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REVIEW ARTICLE

An overview on the applications of nanotechnology in strawberry: A compendious review

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Abstract

Sustainability, food security and fertilizers are the most essential benefits that nanotechnology offers towards sustainable agriculture, which is viewed as a viable approach. This is crucial in improving the amount and quality of agricultural production. Despite having different means of application and various sources of mineral, organic, or chelated fertilizers, these fertilizers have limited efficiencies, with only 5 % nutrients added being used effectively. Therefore, nutrient loss through fertilization should be minimised by utilising nanotechnology/nanomaterial to enhance crop growth and productivity. Because of their reduced drug-loading capacity, the increased surface area-to-volume ratio causes only a substantial portion of an atom to be on the surface, resulting in high responsiveness, improved uptake and high mobility of nutrients by plants. Nanoformulations allow for the effective use of fewer fertilizers, pesticides and fungicides. The review will assist fruit scientists in planning strawberry experiments by applying nanotechnological techniques and be helpful in understanding the inclusive scope and application of nanotechnology in pomology, which will provide support to conventional methods of fruit production.

Keywords: nanofertilizers; nanoformulations; nano micronutrients; nano-particles; strawberry

Introduction

The strawberry (*Fragaria ananassa* Duch.) is an allo-octoploid (2n = 8x = 56) cultivated within the Rosaceae family. It is an artificial hybrid cross between *Fragaria chilonensis* and *Fragaria virginiana*. It is soft and sweet in the test and has the broadest range of adaptability. They are fresh and healthy as they possess good nutritional and medicinal value. Three distinct compounds, namely sugar, acids and aromatic compounds, are primarily responsible for the flavour of strawberry fruits (1). Although strawberries are often consumed for their taste, they can also be used in high-quality processing products such as jam, syrup, candy and ice cream. The strawberry is one of the most extensively cultivated small fruits globally. They are widely grown in Asia, Africa, Canada, South America and many other regions up to a height of 1500m MSL. In India, strawberries are cultivated in various states, including Himachal Pradesh, Uttarakhand, the Northern Hills and Arunachal Pradesh, as well as in non-traditional areas such as Maharashtra, Tamil Nadu, Uttar Pradesh, Karnataka, Assam, Meghalaya, Rajasthan, Punjab and Madhya Pradesh. It has regions cultivated of 1000 ha with animal production of 5000 Mt/ha (2). Strawberry fruit plants require temperate climatic conditions for optimum growth, yield and better quality.

The term "nano" is derived from the Greek word for "dwarf," which signifies a microscopic scale. Conversely, "technology" encompasses the application of diverse tools, techniques and machinery to perform specific endeavors (3). It is usually called nanotech and pertains to the handling and study of matter at 100 billionths of a meter or smaller scale. Due to the nanoscopic wildlife of the objects involved, visualization of such material poses a challenge for most individuals. In agriculture, the practice of nanoparticles with different functionalities is a key aspect of nano agriculture, which aims to improve crop production (4).

All human beings' primary and essential condition is having something to eat or drink, whereas their availability is directly or indirectly connected with agricultural uses. Projections showed that by 2025, the worldwide population will reach eight billion persons and by 2050, it will reach approximately nine billion, indicating a well-recognized need to enhance agricultural production globally to meet the increasing demands of a rising world population (5). Over the past few decades, different substitute approaches like nanotechnology have been introduced in commercial enterprises to meet these challenges. Nanotechnology is a promising solution due to its numerous notable applications, such as nanofertilizers (6). The field of nanotechnology has demonstrated the appropriateness of utilizing materials at the nanoscale or with nanostructured properties, which can be used as carriers for fertilizers and controlled release agents for "smart fertilizers", aiming at reducing costs associated with environmental protection (7). Nanofertilizers are nanoparticles of critical plant nutrients that can be directly applied and dispersed to the rhizosphere on crops in the appropriate time required by crops (8).

In recent times, nanotechnology has found widespread applications in agriculture and horticulture. Nanofertilizers (NFs) are the most explored fruit tree-related factor. NFs have been reported to be critical for increasing vegetative growth, enhancing reproductive growth and flowering, resulting in increased productivity, improved product quality and ultimately reduced fruit waste. These nanomaterials are typically used at small concentrations as sprayed on plants at various periods through several sessions referred to as growth stimulants. Fertilizer nanocomposites (Zn, Fe, Mn, B, N, P, K, Mg and calcite) and other materials that are micro and macro scale NFs have been shown to significantly improve the vegetative and reproductive traits of fruit crops, such as strawberry, date, pomegranate, mango, coffee and grape (9).

Nano-fertilizer technology is a new field with limited literature. However, encompassing many disciplines and having benefited from significant public investments in the past decade, agriculture has only witnessed modest enhancement (10). By manipulating the genes of plants and animals and delivering genes and pharmaceutical molecules to specific cells within the plant or animal at the cellular level, nanotechnology has prospectively increased agricultural productivity (11). Improved quality of fruits on fruit trees can be achieved through applying nano applications that increase tree productivity, enhance nutrient management in modern agriculture and increase the storage potential of fruits as it has been experiential that nano fertilizer used in farming reduces soil erosion hence, reduces pollution resulting from lower fertilizer demand which implies higher return for farmers in terms of economics from use of nanofertilizers in agriculture field (12). Therefore, nanofertilizers for fruit trees should be emphasized while exploring other types of fruit trees' response to nanofertilizers.

Nanomaterials can boost crop output by enhancing the convenience of nutrients in the soil and nutrient absorption by plants. Problems in the agricultural system brought on by using traditional fertilizers may be resolved using nanotechnology. A device, technique, time and the release of N_2 through its absorption by crops may ideally be provided by this methodology (10). Nanofertilizers are materials of nanoscale size, predominantly in the form of nanoparticles, which enclose macro and micronutrients and are administered to crops in a controlled manner. This category of fertilizers comprises three distinct types *viz* nanoscale fertilizers, nanoscale additives and nanoscale layers (Table 1) (13). Their increased surface area-to-volume ratio enhances the chemical, physical and biological possessions and functions of nanoparticles. Nanofertilizers provide certain nutrients in a nano form, which have been shown to augment plant production and growth (14).

The delivery of nutrients to plants in an accessible form is known to enhance nutrient absorption by plants, thereby increasing plant productivity (15). Nanofertilizers uplift nutrient accessibility to developing plant sections, which enhance leaf chlorophyll accumulation, photosynthetic rate, production of dry matter and hence total plant growth. It was observed that seeds treated with nano-TiO_2 had more dry weight, photosynthetic rate and chlorophyll-a production than plants grown from untreated seed (16). However, the efficiency of conventional fertilizer rarely exceeds 30 % to 40 %. Standard fertilizers' effectiveness, consisting of 30-35 % N, 18-20 % P and 35-40 % K, has been stable for decades (17).

Consequently, adding a large number of fertilizers to soils to offset the loss of fertilizers has been shown to have a detrimental impact on the balance of soil nutrients (18). A prior study revealed that nanomembranes possess the potential to serve as a coating for fertilizer particles, thereby enabling the gradual release of supplements (19). In response to the extreme applications of inorganic fertilizers, the implementation of slow-released nanofertilizers has been proposed. Due to their ability to slowly discharge supplements throughout crop production, these nanofertilizers with delayed release properties may represent a promising substitute for soluble inorganic fertilizers.

The traditional practice of applying nutrients to the soil is linked with various limitations in relationships of nutrient accessibility to plants. As a result, the foliar application has emerged as the most effective approach for restoring nutrient deficiencies and enhancing crop productivity and quality (20). Furthermore, it has been evident that this approach can effectively combat environmental contamination and improve nutrient utilization efficiency by reducing the quantity of fertilizer applied to the soil (21). Fertilizers can be included in nanoparticles to increase nutrient absorption. Nanofertilizers

Table 1. Comparison between traditional and nanofertilizers

S. No.	Basis	Traditional fertilizers	Nanofertilizers	References
1	Nutrient release	Nitrogen pollution, which harms aquatic ecosystems and human health, may be a factor	Nutrients may be made to be released slowly, enhancing absorption while lowering leaching and runoff	(63)
2	Soil and water risks	Detrimental effects on the health of the soil, resulting in soil degradation and decreased agricultural output	Risks to the environment and health, include toxicity to plants, animals and people as well as possible buildup in soil and water systems	(64)
3	Composition	Often contains big molecules or particles and is produced from natural resources like rock phosphate and animal feces	Nanoscale-engineered particles consist of metals, ceramics and polymers, among other materials	(65)
4	Crop yield improvement	Possess a track record of enhancing agricultural yields	More quickly reach the root zone than conventional fertilizers, resulting in more effective nutrient absorption	(66)
5	Overall assessment	Before choosing a choice, it is critical to weigh the advantages and disadvantages that may be present	To completely undressed the advantages and hazards and to create safe and efficient goods, more research is required	

may be the best solution for enduring eutrophication problems since they increase nutrient utilization efficiency to reduce macro - and micronutrient deficits (22).

