops cultivated in Zn-deficient soils to recover crop yield, improve food quality, and address malnutrition, globally (Yusefi-Tanha et al. 2020).

Nanoparticles influence in photosynthesis of plant

Plants' ability to change light energy into chemical energy is known as photosynthesis. Although photosynthesis is a vital process in plants, they can only convert 2–4% of the accessible energy in radiation into fresh vegetal growth (Kirschbaum 2011). Advanced research on the point of photosynthesis in plants was done previously through plant breeding and gene manipulation techniques. Recently, studies have demonstrated that incorporation of the two genes of *Cyanobacterium*, and *Synechococcus* in tobacco plants leads to enhanced activity of Rubisco's gene in the plant for carbon fixing (Lin et al. 2014; Liang and Lindblad 2017; Liang et al. 2018; Long et al. 2018). Photosynthesis in engineered plants is more efficient than in native plants. The photosynthesis process was faster than expected because the carbon dioxide fixation was working well**.** Furthermore, in the corral of nanobiotechnology, investigators want to develop bionic plants that can have improved photosynthesis efficacy and biochemical sensing. This study found that the single-wall carbon nanotubes (SWCNTs) in the quarantined chloroplast increased three times greater photosynthetic action than that of controls with significantly improved electron transport rates, and SWCNTs assisted the plants to sense the nitric oxide signalling molecule. The involvement of nanobionics in engineered plants would facilitate innovative and advanced functional properties in the photosynthetic system. Noji et al. (2011) discovered that the complex photosystem II

(PSII) absorbed into a nanomesoporous silica compound (SBA) and activated the constant activity of a photosynthetic oxygen-evolving reaction, indicating light-driven electron transport from water to quinone molecules. They suggested that the PSII-SBA conjugate might possess the properties needed to develop artificial photosynthetic systems and photosensors. SiO_2NPs improve the rate of photosynthetic activity by enhancing carbonic anhydrase activity and the synthesis of photosynthetic pigments (Siddiqui et al. 2014). Photosynthesis may improve with the supply of carbonic anhydrase and CO_2 to the Rubisco (Studer et al. 2014; Rudenko et al. 2020). The TiO_2 nano-anatase has a distinctive photocatalyzed feature; it also increases the absorbance of light and the transformation of light energy into electrical and chemical energy and elicits carbon dioxide acclimatization. It is possible that by stimulating Rubisco (a multifaceted form of Rubisco and Rubisco activase), encourage Rubisco carboxylation, thereby increasing plant growth. TiO_2 NPs protect chloroplasts from ageing in long-term illumination (Gao et al. 2006; Studer et al. 2014; Ahmad et al. 2018; Gohari et al. 2020; Suganami et al. 2020). The nano-anatase effect on the molecular mechanism of the carbon reaction proposes that increasing the Rubisco activase protein levels and activities by eliciting the marker gene for Rubisco activase (RCA) mRNA.TiO_2NPs improve the net photosynthetic rate, water conductivity, and transpiration ratio in plants by improving Rubisco carboxylation and increasing the frequency of the photosynthetic carbon reaction (Suganami et al. 2020)**.** As stated by Khatri and Rathore(2018) and Zhang et al. (2020), nano-anatase vigorously promotes the entire electron transport chain, activity of photoreduction in photosystem II, the evolution of O_2, and photophosphorylation activity in chlorophyll under both ultraviolet and visible light. According to Govorov and Carmeli (2007), metal NPs can activate photosynthetic systems by enhancing the efficacy of biochemical energy production. AuNPs and silver (Ag) nanocrystals bind to the centre of the photosynthetic reaction, thereby forming a novel hybrid system that produces exciting electrons around ten times more, due to plasmon resonance and fast electron–hole separation. The improved mechanisms may aid in the plan for artificial light-harvesting schemes. Pradhan et al. (2015) demonstrated that Cu NPs have a significant influence on the elevation of Chl a content in mung bean plants, indicating that it has a significant influence on the photosynthesis process, as Chl a play an important role in the light-dependent photosynthetic pathway. They also observed higher quantities of carotene and xanthophyll in plants treated with Cu NPs as compared to controls; these mechanisms in the photosynthetic process provide a protective shield for plants against external stress environments. Furthermore, they stated that Cu NPs activate photophosphorylation, the electron transport chain, and the carbon assimilatory pathway in the chloroplast to enhance the process of photosynthetic activity in treated mung bean plants.

Chahardoli et al. (2020) investigated the engineered aluminium and nickel oxide NPs' (Al_2O_3 and NiO NPs) responses at different concentrations on the growth of the plant, oxidative stress, and antioxidant activities in the hydroponically grown tissues of *Nigella arvensis* L. At lower concentrations, the biomass of the plant was significantly enhanced under Al_2O_3 and NiO NP treatment, but reduced at higher concentrations of NP. Several enzymatic antioxidants assayed in shoots and roots, such as ascorbate peroxidase (APX), CAT, POD, and SOD, specify an overall upsurge of activities after exposure to NPs. The antioxidant activities in the plant were enhanced, as were secondary metabolite formation and other allied physiological factors such as total antioxidant activity, total saponin content, and DPPH scavenging activity (Hong et al. 2005; Zheng et al. 2005; Gao et al. 2006; Yang et al. 2006). These results illustrated that nanosized TiO_2 has a positive influence on the plant growth of spinach, whether it is treated in the seeds or sprayed on the leaves. Nano-TiO_2 significantly increased the SOD, POD, and CAT activities, reduced the increased accumulation of reactive oxygen free radicals and malondialdehyde (MDA) levels, upheld the stability of the membrane, and promoted the adsorption of nitrate and stimulated the conversion of inorganic into organic nitrogen. Also, in the spinach leaves, it shows the activity of Rubisco carboxylase was 2.67 times higher than that of Rubisco in the control, and it can hydrolyze ATP in the same way as Rubisco activase. Rubisco and Rubisco activase were activated in spinach, which increased Rubisco carboxylation and photosynthetic carbon reactions. Normal-sized TiO_2 did not have these effects (Gao et al. 2006). One study reported that NP interaction with green algae, which has a cell wall similar to plants, and a toxicity study of nanosized TiO_2 under illumination indicate that NP is slightly inorganic; oxidic NP can interact with plant cells or green algae by way of a parallel cell wall assembly absorbed at the surface of the root and intake into the cell. The NPs can diffuse into cells via the path of intercellular space, the apoplast, and be adsorbed or merged into membranes (Hund-Rinke and Simon 2006). Because plant surfaces carry negative charge into the apoplast, plant cells easily transport negative charge NPs. The Casparian strip forms a barricade to the apoplastic stream flow, and only symplastic passage is possible into the xylem. Conversely, this barricade is not impeccable, which means compounds can go into the xylem through holes or damaged cells without even crossing a cell membrane and being further transported to the shoots. This mechanism was found to be the prime process for the uptake of metal complexes with chelators like EDTA and their transportation to the shoots

