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Review

The Effects of Nanoparticles on Plant Growth, Fruit Yield and Quality, and Production Economics in Strawberry Cultivation

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Abstract

In recent years, in strawberry cultivation, a significant part of agricultural production, nanoparticles (NPs) composed of elements such as iron (Fe), silver (Ag), zinc (Zn), copper (Cu), selenium (Se), titanium (Ti), and nickel (Ni) have been used to improve resistance to drought and salinity stress, promote efficient plant growth, increase yield, and enhance plant resistance to diseases and pests. This study aims to evaluate the effects of using NPs on plant growth, fruit yield and quality, and production economics in strawberry cultivation. The research method is a literature review, a secondary data collection and analysis method. The research materials used include national/international and public/private scientific studies, published articles, journals, and books, as well as the opinions and evaluations of experts on the subject. According to the study findings, the use of NPs in strawberry cultivation increased plant growth, fruit yield/quality, adaptation and resilience to environmental conditions and provided a sustainable income in economic terms. The study findings concluded that if the risks of water and soil pollution associated with NPs are reduced through appropriate NP production methods and correct application doses, NPs will be used more widely as new production technologies that reduce environmental/production costs in agricultural production.

Keywords: agriculture; strawberry cultivation; nanoparticle; production economics; plant nutrition

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1. Introduction

Agriculture, as one of the economic activities, forms the basis of everything built for humanity from A to Z (from physiological needs to self-actualization needs) for the preservation, continuity, and development of human existence [1]. The fundamental principles of economics, such as the scarcity of resources and the need for productivity and efficiency in production, are also valid in agricultural production activities [2]. The way to generate more benefit from scarce resources is through technology. Just as in the past, when existing technological knowledge was used in agricultural production activities, today information and communication technologies, drone technology, biotechnology, and nanotechnology, etc., are used in agricultural production activities [3]. Thanks to this technological knowledge and products, many problems arising in agriculture can be easily solved, and the possibility of carrying out sustainable agricultural production activities effectively and efficiently is obtained [4,5].

According to one hypothesis, while the human population is increasing geometrically, agricultural production capacity is increasing linearly [6]. However, conscious/unconscious damage to agricultural production resources creates pressure on these resources in the process of meeting human needs [7]. Utilizing nanotechnology, an innovative approach to protect, improve, and enhance the production capabilities of scarce agricultural resources, has been brought to the forefront [8].

Nanotechnology is the process of reconstructing the matter of atoms and molecules at the scale of one billionth of a meter (1–100 nanometers), the building blocks of matter, and obtaining new and purpose-built particles [9–11]. Nanotechnology finds application in every field of science and life with a multidisciplinary approach, producing innovative, practical, and lasting solutions. In agricultural production processes, nanotechnology, through its sub-branches of phytonanotechnology in plant science and agronanotechnology in agricultural science, makes significant contributions to increasing yield and quality in agricultural production activities, restoring damaged agricultural resources, obtaining species resistant to salinity, drought, diseases and pests, and producing effective plant nutrition materials [11]. Nanotechnology has undertaken a significant mission, particularly in terms of preserving, improving, and developing the natural balance and agricultural production resources that have been damaged by flawed agricultural production methods that have been practiced for many years and that hinder the realization of sustainable agricultural practices [12–14].

Strawberries, with their high content of vitamin C, antioxidants, calcium, and iron, as well as vitamins A and B and phosphorus [15,16] are a product with high economic value due to their role in meeting human nutritional needs and maintaining health [16,17]. Their pleasant taste and aroma, combined with their consumption fresh and use as a production input in various sectors from food to the chemical industry, have increased demand for strawberries in the fruit market and given them greater economic value [17,18]. This has led to an increase in strawberry production areas and quantities year after year. According to FAO strawberry cultivation data, global production increased from 403,212 ha in 2019 to 436,067 ha in 2024, with production rising from 9,129,018 tons to 10,728,811 tons [19]. In Türkiye, production increased from 16,090 ha in 2019 to 19,651 ha in 2024, with production rising from 486,705 tons to 606,254 tons [19]. In this sense, strawberry production is of great importance.

NPs, a product of the application of nanotechnology in agricultural production processes and composed of atoms and compounds such as Fe, Ag, Zn, and Cu [20] are used in various agricultural applications to increase plant growth, manage diseases, improve soil health, and ensure productivity and sustainability in agriculture [21]. NPs are used in strawberry cultivation to increase yield and quality, thereby reducing production costs and generating higher economic returns.

This study aims to evaluate the effects of using nanotechnology-based NPs, a new research, development, and application area in agricultural production, on plant growth, fruit yield and quality, and production economics in strawberry cultivation by considering different opinions, studies, and findings from the literature in a unifying manner.

2. Review Methodology

This study, which focuses on the effects of NPs on plant development, yield, and quality in strawberry cultivation and the economic analysis of the applicability of NPs in real-world applications, utilized a literature review method. Scientific research manuscripts, review manuscripts, journals, books, and book chapters served as primary data sources. Additionally, publications from authoritative national and international public and private

institutions, along with publications and information provided by subject-matter experts, academics, and practitioners, were utilized as supplementary data sources.

A general assessment was conducted by examining primary and secondary sources regarding the use of nanotechnology-derived NPs in agricultural production, specifically considering findings on their positive contributions to sustainable agricultural activities as well as their potential adverse effects. In the specific context of strawberry cultivation, evaluations were made concerning soil structure, plant development, crop yield, produce quality, and economic feasibility.

In the manuscript, the NP values expressed in different units of measurement (mg kg^{-1}, µg mL^{-1} ppm, g $L^{-1,}$ etc.) used in the studies are converted to mg L^{-1} and presented. Variations in the results of the applications examined were calculated using the formula $(V_1 - V_0)/V_0 \times 100$, where V_1 represents the final value (the result of the application) and V_0 represents the initial value (typically the control value used for comparison).

3. NPs Used in Agricultural Production Activities

With the development of nanotechnology, applications focused on achieving healthy plant growth, increased yield and quality, efficient resource management, minimizing environmental and production costs, and establishing agricultural activities on a sustainable basis in strawberry cultivation can be more easily implemented [22]. In agricultural production, iron oxide, silver, silicon dioxide, titanium dioxide, zinc oxide, and carbon nanotubes (NPs) are generally being tested and used within the scope of sustainable agricultural practices.

3.1. Iron Oxide (Fe_2O_3 or Fe_3O_4) NPs

In agricultural production, FeO NPs are an innovative agricultural technology that finds application as nano-fertilizers that improve nutrient uptake by plants and agents that increase stress tolerance, especially under salinity and drought stress conditions, in order to increase healthy plant growth, product yield and quality [23,24]. In a study conducted by Öztürk Erdem [23] on the Albion strawberry variety, the effects of applying Fe_3O_4 NP at doses of 0, 0.01, 0.1, and 1 mg L^{-1} to strawberry seedlings exposed to salinity stress at concentrations of 0, 30, and 60 mM L^{-1} were examined. The study found that stem length, leaf area, and plant dry weight were statistically significant under salinity and Fe_3O_4 NP interaction, while root length, leaf number, plant fresh weight, and root fresh and dry weights were found to be insignificant [23]. It has been reported that the application of Fe_30_4 NPs at a dose of 1 mg L^{-1} increased shoot length at salinity levels of 30 and 60 mM L^{-1}; the application at 0.01 mg L^{-1} increased leaf area at salinity levels of 0 and 30 mM L^{-1}; and the application at 0.1 mg L^{-1} increased plant dry weight at a salinity level of 30 mM L^{-1}, thereby mitigating the adverse effects of salinity stress on plant growth parameters in strawberries [23]. Hou et al. [24], evaluating studies on FeO NP applications in agricultural production, reported that FeO NPs increased plant growth by 20 to 30%, antioxidant enzyme activity by 10 to 18%, and reduced plant oxidative stress by 20 to 10%, depending on the plant species treated. The study reported that the positive results obtained in FeO NP applications were primarily dependent on the plant species, secondly on the Fe NM (nanomaterials) particle size, thirdly on the application time, fourthly on the dose level, and finally on the Fe NM type [24]. In their study evaluating the efficacy of foliar Fe_2O_3 NP applications at rates of 0, 25, 50, and 100 mg L^{-1} on peanuts subjected to 150 mM L^{-1} salinity stress, Zhang et al. [25] reported that these applications improved photosynthetic characteristics (photosynthesis, stomatal conductance, chlorophyll, etc.) and physiological traits (shoot, root, and biomass) and enhanced biochemical activities (regulation of cellular homeostasis, osmolyte accumulation, and antioxidant components