The intense production of nitrogenous fertilizers and the rapidly diminishing supply of phosphatic and potassium sources of fertilizers will be a significant cause of concern for many nations where liveliness safety is still a goal (23). Macro-nano fertilizers are an alternative option for reducing the bulk quantity of nutrients due to their nanosize dimensions. New fertilizers that are equally environmentally safe and have high nutrient utilization efficiency are needed. Macronutrients such as N, P, K, Mg, S and Ca are collected with nanomaterials to deliver optimum nutrition to the plants through dipping costs of cultivation (24). Research indicates that macronutrients can be helpful to plants *via* soil application, foliar spray and injection (25).

Micronutrients are trace elements that are essential for plant biological, anatomical and physical activities but are needed at lower concentrations (26, 27). Zinc application is a vital trace element for proper development and growth (27). Since zinc is only obtainable in the root zone, which limits plant nutrient uptake, most cultivated land is zinc deficient (28). Due to their extremely small size and large surface area, plants can readily absorb zinc nanoparticles (14, 28). Iron participates in the biosynthesis of the electron transport chain (ETC), as it is a critical nutrient for crop growth and development (29). Nanoparticles, such as iron oxides, have been widely used in catalytic processes, significantly improving crop characteristics, including photosynthesis, chlorophyll content, light absorption, nitrogen and phosphorus uptake and fruit and yield biomass (30).

Thus, nano-biofertilizers are complexes of plant growth-promoting rhizobacteria with a coat of silver nanomaterials (31). The utilization of nano-biofertilizers poses significant difficulties. To address this issue, the advancement of manufacturing processes and mass production will increase the use of nano-biofertilizers in the production of fruit crops. The combined application of nanoparticles with biofertilizers has been proven to recover the growth and development of several fruit crops. At varied dosages ranging from 1-4 ppm as a foliar spray, injection injected into the plant's trunk and soil application of nano-seaweed extract in *Phoenix dactylifera* L. induced fruit weight, pulp weight and weight of bunch (32).

Nano-encapsulation systems enhance the stability of bioactive compounds that are ungraded to unfavourable environmental conditions, including heat, ultraviolet radiation and oxidation. Furthermore, this system enables the controlled release of the encapsulated mixtures (33). Nanoencapsulation is novel nanotechnology that simplifies the precise and slow release of active elements from capsules or particles (34). The creation of engineered nanomaterials marks a significant technological advancement in the era of material design and product development. While the application of nanotechnology in agriculture is still in its early stages, it can potentially transform agricultural systems, particularly the challenges involved with fertilizer application. Utilizing various nanofertilizers reduces fertilizer costs and minimizes emission problems, thereby significantly impacting crop yield. Because they are more reactive, soluble and able to pass through the cuticle, Nanofertilizers may be disseminated precisely and released under control. Nano-fertilizers decrease heavy metal toxicity and abiotic stress while increasing crop development, yield, quality and nutrient utilization efficiency. Presently, there is a focus on the risks associated with consuming technology and engaging in limited activities that only marginally enhance its effectiveness (35).

Research indicates that nanoparticles, particularly Nanofertilizers, are next-generation technology that can upgrade agribusiness systems. Several nanomaterials have demonstrated possible functions in fruit crops regarding plant vigour, yield enhancement and ecological constancy. However, there is still a long way to go in proposing such technology for sustainable fruit production since various problems, such as legal processes, must be solved before large-scale application. The prospective applications of Nanofertilizers will undoubtedly stimulate a revolt in the fertilizer sector and address the matter of food uncertainty in emerging republics (36). Eventually, nano fertilizers may enhance strawberry productivity, fruit quality and nutrient efficiency, resulting in economic benefits. Their greater initial cost is still an incentive though, especially to small-scale farmers. Acceptance is dependent on access, awareness and proven revenue, even when lower usage rates and higher efficiency may balance costs. Support from field-level extension campaigns, local industry and incentives increases economic viability.

Research gap

The use of nanotechnology in horticultural crops is growing in popularity; however, its application in strawberry production remains little understood and scattered. The majority of investigations are confined to laboratory-scale experiments or preliminary trials, despite the fact that they show potential advantages such as improved nutrient delivery, enhanced plant acceptance and a longer shelf life. Comprehensive research investigations assessing the long-term consequences, environmental safety and economic feasibility of nano-formulations in strawberry cultivation are scarce. In addition, little is known about how nanoparticles connect with the physiology of strawberry plants, the nutritional value of their fruit and the bacteria in the soil. For commercial strawberry cultivation, this gap requires methodical research into standardized nano-agrochemical techniques, biosafety assessments and scaling.

Benefits of using nanofertilizers

Because they boost crop quality and soil fertility, nanofertilizers are superior to conventional fertilizers. These fertilizers minimize costs and maximize returns while being nontoxic and less damaging to people and the environment (Fig. 1-3). Research indicates that nanoparticles reduce environmental protection costs while increasing nutrient utilization (37). They significantly promote plant development by preventing disease and enhancing plant consistency through the development of deeper roots in crops (20). Because they enhance agricultural yield, soil fertility and crop quality, nanofertilizers are more effective than regular fertilizers. Nanoparticles reduce ecological costs and enhance the efficiency of nutrient utilization, uptake and plant growth (38, 39).

Impact of nanofertilizers in strawberry

Vegetative growth

The influence of nanoparticles on plant growth and development can be either beneficial or detrimental, or both. Numerous aspects are involved, including the type of nanoparticle employed, the species of plant, the treatment dose,

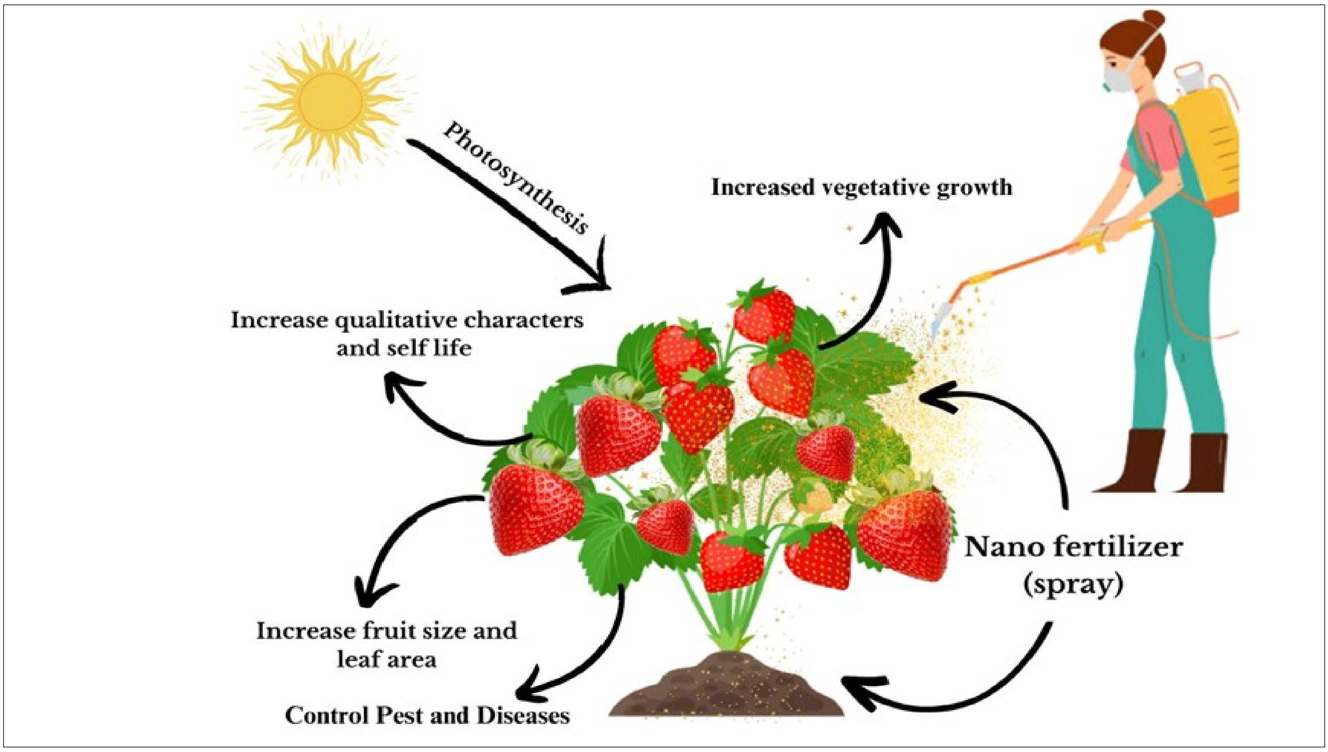

Fig. 1. Overall impact of application of nanofertilizers in strawberry.