(Nowack et al. 2006; Tandy et al. 2006). Based on these facts, we could theorize that, negatively charged NPs may possibly pass into the apoplast of the root cortex and eventually also into the xylem part.

Promising prospects for nanotechnology for the improved plant health and food production

Massive quantities of fertilizers like urea, ammonium salts, and phosphate or nitrate compounds have a considerable impact on improved food production. Nonetheless, they contribute to a slew of negative effects on beneficial soil microflora. Most of the applied fertilizers are not properly uptaken by plants due to overflow, which causes pollution (Peterson 1975; Prashar and Shah 2016; Berg et al. 2017). Fertilizers covered in nanomaterials can resolve this problem. Nanomaterials have probable influences on the gentle discharge of fertilizers, as NPs hold the material more stably in the plant due to the high surface tension of NPs than the conventional approach. Furthermore, nanocoatings provide surface safeguards for more substantial elements (Giroto et al. 2017; Kottegoda et al. 2017; Niemiec and Komorowska 2018).

Agrochemicals

As the world population increases, the food crisis can be alleviated by utilising plant breeding, fertilizers, and plant protection products. After the green revolution era in India, the use of nitrogen in fertilizer with urea effectively increased production by around 29%. However, rampant use of nitrogen in the production of food increases atmospheric N_2O (a greenhouse gas), which influences increased atmospheric temperature and thus contributes to global warming (Park et al. 2012; Fagodiya et al. 2017; Kumar and Indira 2017; Eliazer Nelson et al. 2019; Manuel 2019; Dimkpa et al. 2020). In agriculture, chemical fertilizers like diammonium phosphate (DAP), urea, and single superphosphate (SSP) are used to meet the deficiency of N, P, and K in the soil. However, most parts of these chemical fertilizers are wasted as vapour or run-off. Among applied fertilizers most of which go to the environment, it is estimated that about 40–70% of the nitrogen, 80–90% of the phosphorus, and 50–70% of the potassium cannot be absorbed by a plant, causing loss to the nation and environmental pollution as well (Trenkel 1997; Ombódi and Saigusa 2000). The recent methodology deceits in the usage of nanocoated urea or other chemical fertilizers. The nanocoating's constancy reduces the degree of dissolution of the compost and permits the slow, constant release of coated fertilizer, which is more efficiently absorbed by the plant roots. It was earlier reported that slow-release fertilizers have become an effective way to save fertilizer consumption while minimizing environmental pollution (Wu et al. 2008). In sulphate-deficient soil, sulphur nanocoating fertilizers (≤ 100 nm layer) are worthwhile as slow-release fertilizers, since sulphur substances are beneficial (Ronghao et al. 2016; Duhan et al. 2017; Klikocka and Marks 2018). Nanocoated urea and phosphate release will be helpful, and crop demands will be fulfilled for most deficient soil nutrients. Many biodegradable polymeric materials, such as chitosan NPs (~ 78 nm), have shown promising results for slow NPK fertilizer release (Corradini et al. 2010; Adu-Gyamfi et al. 2019). Polymeric and kaolin biocompatible NPs have potential applications in fertilizer slow discharge actions (Wilson et al. 2008). The nanofertilizers achieve the slow release of fertilizer nitrogen and phosphorus with the plant's absorption, thus preventing the loss of nutrients and avoiding the undesirable nutrients' interactions with microorganisms, air, and water (Emadian et al. 2017). Nutrient absorption by the plants from the soil can be improved using nanofertilizers. The encapsulated form of nanosilica, which forms a dual film on the cell wall of bacteria or fungi after absorption of nutrients and inhibits infections, has a beneficial effect on plant growth under high temperatures and humidity and improves plant resistance to disease infections (Wang et al. 2002; El-shetehy et al. 2020). Silicon-based fertilizers are practiced to activate the resistance of plants, as silicon dioxide NPs can recover the growth of the seedling and root development (Nair et al. 2010) TiO_2, or titanium in its non-toxic form, is used as an additive in fertilizers to enhance food production(Ropers et al. 2017; Lyu et al. 2017). The additives in fertilizers can increase water retention (Emadian et al. 2017). Also, nanoclays play an essential role in the slow release of nitrogen fertilizer (Sharmila et al. 2010). The synthesis of chitosan NPs has been tested with polymethacrylic acid (PMAA) for stuffing NPK fertilizers(Hasaneen et al. 2014). The addition of N, P, and K has a greater anion charge from the calcium phosphate than the potassium chloride and urea charges(Hasaneen et al. 2014; Khalifa and Hasaneen 2018). As a result, it has greater chitosan NPs stability in colloidal polymethacrylic acid (CS-PMAA) suspension (Hasaneen et al. 2014). The dispersals of CS-PMAA pooled with nitrogen are more unstable than those of phosphorus. Positive changes in the colloidal diffusion of CS-PMAA decreased above 500 ppm of nitrogen due to negative groups from the urea molecules (Emadian et al. 2017). For diffusion with potassium, the stability of the solution has been confirmed with the addition of 400 ppm. It revealed that Cl ions (from KCl) didn't disturb the stability of colloidal dispersal with the addition of up to 400 ppm of concentration (de Vasconcelos et al. 2006; Wu et al. 2006).