such as Superoxide Dismutase [SOD], Peroxidase [POD], and Catalase [CAT]). The same study reported that foliar applications of Fe_2O_3 NPs increased plant shoot and root lengths by 20% to 69% and plant biomass accumulation by 36% to 53% compared to the control; that foliar Fe_2O_3 NP applications, particularly at a concentration of 50 mg L^{-1} mitigated the adverse effects of salinity stress on peanut plants; and that, as these results were obtained in a controlled environment, the effects of such applications under field conditions need to be tested [25]. Fatima et al. [26] tested the hypothesis that applications of ZnO NPs (approx. 43 nm) and FeO NPs (approx. 58 nm) at doses of 20, 40, and 60 mg L^{-1} could alleviate the adverse effects of drought stress on plant growth and physiology in three different wheat cultivars (Faisalabad-08, Johar-16, and Aas) under both hydroponic (20% PEG-6000) and pot (water withholding) conditions. Under drought stress, which significantly reduces plant stem and biomass development, chlorophyll content, and crop yield, it has been reported that the Faisalabad-08 wheat variety, which preserves biomass development and chlorophyll content, is the highly tolerant variety best adapted to drought conditions; Aas is a moderately tolerant variety; and Johar-16 is a variety with low tolerance [26]. In the same study, it was reported that ZnO-NP applications generally had a positive effect on shoot development and relative water content, while FeO-NP applications positively influenced osmolyte accumulation and increased wheat yield by 74% compared to the control; consequently, the study findings demonstrated that the combined use of NPs and plants with high drought tolerance could enhance agricultural production capacity [26]. Naseem et al. [27] investigated the effect of Fe NPs, which were synthesized via a green synthesis method using rice straw, on spinach plants subjected to drought stress conditions corresponding to 100% (control), 50% (moderate), and 25% (severe) of field capacity; they reported that physiological and morphological parameters (fresh root weight increased by 12–21%, stem length by 12–42%, SPAD value by 18–64%, etc.) were positively affected by FeO NP applications. In the same study, it was reported that FeO NP applications also improved plant nutrient uptake (K^+ ion increased by 74% in the roots and 14% in the stem) [27].

3.2. Silver (Ag) NPs

In agricultural production, Ag NPs are used to increase agricultural productivity, to combat plant diseases and pests for healthy plant growth with their antimicrobial and especially antiviral properties, and to reduce the use of environmentally harmful chemicals and to clean wastewater within the scope of sustainable agricultural practices [28]. In a literature review, Alfosea-Simón et al. reported that the beneficial effects of Ag NP applications are primarily observed in controlled environments [28]. They noted that achieving success in both controlled and uncontrolled field settings, while avoiding the risks associated with high costs and environmental toxicity, depends on optimizing various factors such as the plant species, NP synthesis method, particle size, and application dosage; consequently, there is a need for data from open and closed-field applications that facilitate the optimization of these variables [28]. According to Atanda et al., Ag NPs were used to control bacterial blight disease in rice cultivation, resulting in a 30% increase in yield [29]. Atanda et al. highlighted the roles of Ag NP applications in crop protection, plant nutrition management, and the mitigation of deleterious chemical reactions affecting plants; however, they also noted that despite the significant potential these NPs hold for agricultural production, the reported beneficial effects of Ag NPs remain under investigation, and that such applications can cause substantial harm to organisms by interacting with target cells, inducing the production of reactive oxygen species (ROS), and disrupting the cellular electron transport chain responsible for energy transfer [29]. In their study investigating the effects of Ag NP applications, which were synthesized via both green

and chemical methods and applied at concentrations of 0.5, 1, 5, and 10 mg L^{-1}, on potato seed germination under high-temperature conditions (32.2 °C), Lina et al. [30] reported that Ag NPs obtained through the green synthesis method represent a suitable alternative in the field of nanopriming due to their smaller size (9.7 nm), superior colloidal stability, cost-effectiveness, biocompatibility, and tunable properties, compared to those produced via chemical synthesis. Lina et al. observed that the optimal application dose for Ag NPs synthesized via green and chemical methods was 5 mg L^{-1}; that Ag NP-treated potato seeds exhibited a germination rate 25% to 30% higher than that of the hydroprimed control group; and that, while plant development stalled in the control group, it continued in the seeds treated with Ag NPs [30].

In their study investigating the effects of applying chemically synthesized Ag NPs at doses of 0, 25, 50, 100, 200, and 400 mg L^{-1} on plant growth and antioxidant activity in Indian mustard (*Brassica juncea*), Sharma et al. [31] reported that the stimulatory effects of Ag NPs were dose-dependent and that the optimal application dose was 50 mg L^{-1}. The study findings indicated that Ag NP treatment positively influenced the fresh weight, root and shoot development, and vigor index of the seedlings; led to improvements in photosynthetic quantum efficiency and increases in chlorophyll content; and reduced ROS levels by triggering specific antioxidant enzymes [31]. In their study, Sharma et al. [31] reported that 50 mg L^{-1} Ag NP applications increased root length by 326% and viability index by 133% in *Brassica juncea* seedlings, while the highest seedling loss was 22% with the 400 mg L^{-1} Ag NP application [31].

In a study on organic tomato cultivation, Trujillo et al. [32] utilized a PVP-AgNP nanocomposite, which was synthesized via a green synthesis method combining Ag NPs (10.8 nm) with the polymer polyvinylpyrrolidone (PVP, acting as a stabilizing agent) at doses of 64, 32, 16, 8, and 4 mg L^{-1}, to combat the harmful effects of fungi and phytopathogenic bacteria; they reported a 98% mortality rate among whiteflies 10 days after applying 64 mg L^{-1} PVP-Ag NPs to tomato plants grown in greenhouse conditions where the pest had caused severe damage. Noting that the PVP-AgNP treatment also controlled powdery mildew in the tomatoes, the researchers concluded that this nanocomposite could serve as an organic alternative to the chemical inputs typically used in organic farming to manage whiteflies and powdery mildew [32].