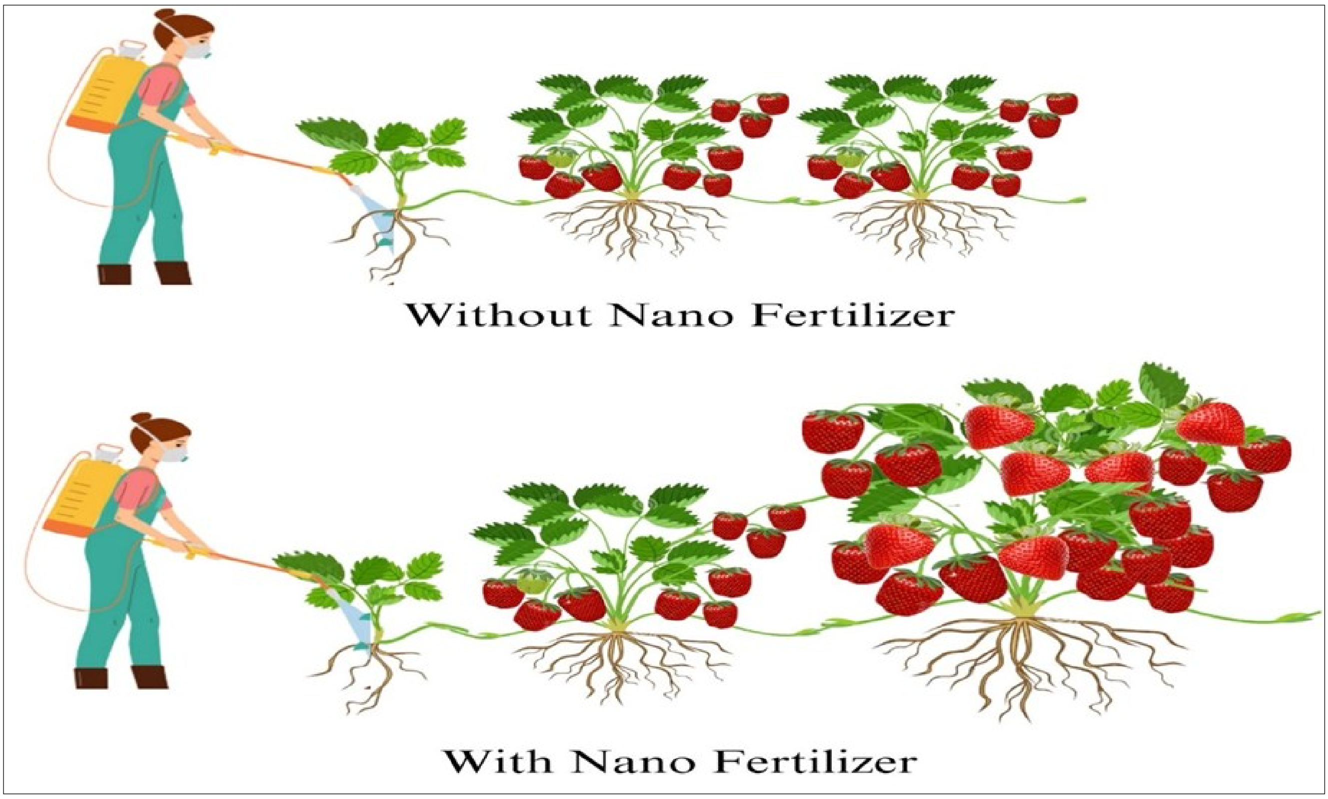

Fig. 2. Effect of nanofertilizers on growth and development of strawberry.

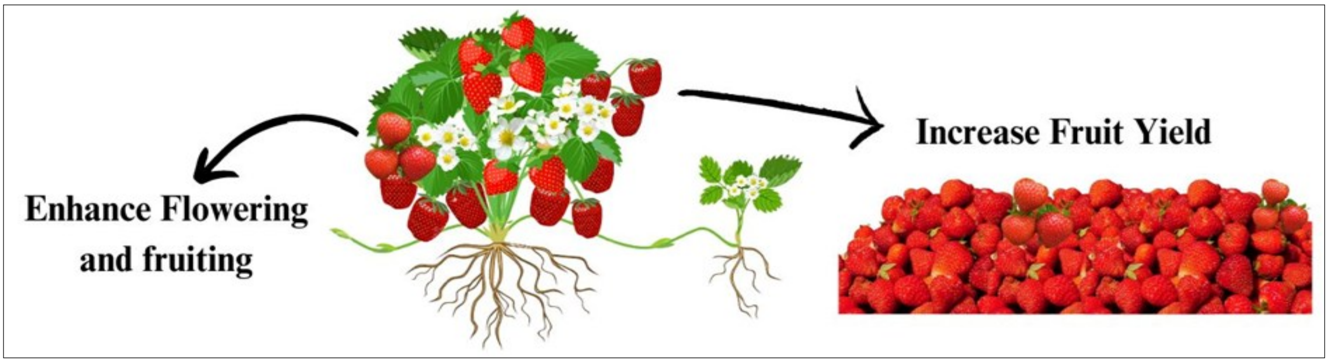

Fig. 3. Effect of nanofertilizers on flowering, fruiting and yield.

the timing of the treatment, and the stage of development (Table 2). A zinc oxide nanofertilizer affected strawberry plant growth and economics. The findings demonstrated that the nanofertilizer boosted strawberry plants' leaf area, shoot length, fresh and dry weight and profitability of the strawberry crop (40). Research indicates that zinc oxide nanoparticles infiltrate the root tissue of ryegrass and promote germination (41). Applying copper oxide nanoparticles by foliar spray on strawberry plant development revealed that the nanofertilizer enhanced the strawberry plants' height, number of leaves and fruit production (42). The impact of titanium dioxide nanoparticles on strawberry plant development and physiology revealed that the type of fertilizer used may affect the efficiency of the nanofertilizer, as it had no visible influence on the growth or physiology of the plants (43).

Flowering and fruiting

Although nanofertilizers improve fruit plant flourishing, growth and production, there is little research on their impact on fruit crop development (Table 3). The foliar spray of calcite nano-fertilizer at 30 ppm promotes flowering and yields higher-quality flowers (44). The effect of zinc oxide nanoparticles (ZnO NPs) on strawberry plant growth, production and fruit quality. Demonstrated that ZnO NPs significantly boosted strawberry flowering (45). The influence of copper oxide nanoparticles (CuO NPs) on strawberry plant production and development shows that CuO NPs strawberry plant development indices such as the height of the plant, the diameter of the stem and leaf area in addition to increasing strawberry flowering, fruiting and yield (46). The impact of iron oxide nanoparticles (Fe_3O_4 NPs) on strawberry plants dramatically boosted strawberry flowering, fruit production and yield while also enhancing quality indicators such as TSS, titratable acidity and total phenolic content (47).

Yield

Various studies have found that using nanofertilizers improves crop output compared to regular or traditional fertilizers (Table 4). It can be attributed to maximum plant growth and enhanced metabolic activities, such as photosynthesis, which results in increased photosynthesis formation and translocation to the plant's economic components. It has also been observed that the foliar application of nanofertilizers considerably boosted crop production (48). If used at low concentrations, several Nanofertilizers, including zinc, zinc oxide, chelated iron and its derivatives, can significantly upsurge the yield and quantity of fruit crops (49). Research indicates that using 70 % more nano nitrogen fertilizer increased production by 11.6 % compared to