Nanofertilizers

Chemical fertilizer is a major problem and a hindrance to achieving reasonable sustainability in agriculture, with limited nutrient use efficiency and environmental constraints associated with chemical fertilizer use. Also, the resulting cost increase of chemical fertilizer reduces profit margins for growers due to overapplication (Zulfiqar et al. 2019). Agriculture production, crop quality, and about 40%–60% of the total global food fabrication depend on plant nutrition (Roberts 2009). Nanofertilizers are economical for the producer as compared to traditional fertilizers. Also, it increases nutrient efficiency and improves plant nutrition and growth (Table 1). Improvement of nutrient efficiency through nanotechnology helps develop the nanofertilizer. Three classes of nanofertilizers have been proposed:

Nanoscale fertilizers (nutrients loaded with or coated with NPs),
Nanoscale additives (nanoscale additives with traditional fertilizers), and
Nanoscale coating (traditional fertilizers contain NPs).

These nanomaterial coatings (such as nanomembranes) can reduce nutrient discharge or increase the solubility of permeable nanofertilizers. Nanotechnology for fertilizers is still in its infancy; on the other hand, it has been adopted for medical and engineering applications (Mikkelsen 2018).

Nanotechnology makes farming more productive by solving problems that haven't been solved before at the smallest possible scale, which gives researchers more hope. Nanotechnology has the potential to transform agricultural production in plant and animal production by enabling better management and conservation. Nanotechnology can meet the rising population's future requests because NPs have exclusive physicochemical characteristics, i.e. high reactivity, high surface area and tuneable pore size (Abobatta 2018). Sustainable agricultural production and efficiency are not possible without agrochemicals, such as pesticides, fertilizers, etc. Plant growth and development depend on fertilizers. Still, they are essential because most useful fertilizers are inaccessible to plants owing to numerous issues, such as leaching, degradation by photolysis, decomposition, and hydrolysis. So, minimizing the fertilization losses and increasing the crop yield with nanomaterials and nanotechnology. Nanofertilizers or nanoencapsulated nutrients possess the properties that are effective for crops, they release the nutrients on-demand, organize the discharge of chemical fertilizers that control plant growth, and improve objective activity (Monreal et al. 2016; Rai et al. 2015). Agrochemicals are problematic in one way or another, like pollution of water or deposits on food products that threaten human beings and ecological health conditions (Carvalho 2017). Therefore, the development of the modern agricultural system with the use of nanotools is an excellent strategy to make a revolution in agricultural practices; nanotechnology can reduce and eliminate the influence of fertilizer, pesticides, etc. on the atmosphere along with enhancing both the quantity and quality of crop yields (Singh Sekhon 2014; Liu and Lal 2015). Nanoparticles treatment to plants and application of nanofertilizers exhibited profound influence on the secondary metabolites content and antioxidant potential status as reported in various plants (Table 2). Similarly foliar spray and seed priming of silver, zinc, copper and gold nanoparticles is reported to exhibit improved growth and productivity in filed as shown in fenugreek, maize, mustard and foxtail millet (Table 3).

Nanopesticides

In recent years, due to the high toxicity and non-biodegradability of pesticides, environmental problems have brought attention to nanofertilizers. Athanassiou et al. (2018) state that nanoformulations are similar to other regular pesticide formulations in that they help in increasing the apparent solubility of a poorly soluble active element or liberating the active element in a relaxed or directed manner, thus protecting the active component against early degradation. Pesticides developed using the nanoformulation method are called "nanopesticides." The preparation of nanopesticides can be accomplished either by using tiny particles of pesticidal active components or additional nanostructured particles with pesticidal properties. Investigators have advanced diverse nanopesticides, such as nanocapsules, nanogels, nanoemulsions, nanospheres, and metal and metal oxide NP formulations (Hayles et al. 2017; Kah and Hofmann 2014). Nanopesticides are showing viable potential to overcome these limitations. Slow degradation and controlled release of active ingredients in the presence of suitable NMs can offer effective pest control over a long period of time (Chhipa 2017). Therefore, nanopesticides are essential for the effective and sustainable management of different pests and minimize the use of synthetic chemicals and their associated environmental risks(Côa et al. 2019) Nanopesticides behave differently from conventional pesticides to increase their efficacy (Kah et al. 2019). It includes the insertion of nanoscale active ingredients into pesticides. The specific properties of these nanoscale materials, like their aptitude to dissolve in water more efficiently than the existing products or their increased stability, are designed to maximize these pesticides' effectiveness. Various kinds of nanoformulations can be used for agrochemicals like nanoencapsulations, nanoemulsions, nanosuspensions, etc. Some common welfare benefits of NPs based pesticide inventions include the augmented solubility of water-insoluble active elements, improved steadiness of the formulation, the removal of lethal organic solvents in contrast to conventionally used pesticides, the ability to slow the discharge of active elements, recovery of their permanence and avoid their early degradation, improve their flexibility and greater insecticidal

Table 1 Overview of developed nanofertilizer and its influence on plant growth parameters