3.3. Silicon Dioxide (SiO_2) NPs

In agricultural production, SiO_2 NPs are applied in sustainable agricultural activities to promote healthy plant growth, increase seed germination rates and seedling development, improve resistance to salinity and drought stress conditions, combat pests, and facilitate plant nutrient uptake by improving soil structure [33]. Jin et al. [34], in their study investigating the effects of SiO_2 NPs on yield, quality, and plant development in two different rice varieties under salinity stress, reported higher values compared to the control group in terms of yield (33.3% and 23.3%), rice quality (2.2% and 1.0%), and plant growth parameters (11.2% and 14.0% in tillering, 18.5% and 10.4% in panicle formation, and 9.3% and 12.9% in root length). In rice production, SiO_2 NPs were reported to increase K+ nutrient uptake by 38.30–49.30%, SOD by 25.5%, and CAT by 31.8% [34]. Jin et al. reported that, under conditions of 0.6% salinity, the application of 30 ± 5 nm SiO_2 NPs at a rate of 15 kg hm^{-2} holds significant potential for improving plant growth, crop yield, and crop quality [34]. Alsaeedi et al. [35], in their study investigating the effects of Si NPs on cucumber germination, observed that the germination index of cucumber plants increased by 28.70–70.30% compared to the control. In conclusion, Alsaeedi et al. [35] found that, in cucumber plants grown in media containing 0, 100, 200, 300, and 400 mg L^{-1} Si NPs, treatment with the application of 200 mg L^{-1} Si NPs enhanced seed germination and plant

growth. Lu et al. [36], who conducted a similar study on tomatoes, observed a 22% increase in germination, a 92% increase in viability index, and a 55% increase in shoot length in tomato plants compared to the control. Lu et al. reported that in tomato cultivation, SiO_2 NP applications at concentrations of 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, 10,000 mg L^{-1} and sizes of 40–46.5 nm showed the best results with the 5000 mg L^{-1} SiO_2 NP application in germination index, seed germination rate, viability index, mean shoot development, and germination time parameters, except for fresh and dry weight, and that SiO_2 NP application has significant potential in tomato cultivation [36].

3.4. Titanium Dioxide (TiO_2) NPs

In plant production, TiO_2 NPs are applied to enable efficient photosynthesis in plants, to increase resistance to heavy metal-containing environments, drought and salinity stress, to improve plant germination and development, to control diseases and pests, to increase product yield and quality, and within the scope of sustainable agricultural production activities [37]. Gül et al. investigated the effects of 20 nm TiO_2 NP applications at concentrations of 0, 100, 200, 300, 400, and 500 mg L^{-1} on seed germination across six different sunflower varieties; they observed that the impact of the TiO_2 NP treatments varied depending on the plant variety and the dosage applied and reported that the best results regarding germination percentage (approximately 20–83%), vigor index (approximately 10–39), and germination time (approximately 2–4 days) were obtained with the 200 mg L^{-1} TiO_2 NP treatment [37]. Mohajjel Shoja et al. [38], in their study investigating the effects of TiO_2 NPs on plant growth in baby sun rose (*Aptenia cordifolia*) plants, found that TiO_2 NP-treated plants showed changes in morphological characteristics and an increase in photosynthetic pigmentation (12% in phenolic compounds and 13% in flavonoid compounds). They reported that TiO_2 NP treatments at doses of 0, 1, 5, 10, and 20 mg L^{-1} significantly affected the morphology, biochemistry, and anatomy of the baby sun rose plant; they further noted that the plant could adapt to media containing up to 20 mg L^{-1} of TiO_2 NPs and could be cultivated in areas with high levels of TiO_2 NP accumulation [38]. Mustafa et al. [39], in their study investigating the effects of green TiO_2 NP applications on germination, plant growth, and yield in two different wheat plants under different salinity stress conditions, observed that the application of 40 mg L^{-1} TiO_2 NPs at a concentration of 100 mM NaCl resulted in a 53.32–57.25% increase in yield and an average 51% increase in plant growth parameters (germination and seedling growth index, seedling length, and seedling fresh weight) compared to the control. In conclusion, they reported that regarding wheat cultivation, which involved NaCl treatments at 50 and 100 mM and TiO_2 NP treatments at 20, 40, 60, and 80 mg L^{-1}, the best results for germination, plant growth, and crop yield parameters were obtained with the 20 and 40 mg L^{-1} TiO_2 NP treatments; conversely, the 60 and 80 mg L^{-1} TiO_2 NP treatments were negatively affected by salinity stress; and ultimately, that foliar application of TiO_2 NPs could enhance the plant's resistance to salinity stress [39].

3.5. Zinc Oxide (ZnO) NPs

In plant production, ZnO NPs are used within the scope of sustainable agricultural practices to increase crop yield, plant growth and germination, protect plant health, facilitate the uptake of plant nutrients, and combat diseases/pests [40,41]. Saurabh et al. [42], in their studies on nanofertilizers in sustainable agricultural activities, found that plant nutrient inputs containing NPs increased the absorption of nutrients from the soil by plants by 30% and crop yield by 20% compared to conventional plant nutrient inputs. Raliya et al. [43], in their studies examining the effect of ZnO NPs synthesized from soil fungi on phosphorus uptake in bean plants, observed an increase in plant growth parameters of 6% in yield, 27%

in plant biomass, and 32.8% in stem length compared to the control. In the same study, it was reported that ZnO NPs promote P uptake, leading to increased plant root volume in the soil rhizosphere layer, increased microbial activity in the soil, and thus the preservation of soil structure and health [43]. In conclusion, they reported that foliar application of ZnO NPs with a size of 2–6.8 nm and a dose of 10 mg L^{-1} improved phosphorus uptake, physical parameters of the plant such as stem and root development, and chemical parameters such as leaf protein and chlorophyll content in beans [43]. Nazir et al. [44], in their study investigating the effects of ZnO-NPs produced from *Withania coagulans* plant extract by the green synthesis method on redox enzymes in wheat, reported that the plant height of wheat treated with ZnO-NPs was 23% higher than the control. According to the study findings, they reported that in wheat grown in pots under conditions of 70% soil moisture content, foliar applications of 25, 50, 100, and 200 mg L^{-1} ZnO NP resulted in 25 mg L^{-1} ZnO NP application being an effective plant nutrient input to increase plant growth, yield, and Zn bioenrichment [44]. Raza et al. [41], in their study investigating the effect of ZnO NPs on plant growth, yield and quality in wheat against drought stress, reported that ZnO NPs at a dose of 150 mg L^{-1} significantly increased plant growth parameters (plant height by 15.5%, spike length by 3.2%, biomass by 16.7%, zinc content by 100% and grain protein by 53.8%) at the grain filling stage compared to the control. Based on the data obtained, they observed that the effects of varying drought stress levels (D_0: control/normal irrigation; D_1: drought at the tillering stage; D_2: drought at the grain-filling stage) and ZnO NP application doses (0, 50, 100, and 150 mg L^{-1}) on drought stress, zinc deficiency, and crop yield depended on the dosage and growth stage; furthermore, they found that the 150 mg L^{-1} ZnO NP application mitigated the adverse effects of drought stress across all parameters examined, suggesting its potential utility in addressing drought conditions [41].