Table 2. Application of nanofertilizers on vegetative growth of strawberry

S. No.	Nanofertilizer	Effect of nanofertilizers	References
1.	Nano-Chitosan-K + K_2SO_4 at the rate of 1000 mg/L	Increased the plant height, fresh and dry weight of the plant and leaf area.	(67)
2.	Nano Zinc at the rate of 200 mg/L Nano Selenium at the rate of 200 mg/L	Increased seedling height, survival rate, length of root and number of leaves. Increased seedling height, root length, leaves and root length.	(68)
3.	Nano NPK + Humic acid at the rate of 200 mg/L nano NPK + 200 mg/L humic acid	Increased the number of leaves, runners leaf area and dry weight of the plant	(69)
4.	Nano-chitosan, Nano-micronutrients and Bio capsules at the rate of 100 ppm	Increased height of the plant, number of leaves, leaf area, plant spread and number of runners	(70)
5 .	Vermicompost + Nano fertilizer	Increased fresh weight and dry weight of the plant.	(71)
6.	Nano Zinc chelate at the rate of 200 ppm + 0.5 % citric acid	Increased fruit length and fruit width	(72)
7.	Nano Zinc Oxide at the rate of 150 ppm	Increased the number of shoots and leaves and enhanced the chlorophyll content	(73)
8.	Nano zinc at the rate of 150 mg/L	Increases the most prominent height	(74)
9.	Nano Iron at the rate of 150 ppm	Increased physiological traits	(75)
10.	Nano Calcium carbonate at the rate of 100 ppm	It improves growth and development and growth	(76)
11.	Nano Phosphorous at the rate of 1 mg/L	Increased growth and development	(77)
12.	Nano Boron at the rate of 100 ppm	Increased height of plant, leaf area and no. of leaves	(78)

Table 3. Application of nanofertilizers on flowering and fruiting of strawberry

S. No.	Nanofertilizer	Trait improved	References
1.	Nano-chitosan, Nano-micronutrients and Bio capsules at the rate of 100 ppm	Earliness in terms of flowering, fruiting and number of nodes	(71)
2.	Nano Zinc Oxide at the rate of 100 ppm	Boosting the quantity, weight and sugar content of the fruits, increased the fruit output and quality of strawberry plants.	(73)
3.	Nano Zinc at the rate of 100 ppm and nano Iron and at the rate of 150 ppm	Increased flowering percentage	(79)
4.	Nano Zinc at the rate of 200 $\mu g\ g^{-1}$	Reported the most substantial influence on flowering initiation, number of flower plants and flowering duration	(80)
6.	Nano Boron at the rate of 200ppm	Increased flowering and fruiting production	(81)
7.	Nano Silicon at the rate of 150 ppm	Increased fruit size, weight, output and quality of strawberry plants	(82)
8.	Nano Iron Oxide at the rate of 1200 ppm	Increased fruit size, sugar content, yield and quality	(83)

Table 4. Application of nano fertilizers on yield and attributing trait of strawberry

S. No.	Nanofertilizer	Trait improved	References
1.	Nano-chitosan, Nano-micronutrients and Bio capsules at the rate of 100 ppm	Increased fruit yield	(70)
2.	Vermicompost at the rate of 10 % + Nano fertilizer + 200 mg/L	Increased fruit size and weight	(84)
3.	Nano Zinc chelate at the rate of 200 ppm + 0.5 % citric acid	Increased fruit weight, shoot dry weight and yield	(72)
4.	Nano NPK at the rate of 3 gm/L	Increased fruit yield	(85)
5.	Nano Zinc at the rate of 200 $\mu g\ g{-1}$	Increased fruit weight	(74)
6.	Nano Iron oxide at the rate of 1000 g/L	Increased dry weight and yield	(86)
7.	Nano Copper at the rate of 200 ppm	Enhanced fruit yield	(87)
8.	Nano Zinc oxide at the rate of 0-400 g/L	Increased fruit yield	(88)

regular fertilizer (50). Nitrogen nano-fertiliser increased nitrogenous fertiliser production by 10.2 % and efficiency by 44.5 % over standard urea fertiliser, saving up to 12.4 % to 41.7 % of N_2 application in the soil (51). Nanotechnology enhances agricultural output by increasing input efficiency and reducing losses by providing a larger, better and more targeted area for different fertilisers and pesticides (52). Zinc oxide nanoparticles (ZnO NPs) considerably increased strawberry fruit production and yield (53).

Pest and disease management

Powdery mildew, root rot, aphids, grey mould and red spiders are the most common diseases and pests of strawberries; powdery mildew is a significant disease of strawberries resulting from reduced fruit setting, insufficient maturation, poor aroma and taste, fruit cracking and distortion and shorted postharvest storage period (Table 5). Powdery mildew outbreaks were observed to limit strawberry productivity by 70 % (54). Pesticide application during the initial phases of crop growth helps drop insect populations below the economic verge level and provides effective control for longer. As such, treating the surface with active chemicals has remained one of the most economical and divergent ways of managing insect pests. To improve the insecticidal value, a nanotechnology method known as "nano-encapsulation" can be applied to keep the active component from opposing ecological conditions and encourage perseverance. Nanoencapsulation contains nano-sized lively element atoms summarized by a thin-walled sac or shell (protective covering). To protect the active ingredient from degradation and increased persistence, a nanotechnological approach of "precise release of the dynamic element" may advance formulation effectiveness and potentially substantially decrease pesticide input and associated environmental risks (55). Several studies on pesticide encapsulation have recently been published. Nano-encapsulation of fungicides, insecticides, or nematicides will aid in developing a preparation that delivers successful pest control while reducing residue formation in soil.

In farming, weeds are another big issue. In India, the application of pesticides is comparatively much less due to two-thirds of its agriculture being rainfed (Fig. 4-5). Herbicides on the market are intended to replace or reduce the growth of weed plants in the soil. Herbicides do not prevent the growth of underground plant parts, such as rhizomes or tubers, which can produce new weeds in the next growing season. Soils containing weeds or weed seeds have a higher probability of yield reduction than soils free of weeds. Crop productivity may rise if herbicide effectiveness is improved through nanotechnology. The summarized nano-herbicides are significant in light of the obligation to design and manufacture nano-herbicides that are environmentally friendly and work independently when there is a spell of rainfall, truly mimicking the rainfed system. (55).

Quality

The enhanced surface area of nanofertilizers enhanced the accessibility of nutrients to horticultural plants. Speeding up the plant system's response or fusion helps improve quality traits, including sugar, oil and protein content (Table 6-8). Applying nano zinc and iron formulations has enhanced protein, starch, IAA, total carbohydrates and leaf chlorophyll in crop grains (56). The application of nanoparticles has improved the quality traits and shelf life of edible fruits, as well as their firmness and the accumulation of various bioactive components, including ascorbic acid, total soluble solids and antioxidant capacity (57). The study gathered fruits based on whether they were entirely pink or had a white tip at the end. As a result, there were no significant changes in colour amongst fertilizations based on our assessed factors. Fruit fertilized with calcium and Lithovit were markedly stiffer than nitrogen-treated and control fruits. Furthermore, 66 % and 100 % RDN fertilized fruits were roughly 30 % softer than CA-CH (58). Zinc oxide nanoparticles (ZnO NPs) affect strawberry plant growth, productivity and fruit quality. The results demonstrated that ZnO NPs quality strawberry fruit such as TSS, ascorbic acid and titratable acidity concentration substantially (59).

Risk assessment

The nano particle-induced toxicity studies on metal-based nanoparticles revealed that the nanoparticles affect social beings' lungs, skin and brain organs (60). Nano biosensors have also been used to identify a wide range of animal and human infections; however, nanotechnology's potential is still limited when it comes to plant pathogens. Specific biocontrol agents, such as fungi, including *Trichoderma viride* and *Trichoderma harzianum*, negatively impact silver nanoparticles (61, 62).

Handling, safety precautions, standards and global norms of Nanoparticles

The international recommendation is to use a biological safety cabinet. Wear masks and nitrile gloves when handling or cleaning up spilled chemicals containing nanoparticles as a precautionary measure. The laboratory used for nanoparticle studies should be maintained in a highly sterile environment. The dusting of fallen chemicals and excess ingredients covering nanoparticles must be prioritized. Such waste can enter the soil and kill beneficial microbes, or it can enter water bodies, causing the extinction of aquatic life (3). While nanofertilizers offer significant benefits for sustainable agriculture, their handling and safety require careful attention due to the potential risks associated with nanoparticle exposure. Standard safety measures include the use of personal protective equipment (PPE), minimizing inhalation or direct contact during application and ensuring proper storage and disposal. However, global regulation of nanofertilizers remains fragmented. The International Organization for Standardization (ISO) and the OECD have established guidelines for nanomaterial characterization and environmental risk assessment. In the EU, nanomaterials are regulated under REACH, requiring detailed safety evaluations, while the U.S. EPA assesses nano-agrochemicals on a case-by-case basis under existing chemical laws. In India,

Table 5. Application of nanofertilizers on pest and disease management of strawberry