Nanofertilizer	Crop name	Amount of Nanofertilizer (ppm)	Impact	References
Au	Pearl millet (*Pennisetum glaucum*)	50	Improved seed germination and growth of seedlings	Parveen et al. (2016)
Ca	Peanut (*Arachis hypogea*)		Nutrient content increased in shoot and root	Liu et al. (2004)
CeO_2	Cucumber (*Cucumis sativus*)	400	Improved scratch and globulin content	Zhao et al. (2014)
CNTs	Date palm (*Phoenix dactylifera*)	0.05–0.1	Shoot length and number of leaf increased	Taha et al. (2016)
	Tobacco (*Nicotiana tabacum*)	5–500	55–64% plant growth improved	Khodakovskaya et al. (2012)
Cu	Lettuce (*Lactuca sativa*)	130–600	Shoot and root length increased	Shah and Belozerova (2009)
CuO	Maize (*Zea mays*)	10	51% plant growth	Adhikari et al. (2016)
Fe/SiO_2	Barley (*Hordeum vulgare*) and maize (*Zea mays*)	0–25	Improved mean germination time	Najafi Disfani et al. (2016)
FeO	Soybean (*Glycine max*)	30- 60	Chlorophyll increased	Ghafariyan et al. (2013)
	Pea (*Pisum sativum*)	250–500	Seed weight and chlorophyll increased	Delfani et al. (2014)
Mg	Cow peas (*Vigna unguiculata*)	2.5	Increment in stem Mg content, chlorophyll content and plasma membrane stability	Delfani et al. (2014)
Mn	Mung bean (*Vigna radiata*)	0.05–1	Shoot length, chlorophyll content and the photosynthesis rate increased	Pradhan et al. (2013)
	Rice (*Oryza sativa*)		Improved Zn uptake 5.66 mg/hill	Yuvaraj and Subramanian (2015)
Mo	Chickpea (*Cicer arietinum*)	8	Plant mass and number of modules increased	Taran et al. (2014)
P	Soybean (*Glycine max*)	100	Improved the growth rate and seed yield by 32.6% and 20.4%	Liu and Lal (2014)
TiO2	Spinach (*Spinacia oleracea*)	0.25–4	Plant dry weight increased by 73%	Zheng et al. (2005)
	Mung bean (*Vigna radiata*)	10	Improvement in plant growth and nutrient content	
	Cowpea (*Vigna unguiculata*)	125	Cowpea yield up to 26–51%	Owolade and Ogunleti (2008)
	Spinach (*Spinacia oleracea*)		N_2 fixation improvement	
Zn	Ryegrass (*Lolium*)	01–2000	Root elongation	Lin and Xing (2008)
	Rice (*Oryza sativa*)	0–150	increase of root and shoot length in rice	Upadhyaya et al. (2015)

Table 1 (continued)

Nanofertilizer	Crop name	Amount of Nanofertilizer (ppm)	Impact	References
ZnO	Mung bean (*Vigna radiata*) and chickpea (*Cicer arietinum*)	01–2000	Growth of the plant improved at 20 ppm in chick pea and mung bean at 1 ppm	Mahajan et al. (2011)
	Cucumber (*Cucumis sativus*)	400–800	Root dry weight and fruit gluten increased	
	Rape seed (*Brassica napus*)	01–2000	Root elongation	Lin and Xing (2007)
	Peanut (*Arachis hypogea*)	1000	34% increment in pod yield per plant	Prasad et al. (2012)
	Chickpea (*Cicer arietinum*)	1.5	Improved shoot dry weight and antioxidant activity	Burman et al. (2013)
	Maize (*Zea mays*)	10	Improved plant height and dry weight	Adhikari et al. (2015)
	Clusterbean (*Cyamopsis tetragonoloba*)	10	Improvement in plant growth and nutrient content	Raliya and Tarafdar (2013)

movement due to reduced particle size and higher surface area, and extend their longevity (Usman et al. 2020).

Nanotechnology for food safety and production

Nanotechnology in the farming and food segments is a relatively new trend compared with pharmaceuticals and drug delivery. Agri-food nanotechnology is multidisciplinary in nature. Nanotechnology has a wide-ranging application in agriculture and the food sector, such as protecting vegetation, nursing plant growth, detecting animal and plant diseases, growing worldwide foodstuff fabrication, enhancing food quality features and reducing waste (Omanović-Mikličanin and Maksimović, 2018). The advancement of nanosized food materials and additives as delivery methods for bioactive composites and pioneering food packing were studied (Nile et al. 2020). Nowadays, with the world's population getting higher, fulfilling all the requirements of agriculture and nutrition for food is difficult. Therefore, we have to adopt new technologies to focus on and minimize this problem to get better agricultural production. Nanotechnological applications can help to achieve sustainable agriculture and food nutrition supply (Bajpai et al. 2018). Recently, food and nutrition abundantly implanted in acquaintances. Specific target-oriented goals in agriculture development depend on health, climate change, social inclusion, natural resources, ecosystem progressions, energy, moral supremacy, etc., and must be acknowledged (Meybeck et al. 2018). With sustainable agricultural practices, nanotechnology has the potential to alleviate people's hunger and poverty**.** In the agriculture zone, an ecological recital is essential, and simultaneously, the contribution of food chain networks is also a prerequisite for agrarian food fabrication (Prasad et al. 2017; Usman et al. 2020). The global population in 2050 needs about 200 million tons of annual meat. The United Nations of Food and Agriculture Organization has already foreseen fulfilling the food requirements for the increasing population and the pressure and further demands of livestock with land to produce feed (FAO 2017). Also, the need for land fronting competition from the crops for other determinations like, biofuels and pharmaceuticals. So, the production of food faces numerous challenges, including a falling ratio of available land due to an increasing population. Agronomy as a food source is an essential trait in a global world of weakening resources and an increasing human population. Modern technologies like nanotechnology and nanobiotechnology are important for agronomic and food skills to meet the increasing world population. Nanotechnology revolutionizes farming and associated fields, together with fisheries and aquaculture. Agricultural practice now includes nanoagriculture, which uses nanosized particles to increase livestock and crop production (Scott and Chen 2013; Ghidan and Antary 2019; Joshi et al. 2019; Mohammad Fakhrul and Karim 2020).