3.6. Selenium (Se) NPs

Se NPs, produced using nanotechnology from Se, a vital trace element essential for the healthy development of living beings such as humans, animals, and plants [45], have found application in agricultural production processes for purposes such as promoting healthy plant growth, providing resistance to biotic and abiotic stress conditions, increasing yield, protecting plants by reducing the harmful effects of heavy metals in the soil, and reducing the uptake of heavy metals by plants, thereby mitigating their harmful effects on plants [46]. Studies examining the effects of Se NP applications in agriculture have generally utilized crops such as wheat, maize, barley, rice, tomatoes, soybeans, canola, carrots, cowpeas, and common beans as research materials [47]. A literature review evaluating Se NPs and synthesis methods reported that applying 20 mg L^{-1} of Se NPs to sunflowers increased plant growth by 167.4% and was effective in eliminating cutworms, a common sunflower pest [46]. The same study reported that Se NP application reduced soil cadmium levels by 25.9–42.4% and plant cadmium uptake by 33.4–37.8%, while facilitating the absorption of micronutrients such as iron, manganese, and zinc [46]. Research on wheat indicated that the application of 0.5–1.0 mg L^{-1} of Se reduced cadmium accumulation in wheat grains by 59–61% [48]. Morales-Espinoza et al. [49] observed that, under 50 mM salinity stress conditions in tomatoes, the best results across all variables were obtained with the control treatment, followed by the 10 mg L^{-1} Se NP treatment. Based on their findings, they reported that Se NP applications positively influenced plant growth, crop yield, antioxidant compound activities, and fruit quality in a dose-dependent manner under salinity stress conditions, and that these applications could mitigate the adverse effects of salinity stress on tomatoes. It has been reported that Se NP applications mitigate the impact of salinity stress on plant growth in tomatoes [49], while a study on peppers indicated that Se NP applications improve soil structure and enhance the plant's defense mechanisms by fostering

better soil–plant interaction [50]. In conclusion, while there is strong evidence that Se NP applications, when performed under the correct dosage, plant type, exposure time, etc., can significantly contribute to agricultural production capacity, it is emphasized that failure to adhere to these conditions can produce equally destructive effects [51].

3.7. Copper Oxside (CuO) NPs

Cupper (Cu) is currently utilized in agricultural production processes for plant nutrition and for protection against diseases and pests; however, the use of chemicals with high Cu content leads to increased Cu levels in the soil, which subsequently leach into water sources and cause water pollution [52]. CuO NPs are a new generation plant nutrient input obtained from Cu, an important micronutrient element used in agricultural production, through nanotechnology and applied to increase the efficiency and productivity of resource use in agricultural production [53]. CuO NP applications hold significant potential for sustainable agricultural practices by promoting healthy plant growth, facilitating nutrient uptake, increasing crop yields, and providing protection against pests, while simultaneously reducing reliance on chemicals [53]. Significant results regarding healthy plant growth have been achieved with CuO NP applications. It has been reported that CuO NP applications on tobacco enhance the plant's resistance to diseases and reduce the incidence of black shank disease by 33.69% [53]. In a study investigating the effects of applying chemically synthesized CuO NPs (with a maximum size of 30 nm) and bulk Cu at various doses (0.0, 0.1, 0.2, 0.5, 1.0, 2.0, 5.0, and 10 mg L^{-1}) on wheat growth and seed germination, İbrahim et al. [54] observed that the application of CuO NPs at a dose of 0.1 mg L^{-1} resulted in chlorophyll formation equivalent to that of the 0.5 mg L^{-1} Cu application. Based on these findings, Ibrahim et al. [54] reported that applying CuO NPs at a concentration of 0.1 mg L^{-1} to wheat could reduce the use of conventional chemical fertilizers by 80%. Furthermore, the study findings reported that the effective toxicity dose was 0.94 mg L^{-1} for CuO NPs and 0.37 mg L^{-1} for pure Cu; that the effective toxicity dose for CuO NPs was approximately 2.5 times that of bulk Cu due to the slow dissolution of CuO NPs; and that the application of CuO NPs as a plant nutrient supplement for wheat could be more beneficial than the use of bulk Cu powder [54]. In their study investigating the effects of 25 nm Cu NP applications at various dosages (0.02, 0.2, 2, and 10 mg L^{-1}) delivered via chitosan-polyvinyl alcohol (Cs-PVA) hydrogels on tomato plant growth, yield, and quality, Hernández et al. reported that the Cu NP treatments caused no toxic effects and identified 10 mg L^{-1} as the optimal application dosage [55]. In tomatoes, the addition of 10 mg L^{-1} of CuO NPs to a chitosan-polyvinyl alcohol treatment increased dry plant biomass by 13%, root biomass by 30%, and yield by 17% [55] and 12.2% [52]; furthermore, in mung beans, the application of 50 mg L^{-1} CuO NPs at 15 °C was reported to increase shoot growth by 13% and root growth by 37% [53]. CuO NP applications have been reported to improve soil physical properties, including organic matter content, water holding capacity, and chemical properties such as pH stabilization and macronutrient content (nitrogen, N; phosphorus, P; and potassium, K), thereby enhancing soil quality [52]. The results obtained from CuO NP applications provide strong evidence that CuO NPs possess significant potential for enhancing agricultural production capacity.

3.8. Nickel Oxside (NiO) NPs

Although Nickel (Ni) is an essential micronutrient for plant growth at low doses, its application in agricultural production entails significant risks due to the difficulty of determining the appropriate dosage. Research indicates that 16% of the world's arable land and 19% of agricultural areas are contaminated with heavy metals, including Ni [56]. Ni, the second most polluting heavy metal in agricultural resources after cadmium, is an important

micronutrient used in agricultural production processes for its positive effects on plant physiology, plant growth, and plant nitrogen metabolism, despite its known risks [57]. In their study investigating the effects and mechanisms of 20–30 nm NiO NP applications (at doses of 5, 50, and 100 mg L^{-1}) on atrazine accumulation in soybeans, Xu et al. [57] emphasized that atrazine accumulation was dependent on the applied NiO NP dose; they observed that while the 100 mg L^{-1} NiO NP treatment increased atrazine accumulation, the 5 and 50 mg L^{-1} treatments reduced it. Ni is crucial for N metabolism in plants, serving as a functional component of eight enzymes (Glx I, Ni-SOD, hydrogenase, MRC, CODH, ACS, and urease) [58]. Thanks to nanotechnology, it is possible to eliminate the harmful effects of Ni element by using NPs obtained from Ni element, thus enabling its more effective and efficient use in sustainable agricultural activities [59]. In their study investigating the effects of NiO NP, bulk Ni, and $NiSO_4$ applications at different doses (0, 10, 50, 100, and 200 mg L^{-1}) on plant growth and crop yield in soybeans, Zhou et al. [60] observed that the application of 50 mg L^{-1} NiO NPs increased seed yield by 39%, total fatty acid content by 28%, and starch content by 19%. In their study investigating the effects of applying $NiFe_2O_4$ NPs (at doses of 5, 50, and 200 mg L^{-1}), $NiSO_4$ (at 33 mg L^{-1}), and EDTA-Fe (at 156 mg L^{-1}) on plant growth, nutrient uptake, and biochemical activities in peanuts, Tang et al. reported that the results regarding $NiFe_2O_4$ NP application provided strong evidence that $NiFe_2O_4$ enhances agricultural capacity and ensures biological safety, thereby demonstrating its potential as a next-generation nano-fertilizer [61]. In a study conducted on peanuts, it was observed that 50 mg L^{-1} $NiFe_2O_4$ NPs significantly improved the plant's photosynthetic capacity, biomass accumulation, seed yield, and nutritional quality, increasing the 1000-kernel weight by 12.3% and total yield by 15.6% [61]. Consequently, research findings indicate that NiO NP applications act as a trace element that promotes plant growth, development, and crop yield by enhancing urea decomposition and nitrogen-fixing enzyme activities [62].