S. No.	Nanofertilizer	Insect- Pest and disease	References
1.	Nano copper 150 mg/L	Control Botrytis, powdery mildew and anthracnose	(89)
2.	Nano chitosan at the rate of 100 ppm	Spider mites and gray mold	(90)
3.	Nanosilver at the rate of 1 g/L	Botrytis, powdery mildew and anthracnose.	(91)
4.	Nano chitosan at the rate of 100 ppm	Powdery mildew, gray mold and botrytis.	(92)
5.	Nano chitosan at the rate of 150 ppm	Aphids and botrytis	(93)
6.	Nano copper at the rate of 150 mg/L	Slugs and snails.	(94)
7.	Nano chitosan at the rate of 200 ppm	Thrips and aphids	(95)

Table 6. Application of nanofertilizers on qualitative characters of strawberry

S. No.	Nanofertilizer used	Trait improved	References
1.	Nano-Chitosan-K+K_2SO_4 at the rate of 1000 mg/L	Improved TSS, vitamin C, acidity and total sugar	(67)
2.	Nano Zinc at the rate of 200 mg/L	Increased chlorophyll content	(68)
3.	Nano Selenium at the rate of 200 mg/L	Increased antioxidant and chlorophyll content	(68)
4.	Nano NPK at the rate of 200 mg/L + Humic acid at the rate of 200 mg/L	Increased chlorophyll content	(69)
5.	Vermicompost + Nano fertilizer at the rate of 10 % Vermicompost + 200 mg/L	Increased pH, total soluble solids, acidity, sugar content, vitamin C and anthocyanin	(71)
6.	Nano Zinc chelate at the rate of 200 ppm + 0.5 % citric acid	Increased fruit pH, titrable acidity, total soluble solids and chlorophyll	(72)
7.	Nano NPK at the rate of 3 gm/L	Increased total soluble solids and lycopene content	(85)
8.	Nano Iron oxide at the rate of 1000 g/L	Quality improvement	(86)
9.	Nano Zinc at the rate of 200 μg g−1	Fruit size (length and width), fruit weight and fruit hardness	(74)
10.	Nano Zinc oxide at the rate of 400 g/L	Enhanced fruit quality	(88)

Table 7. Some of the commercially available nano fertilizers

S. No.	Name of product	Formulation	Form	Company name
1.	Nano DAP	NPK at the rate of 8:16:0	Solid	IFFCO
2.	Nano Urea	4 % N w/v	Liquid	IFFCO
3.	Nano Zn	12 %	Solid	Geolife
4.	Nano Fe	12 %	Solid	Geolife
5.	Nano Mn	13.3 %	Solid	Geolife
6.	Nano combi	Zn-16 % + Mn-3 % + Cu-3 %	Solid	Geolife
7.	Nanofertilizer	NPK at the rate of 0:0:50	Solid	Geolife
8.	Nanofertilizer	NPK at the rate of 17:44:00	Solid	Geolife
9.	Nanofertilizer	NPK at the rate of 19:19:19	Solid	Geolife
10.	Nanofertilizer	NPK at the rate of 00:52:34	Solid	Geolife
11.	Nanofertilizer	NPK at the rate of 13:00:45	Solid	Geolife
12.	Nanomeal bloom	N- 13 %, P-42 %, Mg- 02 %, Zn- 01 % and Mn- 01 %	Solid	Geolife
13.	Nanomeal grow	N- 10 %, P- 50 %, Mg- 02 % and S- 02 %	Solid	Geolife
14.	Nanomeal flora	P- 40 %, K- 25 %, Mg- 02 %, Zn- 01 %, B- 0.4 % and Mn- 01 %	Solid	Geolife
15.	Nanomeal nourish	N- 10 %, P- 40 %, K- 10 %, Mg- 02 %, Zn- 01 % and 0.2 %	Solid	Geolife
16.	Nano combi	Zn, Mn, Cu	Solid	Geolife
17.	Nanomeal start	N- 14 %, P- 14 %, K- 14 %, Ca- 02 %, Mg- 02 %, Fe- 01 %, Zn- 01 %, B- 0.2 %, Mn- 01 %, Mo- 0.2 % and Cu- 01 %	Solid	Geolife
18.	Gromor nano DAP	N- 2 %, P-5 %	Solid	Coromandel
19.	Unikey nano Bio	N-2.5 %, K2O- 2.5 %, OM-32 %	Solid	Unikeyterra
20.	Nanobee agrokill biostimulant	Coconut glucoside: 25 %, Corn glucoside: 21 %, Sugarcane glucoside: 21 %, Palm fatty oil: 10 %, Peppermint oil: 1 %, Neem oil: 1 %, Garlic oil: 1 % and Water 20 %	Liquid	Big haat

Table 8. Foliar spray and soil application techniques compare in terms of efficiency

Parameter	Soil application	Foliar spray
Speed of action	Slower, sustained release	Fast (especially for micronutrients)
Targeting efficiency	Root-specific, broader, distribution	High (leaf-specific)
Application frequency	Less frequent	More frequent
Nutrient types	Both micro- and macronutrients	Micronutrients preferred
Environmental factors	Influenced by soil properties	Can reduce efficiency
Operational ease	Easily integrated with irrigation	Requires specialized sprayers

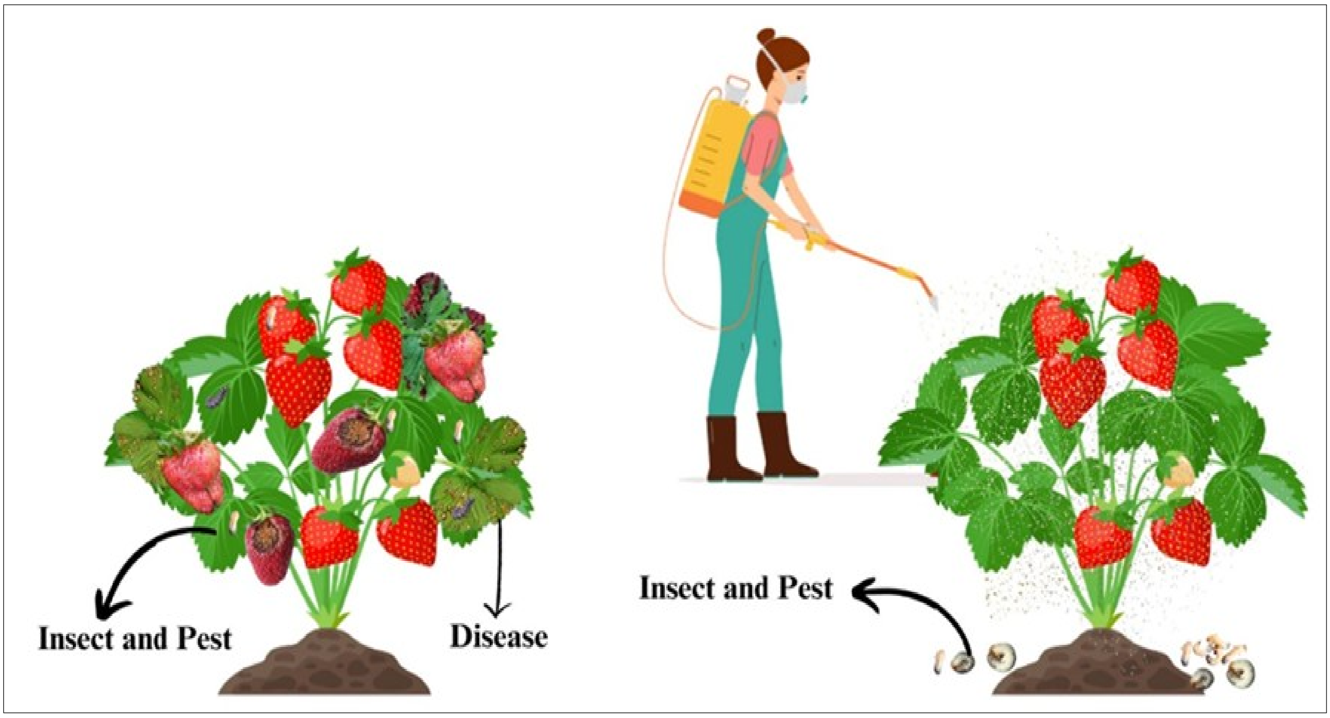

Fig. 4. Effect of nanofertilizers on insects, pests and diseases.

