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NANOTECHNOLOGY APPLICATIONS IN VITICULTURE: NEW APPROACHES FOR SUSTAINABLE PRODUCTION

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Abstract: Viticulture holds a significant place among Türkiye's agricultural activities, supporting not only the economic livelihood of producers but also contributing substantially to the national economy. This study discusses the current status and potential contributions of nanotechnology applications in viticulture and highlights nanotechnology as an innovative approach for sustainable production, environmental protection, and increased efficiency. Global climate change, rising environmental stress factors, and the intensive use of chemical inputs are among the main issues threatening sustainable grape production. One of the new and eco-friendly technologies developed to mitigate these challenges is nanotechnology. By utilizing the unique physical and chemical properties of materials at the nanometer scale, nanotechnology offers innovative solutions for plant nutrition, disease and pest management, and enhanced stress tolerance. The use of nanofertilizers in viticulture increases nutrient uptake due to their slow-release characteristics, while reducing nutrient losses and environmental pollution. Similarly, the use of nanopesticides with controlled-release properties decreases the frequency of pesticide applications and minimizes negative environmental impacts. Studies have shown that different nanoparticle applications improve the morphological, physiological, and biochemical parameters of grapevines under both abiotic and biotic stress conditions, thereby enhancing stress tolerance. Overall, the findings indicate that nanotechnology has great potential to serve as an environmentally friendly and efficiency-enhancing approach that supports sustainable grape production.

Keywords: Nanotechnology, Viticulture, Sustainable production, Nanofertilizers, Nanopesticides, Stress tolerance

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1. Introduction

The grapevine is one of the oldest known plant species, with a history dating back millions of years. Archaeological evidence indicates that grapevine domestication began approximately 6000–8000 years ago, originating from wild Vitis vinifera subsp. sylvestris populations in the Transcaucasia region between the Black Sea and Iran. Among the grapevine species widely distributed across the world, the most economically and agriculturally important is Vitis vinifera L. (Çelik et al., 1998; Grassi and Arroyo-Garcia, 2020).

Türkiye possesses favorable climatic conditions for viticulture and ranks among the world's leading countries in vineyard area and grape production (Çelik et al., 1998; Semerci et al., 2015). In terms of vineyard area, Türkiye ranks fifth globally—after Spain, France, China, and Italy—and seventh in grape production, following China, Italy, France, the United States, Spain, and India (FAO, 2023). The provinces with the largest vineyard areas are Manisa (877.598 da), Mardin (357.692 da), Denizli (293.883 da), Nevşehir (185.253 da), and Mersin (163.921 da). In terms of production, the leading provinces are Manisa (1.139.027 tons), Mersin (319.512 tons), Denizli (295.603 tons), Mardin (161.904 tons), and Gaziantep (163.889 tons) (TÜİK, 2024).

Grapes have high nutritional value and are an important agricultural product due to their versatility for table, dried, and wine grape production (Çelik, 2014; Sümbül and Yıldız, 2022). In 2024, the total grape production in Türkiye was reported as 3.468.000 tons, of which 1.825.915 tons were table grapes, 1.261.347 tons were dried grapes, and 380.738 tons were wine grapes (TÜİK, 2024).

Climate change has accelerated soil erosion, increased the spread of plant diseases and pests, and consequently reduced soil fertility. Moreover, the growing frequency and intensity of extreme events such as droughts and floods have directly affected agricultural productivity (Lavudya and Prabhakar, 2024; Yang et al., 2024; Wang et al., 2024; Farah et al., 2025). As in all agricultural sectors, global climate change also negatively impacts grape production and vineyard sustainability. Grapes are an economically valuable crop, yet they are highly sensitive to environmental changes, leading to yield and quality reductions in vineyards. Therefore, the development of sustainable and restorative practices is crucial to mitigate the adverse effects of climate change (Quintarelli et al., 2024).

Recent studies have shown that nanotechnological applications hold promising potential for addressing agricultural and environmental challenges by improving the efficiency of agricultural inputs, enhancing food safety, and increasing productivity (Usman et al., 2020). Nanotechnology in agriculture has demonstrated significant effects at all stages of production—from seed germination and plant growth to harvesting, processing, storage, and transportation of agricultural products (Saritha et al., 2022).

This study aims to evaluate the role of nanotechnology applications in grapevine nutrition, pest and disease management, and stress tolerance, and to reveal their potential contributions to sustainable production in viticulture.