3.9. Carbon Nanotubes (CNTs)

In plant production, CNTs are used within the scope of sustainable agricultural practices to improve plant growth, germination, and disease resistance, facilitate nutrient uptake, increase carbon fixation, improve product yield and quality, and reduce the effects of chemicals used in agriculture [63]. In a study investigating the effects of CNT applications with diameters of 8–15 nm and lengths smaller than 10 microns at doses of 0, 10, 20, and 40 mg L^{-1} on seed germination and plant development in tomatoes, onions, turnips, and radishes in greenhouse and laboratory environments, it was reported that CNT applications yielded better results in tomatoes and onions compared to radishes and turnips in terms of the seed germination parameter in the laboratory environment. [64]. In the same study, it was reported that the performance of CNTs in a laboratory setting yielded better results compared to a greenhouse environment; for instance, in the case of tomatoes, the application of CNTs at a dose of 40 mg L^{-1} increased root length fivefold in a laboratory setting, whereas it resulted in a threefold increase in a greenhouse environment. [64]. Furthermore, it was noted that the high dose of 40 mg L^{-1} CNTs exerted a toxic effect on the germination of radish and onion seeds [64]. In their study on the effects of TiO_2 NP (20–30 nm), Ag NP (20–30 nm), CNT (20–30 nm), and C60 (50 nm) applications at doses of 100, 200, and 500 mg L^{-1} on the mosaic virus in tobacco plants, Adel et al. [65] reported that while TiO_2 NP and Ag NP treatments were ineffective against the virus, early-stage foliar applications of CNT and C60 at 200 mg L^{-1} halted the replication and spread of the mosaic virus and strengthened the plant's immunity against the virus by enhancing photosynthetic and antioxidant activities. Adeel et al. [65] increased the fresh plant biomass by 32–41% in tobacco plants treated with 100 and 200 mg L^{-1} CNTs against the tobacco mosaic virus pest.

Safdar et al. [63] reported that CNTs reduced pesticide accumulation in pumpkin, maize, tomato, and soybean plants by 21–80% depending on the application dose.

4. The Effects of NPs on Plant Growth, Fruit Yield, Fruit Quality, and Production Economics in Strawberries

In strawberry cultivation, a highly valuable economic activity, growing conditions directly affect plant growth, yield/quality, and production costs, thus impacting the overall economic gain [23,66]. Strawberries are a delicate plant requiring high care; even small changes in production methods can reduce plant growth and yield/quality, increase production costs, and decrease income [67]. NPs are used in strawberry cultivation as a new production method with an important research and application area [68] within sustainable agricultural production activities, aiming to provide healthy plant growth, increased yield/quality, resistance to salinity and drought stress, and efficiency in plant nutrient uptake.

4.1. The Effects of NPs on Plant Growth

Healthy plant growth in strawberries directly affects yield/quality and economic gain [67]. Loera-Alvarado et al. [69], in their study evaluating the effects of ZnO NP and Zn EDTA application on plant growth in strawberry cultivation, reported approximately 52% higher values in crown number compared to the control with the foliar application of a 200 mg L^{-1} dose of ZnO NP. Shahzad et al. [70] observed that the application of a 100 mg L^{-1} dose of Ag NP in open field strawberry cultivation increased plant growth, yield and quality, and nutritional values. In this study, they observed approximately 150% higher values in fresh stem weight and approximately 121% higher values in dry stem weight compared to the control [70]. Aguirre-Noyola et al. [71], in their study investigating the effect of Ag NP application on rooting and propagation of strawberry seedlings in in vitro Murashige and Skoog medium, reported that the application of 200 mg L^{-1} of Ag NP improved the resistance of strawberry plants to environmental changes by 90% and that they remained alive by adapting to the environment. Saini et al. [72], in their study investigating the effects of Zn NP- and ZnO NP-containing fertilizers and normal Zn-containing fertilizers on the Sweet Charlie strawberry variety, observed that the foliar application of 200 mg L^{-1} Zn NP resulted in an increase of approximately 16% in shoot number and 50% in root crown number compared to the 400 mg L^{-1} $ZnSO_4$ application, where the lowest values were observed. In their study investigating the effects of different densities of FeO NP and ZnO NP on plant growth and fruit quality in the Chandler strawberry variety, Kumar et al. [73] observed that the T15 (Recommended Fertilizer Dose (RDF) 150 mg L^{-1} ZnO NP + 150 mg L^{-1} FeO NP) application increased plant growth parameters by approximately 84% in plant height (17.24 vs. 9.38 cm, respectively), approximately 49% in leaf number (46.67 vs. 31.4 cm, respectively), and 32% in petiole length (9.22 vs. 6.98 cm, respectively) compared to the control. Bhowmick et al. [74], in their study investigating the effects of ZnO NP and Zn sulfate on plant growth and fruit yield/quality in strawberries, observed that the 200 mg L^{-1} ZnO NP applications increased plant growth, with the highest values being increased by 25% in plant spread, 61% in number of leaves per plant, 7% in leaf area, 30% in petiole length, and 54% in number of crowns per plant compared to the control. According to the study findings, it was concluded that NP applications significantly affect plant growth in strawberries.

4.2. The Effects of NPs on Fruit Yield

Although product quality is high in agricultural production activities, sufficient product yield is necessary to obtain an economic return in terms of income from the efforts

made [75]. In this sense, yield is an important parameter. Loera-Alvarado et al. [51] reported that in strawberry production, the application of a 200 mg L^{-1} dose of ZnO NP and Zn EDTA resulted in approximately 29% higher fruit yield per plant compared to the control. Shahzad et al. [70] reported that in strawberry production, the application of a 100 mg L^{-1} dose of Ag NP resulted in approximately 267% higher fruit yield per plant compared to the control. Liu et al. [76], in their study investigating the effects of Se NP and Cu NP applications on plant growth, yield, and quality of strawberries under drought stress, observed approximately a 6% increase in yield compared to the control. In a literature review by Kumar et al. [77], it was reported that the application of nano-fertilizer with 70% more N content resulted in an 11.6% higher yield increase compared to conventional fertilizer application. Saini et al. [72] observed that foliar application of 200 mg L^{-1} Zn NP in the Sweet Charlie strawberry variety resulted in a 48% higher yield per plant (853.67 vs. 575.25 g, respectively) compared to the 400 mg L^{-1} $ZnSO_4$ application, where the lowest values were observed. Kumar et al. [73] observed that the T15 application (150 mg L^{-1} ZnO NP + 150 mg L^{-1} FeO NP) resulted in approximately a 150% increase in fruit yield per plant (478 vs. 191 g, respectively) compared to the control. Bhowmick et al. [74], in their study investigating the effects of ZnO NP and Zn sulfate on plant growth and fruit yield/quality in strawberries, observed that the 150 and 200 mg L^{-1} ZnO NP applications, which had the highest values in fruit yield per plant and marketable fruit quantity compared to the control, increased fruit yield by 26–30%. According to the study findings, it was concluded that NP applications significantly affect yield in strawberries.

4.3. The Effects of NPs on Fruit Quality

In strawberries, physical quality characteristics of the fruit (fruit width, length, firmness, and shape) and chemical quality characteristics (total soluble solids (TSS), titratable acidity (TA), and TSS/TA) are effective in determining the economic value of the product [78]. Singh et al. [79], in their study investigating the effects of ZnO NP- and FeO NP-containing fertilizers and nutrient management on plant growth and yield in strawberries, reported that the T7 application (T7: 50% RDF + farmyard manure (FYM) + Vermicompost + Azotobacter + ZnO + FeO) resulted in an approximately 26% increase in TSS and an 8% increase in TA compared to the control. In their study investigating the effect of different densities of FeO NP and ZnO NP on plant growth and fruit quality in the Chandler strawberry variety, Kumar et al. [80] observed that the T15 application (RDF + 150 mg L^{-1} ZnO NP + 150 mg L^{-1} FeO NP) resulted in an approximately 153% increase in TSS (T15 treatment value: 16.97%; control value: 6.70%) and an approximately 41% decrease in TA (T15 treatment value: 0.51%; control value: 0.87%) compared to the control. Bhowmick et al. [74], in their study investigating the effects of ZnO NP and Zn sulfate on plant growth and fruit yield/quality in strawberries, observed that the application of 200 mg L^{-1} ZnO NP, which had the highest value compared to the control, resulted in approximately a 15% increase in TSS and a 7% decrease in TA.