Table 2 Table representing the influence of nanoparticles on plant secondary metabolites and antioxidant activity

Plant	Nanoparticles	Effect of Nanoparticles	Reference
Echinacea purpurea (Purple coneflower) callus	ZnO NPs	Secondary metabolite Flavonoids 3.7 fold	Karimi et al. (2018)
Phaseolus vulgaris (Common bean) in vitro and in vivo	Ag and Cu NPs	Physiological Characteristics	Mustafa et al. (2017)
Calendula officinalis (Marigold)	Methyl Jasmonate and AgNPs	MDA, Chlorophyll, Saponin, Carotenoid, Flavonoids	Ghanati and Bakhtiarian (2014)
Eruca sativa (Garden rocket)	Ag, Cu, and Au NPs	seed germination and seedling growth in	Zaka et al. (2015)
Trigonella foenum-graecum (Fenugreek)	AgNPs	Plant growth and diosgenin	Jasim et al. (2017)
Artemisia annua (Sweet wormwood) (Callus)	CoNPs	artemisinin production and gene expression	Ghasemi et al. (2015)
Prunella vulgaris (Common Self-Heal) (Callus)	Ag and Au NPs	Phenolics, Flavonoids, and Antioxidant activity	Fazal et al. (2016)
Hyoscyamus reticulatus (Lattice Henbane)	FeO NPs	hyoscyamine and scopolamine	Moharrami et al. (2017)
Capsicum annuum (Cayenne pepper)	CuO NPs	Life cycle	Rawat et al. (2017)
Cicer arietinum (Chickpea) *Vigna radiate* (Mung bean), *Phaseolus vulgaris* (Black bean), and *Phaseolus vulgaris* (Red bean)	Hematite NPs	Growth of the plant	Boutchuen et al. (2019)
Allium cepa (Bulb onion)	ZnO NPs	Growth, Flowering and Seed Production	Laware and raskar (2014)
Arachis hypogaea (Peanut)	Metal oxide NPs, FeO, CuO, and TiO NPs	physiological response and reduce nutritional quality	Rui et al. (2018)
Stevia rebaudiana (Sweetleaf)	Cu and Au NPs	Secondary metabolite	Ghazal et al. (2018)
Momordica charantia (Bitter gourd)	AgNPs	secondary metabolites	Chung et al. (2018)
Caralluma tuberculate (Pamanghi)	AgNPs	biomass and secondary metabolites	Ali et al. (2019)
Prunella vulgaris (Common self-heal)	Ag and Au NPs	biomass and industrially important secondary metabolites	Fazal et al. (2019)
Capsicum sp. (Chillies or peppers)	AgNPs	capsaicin	Bhat and Bhat (2016)
Triticum aestivum (Common wheat) stress-tolerant Parabola and stress-sensitive Raweta,	Ag NPs and Ag salt	Morphological characteristics, lipid peroxidation and mobilization of defense system	Barbasz et al. (2016)
Gymnema sylvestre (Australian cowplant)	CuO NPs	GA II, total phenolics, and flavonoids	Chung et al. (2019)
Citrullus lanatu (Watermelon)	Turmeric oil nanoemulsions and Ag NPs	Improves Germination, Growth, Yield, and Quality	Acharya et al. (2020)
Capsicum annuum (Chillies or peppers)	AgNPs	Cytokinin response	Vinković et al. (2017)
Zea mays (Corn)	TiO_2 NPs	Anthocyanins, Carotenoids, Chlorophyll	Morteza et al. (2013)
Withania somnifera (Ashwagandha)	CuO NPs	polyphenols content and antioxidant activity	Singh et al. (2018)
Achillea millefolium (Common yarrow)	Agand Methyl Jasmonate NPs	lipid peroxidation, flavonoid content, and yield of essential oils	Ghanati et al. (2014)

Table 2 (continued)

Plant	Nanoparticles	Effect of Nanoparticles	Reference
Stevia rebaudiana Bertoni (Honey Leaf)	ZnO and CuO NPs	TPC, TAC, TRP and DPPH free radical scavenging activity	Javed et al. (2017)
Corylus avellana (Common hazel)	AgNPs	phenolics, and flavonoids, antioxidants activity, Taxanes content	Jamshidi and Ghanati (2016)
Mentha piperita (Peppermint)	$CuSO_4$ and Cu NPs	Morpho-physiological traits and essential oil	Lafmejani et al. (2018)
Punica granatum (Pomegranate)	MgO and CuO NPs	tannins and phenols	Al-oubaidi and Al-khafagi (2018)
Arabidopsis thaliana (Mouseear cress)	FeNPs	Root Elongation, Antioxidant activity	Kim et al. (2014)
Arabidopsis thaliana (Mouseear cress)	Al_2O_3, SiO2, Magnetite and ZnO NPs	Phytotoxicity (seed germination, root elongation, and number of leaves)	Lee et al. (2010)
Boswellia ovalifoliolata (Salai guggul)	AgNPs	Seed germination and Seedling growth	Savithramma et al. (2012)
Gymnema sylvestre (Australian cowplant)	CuONPs	Gymnemic Acid and Phenolic Compounds	Chung and Thiruvengadam (2019)
Salvia miltiorrhiza (Red sage)	Ag ion,	Tanshinones than Phenolic Acids	Xing et al. (2014)
Nigella arvensis (Wild Fennel)	Al and NiONPs	growth and antioxidant defense	Chahardoli et al. (2020)
Triticum aestivum (Wheat)	TiO_2NPs	Antioxidant activity, leaves and root	Silva et al. (2019)
Cucumis sativus (Garden cucumber)	Cu(OH)2 nanopesticide	Antioxidant and detoxification gene expression	Zhao et al. (2017)
Cucumis sativus (Garden cucumber)	Ag ions and AgNPs	Antioxidant defense systems, respiration, inhibited photorespiration, altered membrane properties and reduced inorganic nitrogen fixation (downregulation of glutamine and asparagine)	Zhang et al. (2018)
Capsicum chinense (Habanero peppers)	$ZnSO_4$ ion and ZnO NPs	physicochemical quality; phenolic compounds; antioxidant capacity	García-López et al. (2019)
Cucumis sativus (Garden cucumber)	CuNPs	Oxidative stress, genotoxicty, and changes in superoxide dismutase (SOD) Gene expression	Mosa et al. (2018)
Capsicum annuum (Chillies or peppers)	SeNPs	Growth, morphology, anatomy, biochemistry, gene expression, and epigenetic DNA methylation	Sotoodehnia-Korani et al. (2020)
Portulaca oleracea (Duckweed)	AgNPs	Physiological and Molecular	Zare et al. (2019)
Stevia rebaudiana (Sweetleaf)	AgNPs	Glycosides Biosynthetic Pathway	Ramezani et al. (2019)
Capsicum annuum (Chillies or peppers)	Nano-chitosan	growth, morphogenesis, physiology, and micropropagation	Asgari-Targhi et al. (2018)
Brassica rapa sp. *rapa* (Napa cabbage)	AgNPs	Physiological, metabolic, and transcriptional effects	Thiruvengadam et al. (2014)