2. Nanotechnology

Nanotechnology is one of the most innovative and promising technologies contributing to the advancement of science and technology in the twenty-first century. The term "nano" refers to one billionth of a meter (10^{-9} m). Nanotechnology is a field that involves the observation, measurement, manipulation, and production of materials at the nanometer (nm) scale. It is defined as a multidisciplinary area of science, engineering, and technology in which unique properties emerge at the nanoscale, offering new application opportunities in diverse disciplines such as chemistry, physics, biology, medicine, engineering, and electronics (Huang et al., 2015; Kolahalam et al., 2019; Bayda et al., 2020; Şaşkın and Özdemir, 2025).

The term nanomaterial is used for materials with dimensions ranging from 1 nm to 100 nm. Depending on their chemical composition, size, shape, and intended use, these materials can be classified as nanocrystals, nanoparticles, nanotubes, nanowires, nanorods, and nanofilms (Can and Gürel, 2023). Because of their small size and high surface-to-volume ratio, nanomaterials exhibit remarkable to chemical and physical properties (Figure 1) (Roduner, 2006; Sanzari et al., 2019).

Among these, nanoparticles represent one of the most widely studied nanomaterials and can occur in various shapes and sizes, such as spherical, cylindrical, conical, tubular, hollow-core, helical, or irregular structures (Figure 1). Their dimensions generally range between 1 nm and 100 nm; structures smaller than 1 nm are often referred to as "atomic clusters." Nanoparticles may exist as loosely aggregated or clustered formations, or as single-crystal or polycrystalline solids in either crystalline or amorphous form (Machado et al., 2015; Ealia and Saravanakumar, 2017; Joudeh and Linke, 2022).

Nanomaterials can be applied to plant roots or vegetative organs, preferably to the leaf surface. The applied nanoparticles can passively penetrate plant tissues through natural nano- or microscale openings such as stomata, hydathodes, stigma, and bark tissues (Eichert et al., 2008; Kurepa et al., 2010; Sanzari et al., 2019). The transport of nanoparticles within plants is influenced by several factors, including particle size, shape, surface characteristics, solution pH, and the presence of other ions or compounds in the medium (Wang et al., 2023).

3. Applications of Nanotechnology in Viticulture

Nanotechnology offers innovative and sustainable solutions to many of the challenges faced in viticulture, such as nutrient management, disease and pest control, and stress tolerance. The integration of nanomaterials into viticultural practices has opened new avenues for improving grapevine productivity and environmental sustainability. Nanotechnology-based materials, including nanofertilizers, nanopesticides, and nanosensors, provide opportunities to increase nutrient uptake efficiency, reduce chemical input, and minimize environmental contamination (Usman et al., 2020; Saritha et al., 2022).

3.1. Nanofertilizers

Nanofertilizers are among the most promising nanotechnological applications in viticulture. Due to their nanoscale size and large surface area, these fertilizers enable the slow and controlled release of nutrients, improving nutrient-use efficiency and reducing leaching losses (Liu and Lal, 2015). The application of nanofertilizers in grapevines enhances nutrient availability in the rhizosphere and increases nutrient absorption through leaves and roots. Studies have demonstrated that nanofertilizers improve photosynthetic activity, chlorophyll content, and overall plant vigor while decreasing the risk of soil and groundwater contamination (Sabir et al., 2014; Aldine et al., 2022).

3.2. Nanopesticides

The use of nanopesticides has gained increasing attention in grapevine protection. Nanopesticides enable the controlled release of active ingredients, prolonging their effectiveness and reducing the frequency of pesticide application (Khot et al., 2012). Their nanoscale properties allow for better adherence to plant surfaces and enhanced penetration into target sites, ensuring higher pest control efficiency with lower chemical doses. Moreover, nanopesticides minimize pesticide residues on grape berries and reduce adverse environmental impacts (Ghormade et al., 2011; Kah and Hofmann, 2014).

3.3. Nanosensors and Precision Monitoring

Nanosensors play a crucial role in precision viticulture by providing real-time monitoring of soil conditions, plant physiological status, and environmental variables. These sensors can detect nutrient deficiencies, water stress, and the presence of pathogens at very early stages (Mukhopadhyay, 2014). The integration of nanosensors into vineyard management systems contributes to more efficient irrigation, fertilization, and pest management practices, thereby promoting sustainable grape production (Rai et al., 2012).