Studies examined within the scope of this work have reported similar findings indicating that NP applications on strawberries make a significant difference by improving plant growth, increasing fruit yield, and enhancing produce quality (Table 1).

Table 1. Studies investigating the effect of NP applications on plant growth, fruit yield, and fruit quality in strawberry cultivation.

Reference	Objective	Materials and Methods	Conclusions
Loera-Alvarado et al. [69]	To evaluate the effects of ZnO NP and Zn-EDTA applications on plant growth and Zn content in leaves and fruits in strawberry cultivation.	Strawberry, ZnO NPs, and Zn-EDTA. Following a randomized experimental design, strawberry seedlings planted in plastic bags filled with a mixture of substrate, peat, and agrolite were treated with ZnO NPs at doses of 0, 100, 200, 500, and 1000 mg L^{-1} and Zn-EDTA fertilizer at a dose of 2.5 mL L^{-1} via both root and foliar application.	While the application of ZnO NPs at a dose of 200 mg L^{-1} significantly enhanced plant growth and crop yield, applications at doses of 200 and 500 mg L^{-1} significantly increased leaf Zn content. Consequently, ZnO NPs serve as an alternative Zn nutrient source to chemical Zn fertilizers regarding plant growth, crop yield, and leaf Zn content.
Shahzad et al. [70]	To evaluate the effects of foliar Ag NP applications at different time intervals and dosages on plant morphology, compositional characteristics, and defense mechanisms in strawberries.	Strawberry and Ag NPs. Based on a randomized plot design, the study consists of 15 treatment combinations involving the foliar application of Ag NPs (maximum 100 nm) to strawberries 90 days after planting, using different time intervals (5, 10, and 15 days) and dosage levels (0, 50, 100, 150, and 200 mg L^{-1}).	While 50 and 100 mg L^{-1} Ag NP applications at 15-day intervals significantly improved various characteristics (plant morphological characteristics, fruit yield, fruit quality, and plant defense system) in strawberries, 150 and 200 mg L^{-1} Ag NP applications resulted in stunted growth, low and poor quality yield, and a weakened defense system. Consequently, foliar applications of 50 and 100 mg L^{-1} Ag NPs at 15-day intervals are recommended for sustainable strawberry cultivation.
Aguirre-Noyola et al. [71]	To evaluate the effects of AgNP applications, obtained by the green synthesis method under in vitro conditions, on photosynthetic pigment production and adaptation in strawberries.	Strawberry, AgNPs, sucrose, and Phytagel. Strawberry explants were treated with 30 g of sucrose and 0, 100, 200 or 300 mg L^{-1} of AgNP obtained by the green synthesis method under in vitro growing conditions (5.8 pH, 24 °C temperature, 16 h light and 8 h darkness artificial lighting, 1.7 g Phytagel gelling agent).	While emphasizing the need for further data, it has been concluded that the application of Ag NPs at various dosages for strawberry seedling production under in vitro conditions achieves a 90% success rate and is both commercially profitable and sustainable.

Table 1. *Cont.*

Reference	Objective	Materials and Methods	Conclusions
Saini et al. [72]	To evaluate the performance (plant growth, crop yield, crop quality, and soil structure) of Zn NP, ZnO NPs and conventional Zn fertilizers in strawberries.	Strawberry, Zn NP, ZnO NPs, ZnSO4, Zn-EDTA and ZnO. Application of Zn NP and ZnO NPs (200, 400, 600 mg L^{-1}), $ZnSO_4$ (200, 400 mg L^{-1}), and chelated Zn-EDTA (100, 200 mg L^{-1}) via foliar spray at 30 and 60 days after planting, following a randomized complete block design with three replicates.	Compared to other treatments, foliar application of 200 mg L^{-1} Zn NPs on strawberries improved plant growth, resulted in flowering at 41.5 days, increased fruit set by 19.9% and yield by 48.3%, enhanced metabolic content, boosted plant nutrient levels in both leaves and fruit, and improved soil microbial activity; consequently, strong evidence was obtained indicating that foliar Zn NP application on strawberries could serve as an alternative to conventional Zn nutrient inputs.
Kumar et al. [73]	To evaluate the effects of ZnO NP and FeO NP applications at doses of 0, 50, 100, and 150 mg L^{-1} on plant growth, crop yield, and fruit quality in strawberries.	Strawberry; ZnO NPs, FeO NPs, and chemical nitrogen, phosphorus, and potassium (NPK) fertilizers. In strawberry trials using a randomized block design, ZnO NP and FeO NP were applied individually or in combination at doses of 0, 50, 100, and 150 mg L^{-1} in 16 different plots, including three replicate controls.	The best results regarding plant growth and fruit yield in strawberries were obtained from the plot where ZnO NPs and FeO NPs were co-applied at a dosage of 150 mg L^{-1} consequently, it was concluded that the combined application of ZnO NPs and FeO NPs at 150 mg L^{-1} was the most effective treatment for plant growth and fruit yield.
Bhowmick et al. [74]	To evaluate the effects of foliar fertilization with ZnO NPs and chemical Zn (zinc sulfate) on plant growth, fruit yield, and fruit quality in strawberries.	Çilek, Çiftlik gübresi, ZnO NP, Kimyasal Zn Gübre (Zn-sülfat, ZnSO4 7H2O) In strawberry trials using a randomized block design, foliar application of ZnO NP at doses of 100, 150, and 200 mg L^{-1} and chemical Zn fertilizer at doses of 2000, 4000, and 6000 mg L^{-1} was performed seven times in three replicates, 30 and 60 days after planting.	In strawberries, foliar application of ZnO NP at doses of 200 mg L^{-1} showed the best performance in terms of plant growth, fruit yield, and fruit quality. In conclusion, it was determined that ZnO NP has the potential to be an alternative to chemical Zn fertilizers.
Liu et al. [76]	To investigate the effects of Se NP and Cu NP applications on plant growth, fruit quality, photosynthetic parameter indices, and physiological characteristics of strawberry plants under drought stress.	Strawberries, Se NPs, Cu NPs, NPK, pots Application of 5–18 nm sized Se NPs and 35–42 nm sized Cu NPs at doses of 200 mg L^{-1}, individually or in combination, to strawberries under three different drought stress conditions consisting of 25%, 60% and 100% water retention rates in the prepared substrate in 12 different combinations, including the control.	While the parameters investigated in strawberries were significantly adversely affected by 25% and 60% drought stress, the combined application of Cu NPs and Se NPs enhanced the plant's agronomic traits and improved fruit yield compared to normal water application. Ultimately, it was concluded that under drought stress conditions, these NPs improved plant growth, fruit quality, and physiological characteristics in strawberries.

Table 1. *Cont.*

Reference	Objective	Materials and Methods	Conclusions
Kumar et al. [80]	To evaluate the effects of ZnO NP and FeO NP applications at doses of 0, 50, 100, and 150 mg L^{-1} on plant growth, crop yield, and fruit quality in strawberries.	Strawberry; ZnO NPs, FeO NPs, and chemical NPK fertilizers. In strawberry trials using a randomized block design, ZnO NP and FeO NP were applied individually or in combination at doses of 0, 50, 100, and 150 mg L^{-1} in 16 different plots, including three replicate controls.	The best results regarding fruit yield and fruit quality in strawberries were obtained from the plot where ZnO NPs and FeO NPs were co-applied at a dosage of 150 mg L^{-1} consequently, it was concluded that the combined application of ZnO NPs and FeO NPs at 150 mg L^{-1} was the most effective treatment for plant growth and fruit yield.