Table 3 Relevance of nanoparticles on crop production under field conditions

Plant	Type of NPs	Mode	Field relevance	References
Trigonella foenum-graecum (fenugreek)	AgNPs	Foliar application 40 mg/l	AgNPs increased yield components, growth and biochemical parameters	Sadak, 2019
Zea mays (maize)	Zn encapsulated chitosan NPs	Seed priming and foliar application (0.01–0.16%)	Increased grain yield from 20.5 to 39.8% and also enriched the grain with zinc micronutrient from 41.27 to 62.21 µg/g dw	Choudhary et al., 2019
Brassica juncea (cv. *pusa jaikisan*)	AuNPs	Foliar spray	Optimal increase in seed yield was recorded at 10 ppm with 19% increase in seed yield per plant	Arora et al., 2012
Avena sativa (Oat) and *Trifolium alexandrinum* (Berseem)	ZnO, TiO_2, CuO and Ag NPs	Seed priming	All the four NPs at lower dose (750 mg) significantly enhanced germination percentage, seedling vigour and yield traits as compared to control in both the crops	Maity et al. 2018
Zea mays (Maize)	CuNPs	Seed priming	Positive effect on plant productivity with increased total seed number and grain yield under drought stress conditions	Nguyen et al., 2020
Setaria italica (Foxtail Millet)	ZnO NPs	Foliar Spray	Concentrations of 2.6 mgL^{-1} ZnO NPs with twice foliar spary in field trial showed the maximum significant changes in millet grain oil and the total nitrogen content nutritional factors	Kolenčík et al. 2019

Prerequisites of nanotechnology in food industries

Food processing

Food processing is the conversion of raw elements into foods and other forms that are marketable and have a long shelf life. Processing includes pathogen prevention, toxin removal, and improving and preserving food evenness for healthier marketing and distribution. Processed foods are typically less liable to early spoilage than fresh foods and are restored to a state suitable for long-distance transport from the source to the consumer. All of these assets have been enhanced by the current convergence of nanotechnology. Nanocapsule conveyance systems play an essential role in the processing region, and the functional assets are preserved by encapsulating simple solutions like emulsions, colloids, biopolymers, and others into food products (Chellaram et al. 2014; Paredes et al. 2016; Amit et al. 2017). Existing nano-foods include nanoscale ingredients and additives in emerging nanoemulsion-based ice cream with a lower fat content but a fatty consistency and flavour. NPs have improved colour and stability during processing, improved flow properties, and increased shelf life of food products. For example, aluminosilicate is used in granular or powdered processed foods

Table 4 Common ingredients used in food nanoformulations

Components	Examples	References
Functional ingredients	Carotenoids; vitamin E; omega-3, -6, and -9 fatty acids; phytosterols; curcumin; coenzyme Q	Laouini et al. (2012), Qian et al. (2012), Saberi et al. (2013)
Emulsifiers	Sodium dodecyl sulphate; Tween® 20–80; Span® 20–80; phospholipids; casein; whey protein; soy protein	Lam and Nickerson (2013), Adjonu et al. (2014), Guttoff et al. (2015)
Oils	sunflower, soybean, fish, mineral, basil, olive, corn, cinnamon, coconut, castor, and essential oils	Donsì et al. (2011), Ghosh et al. (2013), Lane et al. (2014)
Ripening retardants	Long-chain triglyceride; mineral oil; ester gum	Joe et al. (2012), Ghosh et al. (2014)

as anticaking agents, whereas anatase TiO_2 is a common food whitener and brightener additive found in confectionery, a few sauces, and cheeses (Alfadul and Elneshwy 2010; Masood et al. 2019). Nano-encapsulated bioactives include vitamins, isoflavones, co-enzymes, carotenoids, flavonoids, food colouring substances, preserving agents, and a few other bioactive ingredients. These products can be found in a variety of food additives and beverages, as well as in vitamin E nano-resolution, which is specifically designed for pure beverages such as athletic beverages, flavourings, and enriched waters. The efficiency of these elements depends on conserving and increasing their bioavailability. Nano-encapsulating or nano-sizing active constituents deliver better bioavailability, enhanced solubility and amplified effectiveness than those materials in higher or micro-encapsulated form (Table 4). The higher the force of the NPs additives, the lower the concentration of the prerequisite additives and their chemical reactivity (Mozafari et al. 2006; Coelho et al. 2007; dos Santos et al. 2018). Nanotechnology can be used to manipulate food products for the effective delivery of protein and antioxidants. The encapsulated system developed results in nanospheres or microspheres (Singh et al. 2017; Lengyel et al. 2019). Nanosized self-assembled essential lipids serve as a liquid transferor of healthy components that are insoluble in water and fats, called nanodrops. They are used to constrain cholesterol transportation from the digestive system into the bloodstream (de Azeredo 2009; Arora and Padua 2010; Rhim et al. 2013).