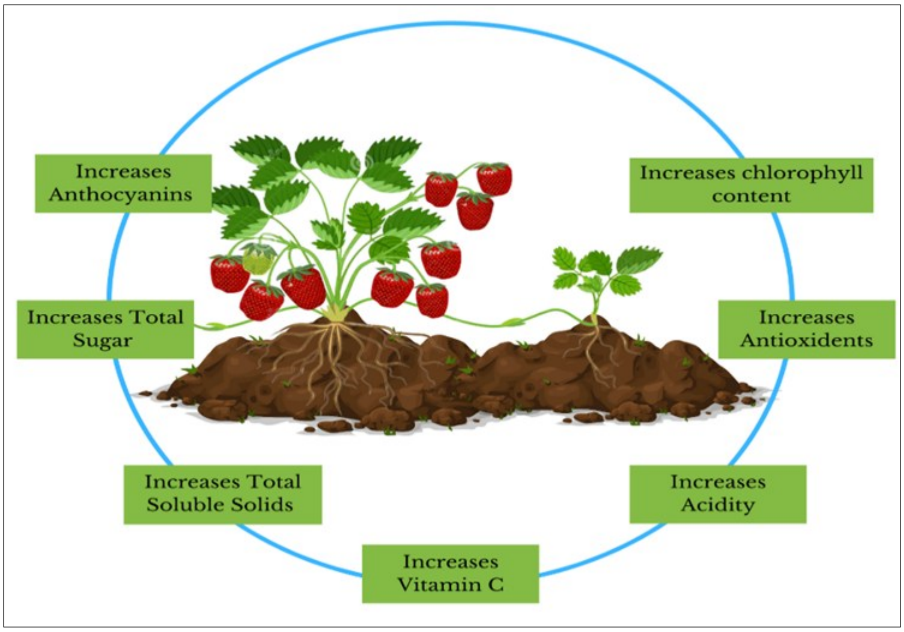

Fig. 5. Impact of nanofertilizers on the quality of strawberry.

agencies such as ICAR and DBT have initiated biosafety protocols and nano urea has been approved under the Fertilizer Control Order (FCO). Despite these efforts, there is still a lack of harmonized global standards, long-term field studies and nano-specific labeling requirements. Addressing these gaps is essential to ensure the safe and effective integration of nanotechnology in agriculture. Despite these efforts, a shortage of harmonised global norms, long-term field research and nano-specific labelling regulations remains. Resolving these gaps is important to ensure the safe and effective incorporation of nanotechnology in agriculture.

Conclusion and Future Prospects

Nanotechnology still has a long way to go in its application in fruit production. However, it still has more applications than expected in the future. There is potential for enhancing the quality of human life through this technology in fields such as sustainable and high-quality fruit production and improved food for the public. The risks associated with nanotechnology should be mitigated by scientists, while there is an urgent need to establish proper regulatory authorities and laws for regulatory purposes. Generally, strawberries are highly nutrient-demanding crops with precise nutrient requirements; thus, precise crop nonfertilizer application approaches will be necessary. For nano products to make economic sense, they must be affordable, in addition to being eco-safe, because they must address the challenges and concerns of resource-poor and marginal growers. Because fruit crops vary significantly in terms of planting methods and the duration required before harvesting, nanofertilizers require different application methods that are standardized according to the specific crop, such as strawberries. Therefore, appropriate management strategies and safety precautions should always be taken to minimise the risks associated with phytotoxicity resulting from nanoparticle handling.

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Authors' contributions

SK contributed to drafting the manuscript outline, writing the initial draft, participated in conceptualization and methodology, and performed the final editing and review. PK was involved in drafting the manuscript, contributed to conceptualization and supervision, and supported methodology development. S helped draft the outline and manuscript, and assisted in methodology and supervision. SP contributed to conceptualization and methodology design. SR provided supervision and contributed to the methodological framework. SS was involved in supervision, final editing and review of the manuscript. US conducted formal analysis and investigation during the study. AK contributed to data investigation and formal analysis. All authors reviewed and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

References

1. Liu C, Zheng H, Sheng K, Liu W, Zheng L. Effects of melatonin treatment on the postharvest quality of strawberry fruit. Postharvest Biol Technol. 2018;139:47–55. https://doi.org/10.1016/j.postharvbio.2018.01.016
2. NHB. Indian Horticulture Database [Internet]. Gurgaon: National Horticulture Board; 2022 [cited 2025 Jul 24]. Available from: https://www.nhb.gov.in/.
3. Jeevanandam J, Barhoum A, Chan YS, Dufresne A, Danquah MK. Review on nanoparticle and nanostructured materials; History, source, toxicity and regulation. Beilstein J Nanotechnol. 2018;9:1050–74. https://doi.org/10.3762/bjnano.9.98
4. Bhattacharya A, Bhaumik A, Rani UP, Mandal SS, Epidi TT. Nano-particle-A recent approach to insect pest control. Afr J Biotechnol. 2010;9:3489–93.
5. FAO/WHO guidelines for the evaluation of probiotics in food [Internet]. London, Ontario: Food and Agriculture Organization of the United Nations/World Health Organization; 2002 [cited 2025 Jul 24] Available from: www.fao.org