4.4. NP Applications in Strawberries (Production Method, Size, Plant Type, Timing of Application, and Dosage)

An examination of research on the application of NPs in strawberry cultivation, which covers areas such as plant growth, crop yield, product quality, pest and disease management, and resilience against environmental stressors, leads to the conclusion that "green synthesis" is the most suitable method for producing metallic or nutrient-based NPs, considering both environmental impact and production costs [22,71]. Furthermore, it has been reported that, compared to physical and chemical synthesis methods, the green synthesis approach increases NP yield by approximately 50%, while reducing energy consumption by about 30% and production costs by approximately 40% [81]. However, significant problems remain in green synthesis methods for NP production, such as the lack of a universally applicable plant species suitable for large-scale NP synthesis, the fact that these plants are endemic to different geographical areas, and the timing of material collection from these plants [81]. In this sense, an attempt is being made to overcome this issue by utilizing local sources for the plant species to be used in green synthesis [81].

The size range of 1–100 nm, which is considered one of the most significant characteristics of NPs [33,82–85], is regarded as the optimal size for their use in agricultural production activities and in applications related to strawberry cultivation [71,77]. According to one study, a size of approximately 50 nm is most effective for plant gene regulation [85]; meanwhile, research on strawberries has shown that the application of Ag NPs with a maximum size of 100 nm enhances plant morphology, fruit yield and quality, and the plant's defense systems [70,85].

In studies evaluating the success of nanoparticle (NP) applications based on the plant type used, it was observed that the strawberry cultivars employed as plant material included commercially grown varieties such as the short-day cultivars 'Sweet Charlie' [72], 'Chandler' [73,80], 'Winter Dawn' [74,79], 'Fen Yu No. 1' [76], and 'Festival' [86], as well as the day-neutral cultivar 'Albion' [23].

The application dosage of NPs plays a significant role in achieving desired benefits in agricultural production and strawberry cultivation. In strawberry cultivation, NPs have been applied at various dosages for different purposes; for instance, it has been reported that the most effective dosages for promoting vegetative growth in plants are 150 mg L^{-1} of ZnO NPs and FeO NPs [73,77] and 200 mg L^{-1} of Ag NPs [71], Zn NPs [77], ZnO NPs [72,74], and Se NPs [77].

Based on NP applications in strawberries, the following doses have been found to be effective for crop yield: 100 mg L^{-1} of Zn NPs [77], ZnO NPs [77], and Ag NPs [70]; 150 mg L^{-1} of ZnO NPs + FeO NPs [77], Fe NPs [77], and Si NPs [77]; and 200 mg L^{-1} of ZnO NPs [51,77], Zn NPs [72,77], Zn-EDTA [51], Se NPs, and Cu NPs [76].

In studies on fruit quality in strawberries involving the application of NPs, it has been observed that the following doses were used: 150 mg L^{-1} of ZnO NPs [79,80] and FeO NPs [79,80]; 200 mg L^{-1} of Se NPs [77] and ZnO NPs [74,77]; 400 g L^{-1} of ZnO NPs [22]; and 1000 g L^{-1} of FeO NPs [77].

In field-grown strawberry cultivation, the optimal timing for NP application varies depending on the specific type of NP used. For Ag NPs, research indicates that when applied foliarly at intervals of 5, 10, or 15 days over a 90-day period following planting, the most effective frequency is every 15 days [70]. Another study, which involved applications to both leaves and roots every 7 days for 56 days post-planting [86], found that for ZnO NPs, the most effective application timing was at 30 and 60 days after planting [72,74].

Research findings indicate that these effects are also observed in open-field cultivation. For instance, similar to the positive outcomes on plant growth reported for Ag NP applications at doses of 100 and 200 mg under in vitro cultivation conditions [71], it has been reported that a 100 mg dose of Ag NPs in open-field settings yields improvements in plant growth, as well as in crop yield and quality [70]. Furthermore, it has been suggested that Ag NP applications at doses of 50, 100, and 150 mg could be effective for sustainable strawberry cultivation [70]. In a similar study, it was observed that Ag NP applications within the 40–120 range influence plant growth and fruit yield [86].

4.5. The Effects of NPs on Production Economy

In agricultural production activities, new production methods, new inputs, etc., cannot be sustainable unless an optimal balance is achieved and economically viable across parameters such as healthy plant growth, product yield/quality, and environmental/production costs. In this context, the use of nanotechnology-based NPs, a new production method within agricultural production activities, must yield economically satisfactory results in the agricultural production process. This section will evaluate the economic benefits of NPs used in strawberry production, considering both economic income and environmental/production costs. The NP input and production quantity data obtained from the studies examined within the scope of this work were analyzed based on prices formed under market conditions. The results are presented in Table 2.

Table 2. Economic analysis, pro forma income statement.

Pro Forma Income Statement	**Saini et al. [72]**		**Kumar et al. [73]**	
	$ZnSO_4$ [1]	**Zn NP [2]**	**RDF [3]**	**RDF + ZnO NP [2] / FeO NP [4]**
A. Total production revenues (€/da) = (2 × 3)	21,756.77	32,287.01	7223.89	18,078.64
1. Yield per Plant (g/plant)	575.25	853.67	191.00	478.00
2. Total production kg (6.000 plant/da × 1/1000 g)	3451.50	5122.02	1146.00	2868.00
3. Average price per kg (€) [5]	6.30	6.30	6.30	6.30
B. Total production costs (€/da) (1 + 2+3 + 4+5 + 6+7)	2097.23	2325.23	2003.63	2486.03
1. Land cultivation costs (€/da)	180.10	180.10	180.10	180.10
2. Seedling cost (€/da) 6000 plant × €0.17/seedling	972.55	972.55	972.55	972.55
3. Labor costs (planting, maintenance, and harvesting) (€/da)	310.68	310.68	310.68	310.68
4. Harvesting costs (transportation, packaging) (€/da)	72.04	72.04	72.04	72.04
5. Maintenance costs (€/da)	171.10	171.10	171.10	171.10

Table 2. *Cont.*

Pro Forma Income Statement	Saini et al. [72]		Kumar et al. [73]	
	$ZnSO_4$ [1]	Zn NP [2]	RDF [3]	RDF + ZnO NP [2] / FeO NP [4]
6. Irrigation costs (€/da)	72.04	72.04	72.04	72.04
7. Total plant nutrition cost (€/da) [6]	318.73	546.73	225.13	707.53
C. Net profit (€/da) = (A − B)	19,659.53	29,961.77	5220.26	15,592.60