Food safety

Nanomaterials are the essential components of many chemical and biological sensors, which have been explored to improve existing devices' performance or bring a new perspective to food safety. Nanomaterials' functions are implemented for two purposes: to improve the response characteristics of the transducers and as immobilization matrices for the receptors. Nanomaterials used in electrochemical biosensors for food safety mainly include carbon-based nanomaterials, metal and metal oxide NPS, magnetic NPs, and molecularly imprinted polymers (Zeng et al. 2016; Mustafa and Andreescu 2020). Nanotechnology can detect minute amounts of a chemical pollutant, bacteria, or virus in foodstuffs. The combined biosensors of the biological molecules and nanomaterials significantly reduced response time to a prospective problem. It will result in extra care for the food handling scheme. Nano-sensors established by researchers at Purdue and Clemson universities use NPs, which can either be appropriate to colours, flavours, or industrial magnetic resources. These NPs can selectively suppress any food pathogen. These sensors also detect either magnetic materials or infrared light and can signal the occurrence of even a tiny hint of dangerous pathogens. The benefit of such a scheme is that, hypothetically, thousands of NPs can be positioned on a single nanosensor to swiftly and precisely sense any number of diverse bacteria and pathogens. Likewise, these nano-sensors will be able to advance access to the minute clefts where the pathogens habitually hide. The impact of nanotechnologies on the detection of pathogenic microorganisms in food and the development of nanofood safety are also being investigated at Cornell University's biosensors research laboratory and bioanalytical microsystems**.** These studies focused on developing fast and portable biosensors for detecting pathogenic microorganisms in the environment and food. The scheme places emphasis on the precise and rapid recognition of pathogens in regular drinking water analysis, food examination, environmental analysis, and clinical diagnostics (Shefer and Shefer 2003a, b; 2005). Because of their antagonistic effects on human health and influence on environmental systems, AgNPs could directly improve the world's food supply without being used in food. AgNPs work as antimicrobial agents in foods to grow food-related claims such as microbe-resistant materials or non-biofouling shells. Ag ions are precisely sensitive and may react with the negatively charged cell membrane, providing a supplementary involvement to AgNPs' bactericidal effect (Ghorbanpour et al. 2020; Zorraquín-Peña et al. 2020; Hutapea et al. 2022). The benefits of Ag antimicrobial agents are that they can be easily incorporated into various constituents, such as textiles and plastics. AgNPs are valuable in a broad range of applications**,** as they preserve their antimicrobial action in situ, whereas traditional antimicrobial agents would be unstable (Franci et al. 2015). According to (Carbone et al. 2016), AgNPs may be assimilated into non-degradable (vinyl alcohol, polyvinyl chloride, and polyethylene) and recyclable (starch, cellulose, agarose, and chitosan) polymers to produce food packages.

The AgNPs may also provide clues to novel methods for killing foodborne pathogens and augmenting food security (Flood 2010). They also illustrated that NPs can provide us with multi-component antimicrobial fusions that would be substantially compatible with other compounds to kill microorganisms and improve food safety (Zorraquín-Peña et al. 2020). Nanotechnology might also be pragmatic in the analysis of food to notice reasonably low-slung quantities of toxins formed by microorganisms. E.g., *Staphylococcus aureus* can synthesize the thermostable enterotoxins A, B, C, D, and E. Around 100–200 ng of these enterotoxins is enough to cause a lethal infection. Hence, this bacterium in foodstuff might turn into a hazard reaction in health system, if it preserved at a temperature that favours its growth. Nanotechnology has developed a method for detecting *S. aureus* that employs magnetic beads to detect the maximum number of strains of *S. aureus* at a low and viable cost. It will lead to improved food safety. Analogous effects were also found for *Listeria monocytogenes*. Aflatoxin are teratogenic, carcinogenic, mutagenic, and immunosuppressive materials produced as secondary metabolites on a variety of food products by the fungi *Aspergillus flavus* and *Aspergillus parasiticus*. The highest tolerance level in mice is 2 ng AFB1/g. For AFB1 detection**,** a competitive ELISA test using a 96-well microplate for immunosensors has been industrialized. This method pools the great selectivity of immune study with the comfort of electrochemical probes and multi-sample analysis (Argudín et al. 2010; Hernández-Cortez et al. 2017; Wang et al. 2017). These applications of nanotechnology in food examination would advance food quality and safety and regulate the vulnerabilities that might disturb human health.

Food packaging

Nanomaterials useful in food packaging are categorized into two classes: inorganic and organic materials. For the prior materials, metals, metal oxides, and clay NPs merged into bionanocomposite films and nanofibers can be considered (Huang et al. 2018; Chaudhary et al. 2020; Jafarzadeh et al. 2020). Besides conventional bacteriostatic AgNPs, some inorganic agents, like oxidized NPs, including ZnO, CuO, MgO, TiO_2, and Fe_3O_4, have attracted considerable attention due to their conflict with rough processing conditions and improvements in potent inhibition against foodborne pathogens. As far, the resources like several clays, they may possibly bid resistance to water vapor and gases and recover biopolymers' mechanical strength (Attaran et al. 2017). The second group is organic materials including, halogenated compounds, phenols, plastic polymers, quaternary ammonium salts, plus natural polysaccharide or protein materials such as chitin, chitosan, zein, and whey protein isolates, which have been currently greatly assessed (Perinelli et al. 2018).