6. Naderi M, Shahraki DAA, Naderi R. Application of nanotechnology in the optimization of formulation of chemical fertilizers. Iran J Nanotechnol. 2011;12:16–23.
7. Chinnamuthu CR, Boopathi PM. Nanotechnology and agroecosystem. Madras Agric J. 2009;96:17–31. https://doi.org/10.29321/MAJ.10.100436
8. Subramanian KS, Tarafdar JC. Prospects of nanotechnology in Indian farming. Indian J Agric Sci. 2011;81:887–93.
9. Zahedi SM, Karimi M, Teixeira da Silva JA. The use of nanotechnology to increase quality and yield of fruit crops. J Sci Food Agric. 2020;100(1):25–31. https://doi.org/10.1002/jsfa.10004
10. De Rosa MC, Monreal C, Schnitzer M, Walsh R, Sultan Y. Nanotechnology in fertilizers. Nat Nanotechnol. 2010;5(2):9. https://doi.org/10.1038/nnano.2010.2
11. Maysinger D. Nanoparticles and cells: Good companions and doomed partnerships. Org Biomol Chem. 2007;5:2335. https://doi.org/10.1039/b704275b
12. Al-Hchami SHJ, Alrawi TK. Nano fertilizer, benefits and effects on fruit trees: A. Plant Arch. 2020;20(1):1085–88.
13. Mejias JH, Salazar F, Amaro LP, Hube S, Rodriguez M, Alfaro M. Nano fertilizer: A cutting-edge approach to increase nitrogen use efficiency in grasslands. Front Environ Sci. 2021;9:18–19. https://doi.org/10.3389/fenvs.2021.635114
14. Dimkpa CO, Bindraban PS. Fortification of micronutrients for efficient agronomic production: A review. Agron Sustain Dev. 2016;36(1):7. https://doi.org/10.1007/s13593-015-0346-6
15. Guru T, Veronica N, Thatikunta R, Reddy SN. Crop nutrition management with Nanofertilizers. Int J Environ Sci Technol (IJEST). 2015;1(1):4–6.
16. Zheng L, Hong F, Lu S, Liu C. Effect of nano-TiO_2 on strength of naturally aged seeds and growth of spinach. Biol Trace Elem Res. 2005;104:83–91. https://doi.org/10.1385/BTER:104:1:083
17. Subramanian KS, Manikandan A, Thirunavukkarasu M, Rahale CS. Nano-fertilizers for balanced crop nutrition. In: Rai M, et al., editors. Nanotechnologies in food and agriculture. Cham: Springer; 2015. p. 69–80. https://doi.org/10.1007/978-3-319-14024-7_3
18. Baruah S, Dutta J. Nanotechnology applications in sensing and pollution degradation in agriculture. Environ Chem Lett. 2009;7:191–204. https://doi.org/10.1007/s10311-009-0228-8
19. Tarafdar JC, Agarwal A, Raliya R, Kumar P, Burman U, Kaul RK. ZnO nanoparticles induced synthesis of polysaccharides and phosphatases by *Aspergillus* Fungi. Adv Sci Eng Med. 2012;4:1–5. https://doi.org/10.1166/asem.2012.1160
20. Roemheld V, El-Fouly MM. Foliar nutrient application challenges and limits in crop production. Proceedings of the 2nd International Workshop on Foliar Fertilization, Bangkok, Thailand; 1999. 4–10
21. Abou-El-Nour EAA. Can supplemented potassium foliar feeding reduce the recommended soil potassium. Pak J Biol Sci. 2002;5:259–62. https://doi.org/10.3923/pjbs.2002.259.262
22. Shukla P, Chaurasia P, Younis K, Qadri OS, Faridi SA, Srivastava G. Nanotechnology in sustainable agriculture: Studies from seed priming to postharvest management. Nanotechnol Environ Eng. 2019;4(1):11. https://doi.org/10.1007/s41204-019-0058-2
23. Schader C. Cost-effectiveness of organic farming for achieving environmental policy targets in Switzerland [dissertation]. Aberystwyth (Wales): Aberystwyth University; 2009
24. Ditta A, Arshad M. Applications and perspectives of using nanomaterials for sustainable plant nutrition. Nanotechnol Rev. 2016;5:209–29. https://doi.org/10.1515/ntrev-2015-0060
25. Sharonova NL, Yapparov AK, Khisamutdinov NS, Ezhkova AM, Yapparov IA, Ezhkov VO, et al. Nanostructured waterphosphorite suspension is a new promising fertilizer. Nanotechnol Rus. 2015;10:651–61. https://doi.org/10.1134/S1995078015040187
26. Noreen S, Fatima Z, Ahmad S, Ashraf M. Foliar application of micronutrients in mitigating abiotic stress in crop plants plant nutrients and abiotic stress tolerance. In: Plant nutrients and abiotic stress tolerance. Singapore: Springer; 2018. https://doi.org/10.1007/978-981-10-9044-8_3
27. Broadley MR. Zinc in plants. New Phytol. 2007;173:677–702. https://doi.org/10.1111/j.1469-8137.2007.01996.x
28. Lindsay WL. Zinc in soils and plant nutrition. Adv Agron. 1972;24:147–86. https://doi.org/10.1016/S0065-2113(08)60635-5
29. Lindsay WL, Schwab AP. The chemistry of iron in soils and its availability to plants. J Plant Nutr. 1982;5:821–40. https://doi.org/10.1080/01904168209363012
30. Madhura L, Singh S, Kanchi S, Sabela M, Bisetty K. Nanotechnology-based water quality management for wastewater treatment. Environ Chem Lett. 2019;17:65–121. https://doi.org/10.1007/s10311-018-0778-8
31. Malusá E, Vassilev N. A contribution to set a legal framework for biofertilizers. Appl Microbiol Biotechnol. 2014;98:6599–607. https://doi.org/10.1007/s00253-014-5828-y
32. Jubeir SM, Ahmed WA. Effect of nano-fertilizers and application methods on vegetative growth and yield of date palm. Iraqi J Agric Sci. 2019;50:267–74.
33. Anton N, Benoit JP, Saulnier P. Design and production of nanoparticles formulated from nano-emulsion templates: A review. J Control Release. 2008;128:185–99. https://doi.org/10.1016/j.jconrel.2008.02.007
34. Saifullah M, Shishir MRI, Ferdowsi R, Rahman MRT, Van-Vuong Q. Micro and nanoencapsulation, retention and controlled release of flavor and aroma compounds: A critical review. Trends Food Sci Technol. 2019;86:230–51. https://doi.org/10.1016/j.tifs.2019.02.030
35. El-Saadony MT, Lmoshadak AS, Shafi ME, Albaqami NM, Saad AM, El-Tahan AM, et al. Vital roles of sustainable nano-fertilizers in improving plant quality and quantity updated review. Saudi J Biol Sci. 2021;28(12):7349–59. https://doi.org/10.1016/j.sjbs.2021.08.032
36. Sharma S, Rana VS, Pawar R, Lakra J, Racchapannavar V. Nanofertilizers for sustainable fruit production: A review. Environ Chem Lett. 2021;19:1693–714. https://doi.org/10.1007/s10311-020-01125-3
37. Naderi MR, Abedi A. Application of nanotechnology in agriculture and refinement of environmental pollutants. J Nanotechnol. 2012;11(1):18–26.
38. Bayat M, Pakina E, Astarkhanova T, Sediqi AN, Zargar M, Vvedenskiy V. Review on agro-nanotechnology for ameliorating strawberry cultivation. Res Crops. 2019;20(4):731–36. https://doi.org/10.31830/2348-7542.2019.108
39. Ahmad R, Ali S, Rizwan M, Abbasi GH, Zahir ZA. Nanofertilizers and their roles in sustainable agriculture. ACS Sustain Chem Eng. 2019;7(18):15881–93.
40. Rajendran K, Aswath C, Selvaraj R. Zinc oxide nano fertilizer enhances the growth, yield and economics of strawberry. Sci Hortic. 2017;225:225–32.
41. Lin D, Xing B. Root uptake and phytotoxicity of ZnO nanoparticles. Environ Sci Technol. 2008;42(2):5580–85. https://doi.org/10.1021/es800422x
42. Salama HM, Al-Obeed RS. Foliar application of copper oxide nanoparticles enhances growth, yield and fruit quality of strawberry. Int J Agric Biol. 2019;22(6):1223–29.
43. Li X, Zhang X, Li W, Zhang X. Effect of titanium dioxide nanoparticles on the growth and physiology of strawberry plants. PLoS One. 2018;13(6):e0199286.
44. Sabir A. Improvement of the pollen quality and germination levels in grapes (*Vitis vinifera* L.) by leaf pulverizations with nano size calcite and seaweed extract (*Ascophyllum nodosum*). J Anim Plant Sci. 2015;25:1599–605.
45. Khan MN, Mobin M, Abbas ZK, Al-Shaeri M, Siddiqui MH. Zinc oxide nanoparticles enhance the growth and yield of strawberry plants. Sci

Hortic. 2017;219:191–97.

46. Etesami H, Ghanbari A, Alikhani HA, Khoshkholgh-Sima NA. Foliar application of copper oxide nanoparticles enhances growth, yield and physiological responses of strawberry plants. Appl Nanosci. 2017;7(7):581–88.

47. Rashid MI, Maqbool Z, Khalid N, Naveed M, Shahid M. Iron oxide nanoparticles regulate plant growth, fruit yield and quality of strawberry plants under foliar spray. Ecotoxicol Environ Saf. 2021;215:112163.

48. Chaudhari V, Vairagade V, Thakkar A, Shende H, Vora A. Nanotechnology-based fungal detection and treatment: current status and future perspective. Naunyn-Schmiedeberg's Arch Pharmacol. 2024 Jan;397(1):77–97. https://doi.org/10.1007/s00210-023-02662-8

49. Rana RA, Siddiqui MN, Skalicky M, Brestic M, Hossain A, Kayesh E, et al. Prospects of nanotechnology in improving the productivity and quality of horticultural crops. Hortic. 2021;7(10):332. https://doi.org/10.3390/horticulturae7100332

50. Zhang Z, Li M, Chen W, Zhu S, Lui N, Zhu L. Immobilization of lead and cadmium from aqueous solution and contaminated sediment using nano hydroxyapatite. Environ Pollut. 2010;158:514–19. https://doi.org/10.1016/j.envpol.2009.08.024

51. Huang S, Wang L, Lui L, Hou Y, Li L. Nanotechnology in agriculture, livestock and aquaculture in China- A review. Agron Sustain Dev. 2015;35. https://doi.org/10.1007/s13593-014-0274-x

52. Shang Y, Hasan MK, Ahammed GJ, Li M, Yin H, Zhou J. TiO_2 nanoparticle as an effect nano pesticide for cotton leafworm. Agri Eng Int: CIGR J. 2017;19(61):61–68.

53. Rana VS, Sharma V, Sharma S, Rana N, Kumar V, Sharma U, et al. Seaweed extract as a biostimulant agent to enhance the fruit growth, yield and quality of kiwifruit. Hortic. 2023;9(4):432. https://doi.org/10.3390/horticulturae9040432

54. Mahmud MS, Zaman QU, Esau TJ, Chang YK, Price GW, Prithiviraj B. Real-time detection of strawberry powdery mildew disease using a mobile machine vision system. Agron. 2020;10(7):1027. https://doi.org/10.3390/agronomy10071027

55. Elizabath A, Babychan M, Mathew AM, Syriac GM. Application of nanotechnology in agriculture. Int J Pure Appl Biosci. 2019;7(2):131–39. https://doi.org/10.18782/2320-7051.6493

56. Mahanta N, Dambale A, Rajkhowa M, Mahanta C, Mahanta N. Nutrient use efficiency through Nanofertilizers. Int J Chem Stud. 2019;7(3):2839–42.

57. Vargas ERL, Ortiz HO, Pliego GC, Romenus KDA, Fuente CDL, Mendoza AB, et al. Foliar application of copper nanoparticle increases the fruit quality and the content of bioactive components in tomatoes. Appl Sci. 2018;8(7):1020. https://doi.org/10.3390/app8071020

58. Weber CN, Koron D, Jakopi J, Veberi R, Hudina M, Cesnik BH. Influence of nitrogen, calcium and nano-fertilizer on strawberry (*Fragaria × ananassa* Duch.) fruit inner and outer quality. Agron. 2021;11:997. https://doi.org/10.3390/agronomy11050997

59. Kumar A, Rajan R, Pandey K, Ramprasad RR, Kaur G, Vamshi T, Singh T. Impact of new generation plant growth regulators on fruit crops–A review. Hortic Sci. 2024;51(1):1–22. https://doi.org/10.17221/166/2022-HORTSCI

60. Rai RV, Bai JA. Nanoparticles and their potential application as antimicrobials. In: A_. Méndez V, editor. Science against microbial pathogens: Communicating current research and tech; 2011. p.197-209.