€, Euro; As of 27 October 2026, the Türkiye Republic Central Bank's selling exchange rate is €1 = 52.5241 Turkish Lira; 1 decare (da) 1000 m^2; RDF, (Recommended Fertilizer Dose); [3] RDF cost is €236.79; [6] total plant nutrition cost = RDF cost + NP cost; the prices of Zn NP, ZnO NP and FeO NP were obtained from the Nanografi Advanced Materials (Ankara, Türkiye) website on 29 October 2026. Available at https://shop.nanografi.com/nanoparticles/zinc-zn-nanopowder-nanoparticles-high-purity-99-9-size-60-70-nm/ (accessed on 29 October 2026), https://shop.nanografi.com/nanoparticles/zinc-oxide-zno-nanopowder-nanoparticles-purity-99-5-size-30-50-nm/ (accessed on 29 October 2026) and https://shop.nanografi.com/nanoparticles/iron-fe-nanopowder-nanoparticles-purity-99-55-size-50-nm-metal-basis/ (accessed on 29 October 2026) respectively; The price of $ZnSO_4$ powder was obtained from the Merck (Darmstadt, Germany) website on 29 October 2026. Available at https://www.sigmaaldrich.com/TR/en/product/sigald/z4750 (accessed on 29 October 2026); All costs except NP costs are assumed to be constant. Strawberry production costs were taken from the https://www.hanimkoylu.net/ (accessed on 29 October 2026) website as average values for 2025 [87]. [1] For $ZnSO_4$, the RDF is 400 mg L^{-1}; the liquid mixture applied is 60 L; the amount of $ZnSO_4$ applied is 240 mg L^{-1} and the price of 1 g of $ZnSO_4$ is €0.39, the total input cost is €93.60. [2] For Zn NP and ZnO NP, the RDF is 400 mg L^{-1}; the liquid mixture applied is 60 L; the amount of Zn NP and ZnO NP applied is 120 mg L^{-1} and the price of 1 g of Zn NP and ZnO NP is €2.68 and €1.92 respectively, the total cost of Zn NP and ZnO NP per decare is €321.60 and €230.40 respectively. [4] For FeO NP, the RDF is 150 mg L^{-1}; the liquid mixture applied is 60 L; the amount of FeO NP applied is 90 mg L^{-1} and the price of 1 g of FeO NP is €2.80, the total input cost is €252.00. [5] The average selling price of strawberries per kg is €6.30 (lowest at €4.50, highest at €8.10): Antalya Metropolitan Municipality wholesale fruit market selling price as of 29 October 2026. https://www.antalya.bel.tr/tr/halden-gunluk-fiyatlar (accessed on 29 October 2026).

The average yield per plant values used as a reference in the economic analysis of strawberry cultivation were the yield values obtained in the study conducted by Saini et al. [72] on the Sweet Charlie strawberry variety and the yield values obtained in the study conducted by Kumar et al. [73] on the Chandler strawberry variety. According to Table 2, the use of NPs in strawberry production is seen to increase product yield and therefore income in economic terms. The data in Table 2 shows that the economic income obtained varies depending on whether NPs are used in production, the strawberry variety selected for production, and the application dose of the NPs used. According to Table 2, the use of NPs in strawberry production increases yield and profitability, ensuring economic sustainability. In the study conducted by Saini et al. [72], NPs increased profitability by 52% compared to control. In another study conducted by Kumar et al. [73], NP applications increased profitability by 199% compared to the control (Table 2). The key here is identifying the environmental costs and determining whether the project is sustainable. However, this is not an easy process. According to the results of the studies evaluated within the scope of this work, the most significant environmental cost is the accumulation of engineered NPs and metal oxide NPs in water and soil, harming the environment, humans, and other living beings [88]. To keep the environmental costs of NPs in agricultural production at an acceptable level and to obtain the desired benefits from NPs, it is important to determine the correct dosage of NPs and to ensure that the production method is environmentally friendly [89]. There are two different approaches to the production of NPs: top-down, which includes laser ablation, mechanical milling, electron beam deposition, spraying, abrasion, and grinding or milling methods; and bottom-up, which includes sol–gel, co-precipitation, hydrothermal, and biological, also known as green synthesis, methods [88]. The most suitable method for use in agricultural production activities is the green synthesis method, which aims to

produce environmentally harmless pure NPs using plant and fruit extracts or biological organisms with simple, economical and highly repeatable techniques [90].

5. Potential Harmful Effects of NPs on the Environment, Humans, and Other Living Beings

According to the study findings, nanotechnology-based Ag, Fe, Cu, Zn, Ti, Ni, Si, Se, and CNT NPs offer strong evidence of their significant potential for sustainable agricultural practices, providing advantages such as improving and regulating soil structure; ensuring healthy plant growth; increasing crop yield and quality; combating pests and diseases; and enabling efficient and effective resource utilization [20,59]. However, alongside these positive benefits, many scientific studies have highlighted the risks posed by NPs due to their unique characteristics (very small structure; potential to spread over large areas; high reactivity; high toxicity) that negatively impact the environment, humans, and other living beings [91,92]. NPs used in agriculture (especially those of metal origin, with their toxic structures) pose risks of potentially harmful effects on the environment (soil, plants, biodiversity, and water resources).

The accumulation of highly reactive and toxic metal-based NPs in soil can have adverse effects on the soil's physical structure, chemical composition, and microbial communities [21]. It has been shown that NP accumulation in soil disrupts key microbial communities that perform vital functions in organic matter decomposition, as well as nitrogen and carbon cycling [68]. Soil pH, which has a direct impact on soil fertility and health, determines the degree of soil acidity or alkalinity while also influencing the uptake of nutrients by plants [93]. pH, one of the soil chemical quality parameters, is the most influential factor on the status of NPs in the soil, while high pH levels reduce Zn bioavailability. pH also affects the accumulation of NPs in the soil [94]. A study on this subject reported that while CuO NPs increased the pH (from 4.9 to 5.4) through ionization and the formation of hydroxyl groups, TiO_2 NPs and cerium oxide (CeO) NPs lowered the pH by 0.1–0.3 units [95]. Highly reactive and toxic metal-based NPs accumulating in the soil can reach plant cells via roots or leaves, triggering ROS production; this ROS production leads to oxidative stress, which alters cellular functions and defense mechanisms and can potentially result in the death of the plant [68,96–98]. While the negative impact of NPs on biodiversity varies depending on sensitivity and exposure time, their reactive and toxic properties, as well as their very small size, allow them to easily reach cells and cause serious harm to living organisms, thereby altering biodiversity [99].

In conclusion, while the findings regarding the use of NPs examined in this study suggest that they will make a significant positive difference in sustainable agricultural production in general and strawberry production processes in particular, more data is needed regarding factors such as the right plant, the right application dose, the right application time, the right application stage, and the right NP extraction method, which are effective in the agricultural production process, in order for NPs to produce the expected benefits.

6. Conclusions

NPs, a product of nanotechnology and a new technological advancement, offer promising solutions in many fields, including agricultural production, for healthy plant growth, increased product yield/quality, reduced environmental/production costs, and sustainable economic income. This study was conducted to examine the applicability of the benefits desired with NPs in strawberry cultivation. According to the study findings, NPs increased plant growth parameters by approximately 52% in crown number, approximately 150% in fresh stem weight, and 90% in the plant's adaptation and resistance to environmental changes. In different studies, applications with different NPs at different doses resulted

in increases ranging from 6% to 267%. In terms of fruit quality, NPs increased the TSS value by approximately 26% and the TA value by 8%. According to the study findings, NP applications were found to increase economic profitability by 52% to 199%. However, alongside the benefits they provide in agricultural production, uncertainties surrounding the use of NPs, such as their toxic nature leading to pollution by accumulating in soil and water, and the harm they may cause to nature, humans, and other living beings, have led to objections to their use. The study findings strongly support the idea that if appropriate NP production methods and dosages are used, NPs can find application in strawberry production in terms of sustainable agricultural practices. According to the research findings examined, NP applications are highlighted as having significant potential in increasing the capacity for sustainable agricultural production, and it is emphasized that more data is needed for future studies to ensure that this potential provides the same benefits under all conditions and applications. Specifically, future studies are called for to gather more data regarding suitable plant species, appropriate NP production methods, the optimal dosage, duration, and stage of application during the production process, and potential risks to the environment, humans, and other living organisms.

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