Recent nanotechnology applications in food science have ensured a significant influence on the food industry with the molecular combination of novel food products or fixings that increase the security and shelf-life of the food. The growth of nanostructured materials comprises physical, chemical, and biological properties that are significantly different from those of their unpackaged parallels in food structures. Nanotechnology has impending applications in the food zone, including food packaging and safety, leading to enhanced eminence and conservation of foodstuffs. Some foods, like milk and milk derivatives, contain nanoscale constituents such as casein and other milk proteins (Pathakoti et al. 2017; Nile et al. 2020). The foremost tenders of nanostructured supplies in food are liposomes, nanocomposites, nanoemulsions, NPs, proteins, biopolymeric nanostructured films, and cellulose-based NPs. These materials enable precise proclamation, improve solubility, advance bioavailability, and defend bioactive modules during production and packing (Pathakoti et al. 2017).

Nanotoxicity

The toxicity of nanomaterials and nanocomposites on plant systems was well illustrated (Ibrahim et al. 2019). Studies in this regard prove that it has full applications in agriculture. For example, the effect of nanohexaconazole on soil microbes behaves similarly to the commercial formulation hexaconazole (Contaf Plus) with no side effect on soil microbiota (Kumar et al. 2015). In the case of ZnO NPs with thiram, it has antifungal properties and degrades the extra thiram after the antifungal process (Xue et al. 2014). CeO_2 NPs and ZnO NPs' effects on the life cycle of corn (*Zea mays*) plants were found to be that CeO_2 NPs altered the position of calcium in kernels, and ZnO NPs reduced photosynthesis by 12%, stomatal conductivity by 15%, and chlorophyll content by 10%. The yield was reduced by 38 and 49% in the cases of CeO_2 and ZnO, respectively (Zhao et al. 2015).

Nanomaterials' mobility, bioavailability, and toxicity have required attention for a better understanding of risk factors. The use of nanomaterials and their exposure may be a hazard, which still needs to be known in-depth. NPs and their materials will most likely be released into the environment from construction services, landfills, wastewater treatment plants, or nonpoint sources such as clothing made from NP-containing materials. Unintentional discharge of NPs during creation or transportation is also possible. There are various NPs that directly get injected into groundwater, leading to pollution, especially with chlorinated solvents. The different ways to dump the NPs, whether in soil/ water, or the atmosphere, all result in the interaction of NPs with plants, either directly or indirectly, via sewage treatment plants (Nowack and Bucheli 2007). The AgNPs affect the growth, physiology, and morphology of the aquatic plant duckweed (*Spirodela polyrhiza*). The harmfulness of AgNPs and $AgNO_3$ indicated that Ag content in plant tissue increased considerably with higher concentrations of $AgNO_3$ and AgNPs. AgNPs and $AgNO_3$ expressively reduced the biomass of the plant, produced colonies of *S. polyrhiza* to crumble, and also resulted in root abscission. The physiological study revealed that AgNPs and $AgNO_3$ pointedly reduced nitrate-nitrogen content in plant tissue, chlorophyll a/b (Chl a/b) content, and chlorophyll fluorescence (Fv/Fm). Variations in soluble carbohydrate and proline content were also identified after $AgNO_3$ and AgNPs treatment (Jiang et al. 2017). These acts of NP exposure will have a harmful effect on the environment and human health. There are some studies regarding the application of NPs to plants. There is a crucial point in the view that metal NPs cause phytotoxicity via the closure and discharge of greater concentrations of essential ions (Ma and Mumper 2013; Anjum et al. 2015).

Overlying challenges and future perspectives

Nature has both disease-inducing and disease-preventive incentives. Science is the link between nature and disease, examining biological problems in nature and developing solutions to them. Any particle has the power to bring about changes in the environment. When we go with the disease protection concept, we always look forward to an agent or an elicitor with significant activity and minor concentration. In this context, nanoformulation is one of the most significant approaches. Nanotechnology includes diverse fields of science involving the manipulation of materials at the atomic and molecular level. Agricultural nanotechnology was developed in the 1990s, and it is now functionalized globally in various sectors of farming. Agro-nanotechnology enables sustainable food production by developing healthy potential plant systems that can improve plant germination, growth, yield, and quality. The scientific venture of nanotechnology provides us considerable benefits in all areas, and it is also essential to move toward a responsibility to make wise use of nanotechnology. The vision of nanotechnology was initiated in 1959 by Richard Feynman in his visionary talk "There is Plenty of Room at the Bottom," wherein he illustrated the possible manipulation of atoms. Presently, a branch of that vision has been recognized, but it remains indistinct as to the possible extent of manipulations at the atomic level. The concept of nanotechnology in the farming sector helps develop good health in society's economic status by transforming a pathogenic form into a non-pathogenic, environmentally friendly, and sustainable form**.** Also, minimize the use of hazardous chemicals for short-term benefits. Nanotechnology has created an era by grabbing significant funds globally. There is no doubt, that it will further channel and revolutionize the mainstream of the science vision to overcome all the constraints in agriculture by improving the green econom**y.** Further, research bodies have to engage in the utilization of naturally available solutions to improve the plants' growth and health potential. Besides, it is also essential to minimize the use of hazardous chemicals for short-term benefits and step forward to improve the ecosystem's strength in bringing out long-term benefits to agricultural commodities.

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Declarations

Conflict of interest All the authors declare that there is no conflict of interest.

Informed consent We affirm that all the authors have seen, prepared, and agreed to the submission of the paper and their inclusion of name(s) as co-author(s). We also declare that there are no conflicts of interest for the same.

Research involving human participants and/or animals This article does not contain any studies with human participants or animals performed by any of the authors.

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