61. Mahdizadeh V, Safaie N, Khelghatibana F. Evaluation of antifungal activity of silver nanoparticles against some phytopathogenic fungi and *Trichoderma harzianum*. J Crop Prot. 2015;4:291–300.

62. Kah M. Nano pesticides and nanofertilizers: Emerging contaminants or opportunities for risk mitigation. Front Chem. 2015;3:1–6. https://doi.org/10.3389/fchem.2015.00064

63. Stepanova M, Skalny A, Miroshnichenko S, Seregin I. Environmental and health risks of nanofertilizers: A review. J Hazard Mater. 2020;383:121–85.

64. Guo S, Huang J, Jiang S, Cai Q, Zhao Y. Application of nanotechnology in agriculture: Prospects and challenges crop journal. Crop J. 2017;5(1):1–12.

65. Malakouti MJ, Dadpour MR. Nano-fertilizers and their roles in sustainable agriculture. Int J Agric Biol. 2017;19(5):1243–50.

66. Sharpley AN, Bergström L, Aronsson H, Bechmann M, Bolster C, Börling K, et al. Future agriculture with minimized phosphorus losses to waters: research needs and direction. Ambio. 2015;44(2):163–79. https://doi.org/10.1007/s13280-014-0612-x

67. Abd-Elrahman SH, El-Gabry YAEG, Hashem FA, Ibrahim MFM, El-Hallous EI, Abbas ZK, et al. Influence of nano-chitosan loaded with potassium-on-potassium fractionation in sandy soil and strawberry productivity and quality. Agron. 2023;13:11–26. https://doi.org/10.3390/agronomy13041126

68. El-Bialy SM, El-Mahrouk ME, Elesawy T, Omara AED, Elbehiry F, El-Ramady H, et al. Biological nanofertilizers to enhance growth potential of strawberry seedlings by boosting photosynthetic pigments, plant enzymatic antioxidants and nutritional status. Plants. 2023;12(2):302. https://doi.org/10.3390/plants12020302

69. Al-Qadi RA, Alimam NMA. Response of three varieties of strawberry to the nano-npk fertilizer, humic acid. Int J Agric Stat Sci. 2023;19(1):89–99. https://doi.org/10.59467/IJASS.2023.19.89

70. Singh RK, Mishra S, Bahadur V. Effect of nano-chitosan, nano-micronutrients and bio capsules on yield and quality of strawberry (*Fragaria × ananassa*) cv. Winter Dawn. Biol Forum - Int J. 2023;15(5):289–95.

71. Mustafa NS, Moustafa YTA, El-Dahshouri MF, EL-Sawy SMM, Eman S, El Hady LF, et al. Combination vermicompost and nano-fertilizer applications and its impact on growth performance of strawberry. Middle East J Agric Res. 2022;11(1):70–80. https://doi.org/10.36632/mejar/2022.11.1.7

72. Sadeghi P, Hassanpour H. Foliar application of zinc chelate nanoparticles on quantitative and qualitative characteristics of Sabrina strawberry cultivar in different solubilization conditions. J Hortic Sci. 2022;36(2):471–87.

73. Alzahrani NA, Aljaddani AA, Alzahrani AA, Alsoufi MS, El-Gaaly GA. Impact of zinc oxide nanoparticles on the growth and yield of strawberry plants. Nanosci Nanotechnol Lett. 2021;13(2):181–86.

74. Saini S, Kumar P, Sharma NC, Sharma N, Balachandar D. Nano-enabled Zn fertilization against conventional Zn analogs in strawberry (*Fragaria × ananassa* Duch). Sci Hortic. 2021;282:110016. https://doi.org/10.1016/j.scienta.2021.110016

75. Madani H, Sharifi RS. Effect of nano-chelated iron on vegetative growth and physiological traits of strawberry. Sci Hortic. 2020;262:109096.

76. Xie Y, Zhu H, Chen J, Zhao X. Effect of nano calcium carbonate fertilizer on the growth and development of strawberry. J Plant Nutr. 2020;43(7):972–81.

77. Fattahi M, Fattahi S, Mousavi SM. Effect of foliar application of boron on growth, yield and fruit quality of strawberry cv. Selva. J Plant Nutr. 2018;41(5):645–52.

78. Dikilitas M, Yildirim E, Avc M. Foliar boron application improves the growth, yield and quality of strawberry. J Plant Nutr. 2016;39(12):1749–57.

79. Mahmood MM, Al-Dulaimy AF. Response of strawberry CV. festival to culture media and foliar application of nano and normal micronutrients. IOP Conf Ser Earth Environ Sci; 2021. 904:12–67. https://doi.org/10.1088/1755-1315/904/1/012067

80. Chhipa H. Nanofertilizers and nanopesticides for agriculture. Environ Chem Letters. 2017 Mar;15(1):15–22. https://doi.org/10.1007/s10311-016-0600-4

81. Chaeikar SM, Golozani GK. Effect of foliar application of nano-boron fertilizer on quantitative and qualitative characteristics of strawberry. J Plant Nutr. 2019;42(15):1796–802.

82. Shahabivand S, Ghorbanpour M, Khoshgoftarmanesh AH. Nano-silicon fertilization improves yield and fruit quality of strawberry. J Plant Nutr Soil Sci. 2019;182(1):76–82.

83. Safari M, Ghanati F, Hajiboland R, Rezazadeh SH. Effects of foliar application of iron oxide nanoparticles on growth and physiological traits of strawberry plants. Sci Hortic. 2017;219:248–55.

84. Thakur V, Sharma S, Kumar A, Kumar R. Unraveling nanoparticles efficiency in solanaceae crops: Mechanistic understanding, action and stress mitigation approaches. Ecol Front. 2024;44(6):1097–108. https://doi.org/10.1016/j.ecofro.2024.05.004

85. Abdullah KM, Amran HA, Kadhim ZK, Lateef SM. Effect of spraying with normal and Nano NPK fertilizers and their interference in growth indicators of strawberry seedlings *Fragaria ananassa* Duch. Ruby gem cultivar. J Kerbala Agric. 2021;1:8. https://doi.org/10.59658/jkas.v8i1.877

86. Samimi Z, Rezaei M, Sajedi NA. Impact of foliar application of iron oxide nanoparticles on growth, yield and fruit quality of strawberry (*Fragaria* × *ananassa*). Sci Hortic. 2021;278.

87. Qayyum MF, Rizwan M, Rehman MZ, Ali S, Sohail MI, Khalid H, et al. Nano-copper oxide prime induced growth, yield enhancement and metal immobilization of strawberry (*Fragaria* × *ananassa* Duch.). J Plant Nutr. 2021;44(13):2022–37.

88. Abbasi AR, Hajiboland R, Sadeghzadeh B. Effects of different sources and concentrations of zinc oxide nanoparticles on strawberry (*Fragaria* × *ananassa*) growth, yield and fruit quality. J Plant Nutr. 2020;43(15):2187–98.

89. El-Shewy HM, Abd El-Kader SM, El-Ghany EMA, El-Komy MA. Nano-copper as a promising alternative fungicide against strawberry *Botrytis cinerea*. Ecotoxicol Environ Saf. 2020;194:110459.

90. El-Banna AA, Abdel-Alim MA, Abd-Elrahman MA. Nano chitosan as a potential tool in integrated pest management: A review. Int J Biol Macromol. 2019;130:597–612.

91. El-Ghany EMA, El-Komy MA, Abd El-Kader SM, El-Shewy HM. Nano-silver as a promising alternative fungicide against strawberry powdery mildew. Sci Hortic. 2019;249:431–37.

92. Zhang Y, Chen Y, Li J, Hu Q. Nano-chitosan as a new carrier for controlled-release of pesticide. Mater Sci Eng. 2017;81:40–48.

93. Ahmed A, Khan MS, Musarrat J. Nano chitosan-mediated abiotic stress tolerance in plants: A review. Plant Physiol Biochem. 2017;111:14–26.

94. El-Katatny MH, Mahmoud SE. Nano copper for controlling powdery mildew and gray mold diseases of strawberry plants. J Plant Dis Prot. 2017;124(1):1–7.

95. Sharma S, Sharma G, Kumar P, Likhita J, Dhanapati K, Attri D, et al. Unveiling the potential of nanotechnological approaches in biological system for sustainable production and crop resilience against stress. Ecological Frontiers. 2025;(xx):1–19. https://doi.org/10.1016/j.ecofro.2025.06.020

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