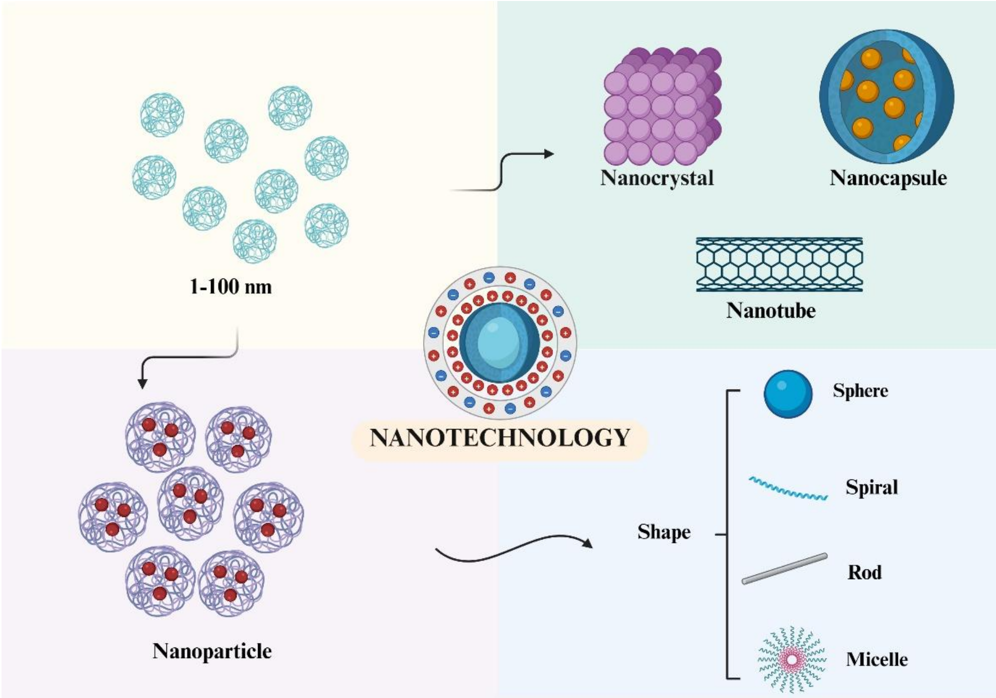

Figure 1. Classification and shapes of nanomaterials.

3.4. Enhancement of Stress Tolerance

Nanotechnology also contributes to improving grapevine tolerance against abiotic stresses such as drought, salinity, and temperature extremes. Nanoparticles such as Fe_3O_4, ZnO, and TiO_2 enhance antioxidant enzyme activities, reduce reactive oxygen species (ROS) accumulation, and improve water-use efficiency under stress conditions (Sabir et al., 2014; Abou El-Nasr et al., 2021). Several studies have shown that nanoparticle applications can enhance morphological, physiological, and biochemical traits in grapevines, helping plants maintain growth and productivity under unfavorable environmental conditions (Şaşkın and Özdemir, 2025).

Overall, the application of nanotechnology in viticulture represents a promising and environmentally friendly approach to achieving sustainable grape production. The adoption of nanotechnological innovations can reduce input dependency, improve resource-use efficiency, and support the long-term resilience of viticultural systems.

3.5. Plant Nutrition

Plants require essential nutrients during growth, development, and yield formation. Deficiency or excess of nutrients can lead to physiological and morphological disorders in the roots, shoots, leaves, and fruits of plants (Esetlili and Anaç, 2010). As in other cultivation systems, fertilizer applications in vineyards should be planned according to the climatic and soil conditions of the region, as well as the grape variety, rootstock, and irrigation method used. Therefore, soil and leaf analyses should be conducted to determine nutrient requirements accurately (Yağmur and Okur, 2018). Excessive and unplanned use of chemical fertilizers can cause various adverse effects on the environment and ecosystem (Savci, 2012; Srivastav et al., 2024). However, it is possible to increase crop productivity without harming nature. Recent studies have shown that nanotechnology offers significant potential for sustainable and environmentally friendly agricultural practices.

Nanoparticles can be synthesized using various methods, including physical (fragmentation), chemical (ultrasonication), and biological (enzyme-mediated) techniques. Among these, biological synthesis is considered the most eco-friendly and cost-effective method since plant leaves are used as raw material and no toxic effects are observed (Ainomugisha et al., 2024; Quintarelli et al., 2024; Zafar and Iqbal, 2024). Nanofertilizers, due to their high absorption capacity and enhanced nutrient-use efficiency, minimize nutrient losses and facilitate nutrient uptake by plants (Fatima et al., 2021). These fertilizers allow plants to utilize nutrients more efficiently and improve nutrient management (Figure 2). Nutrients can be applied individually or in combination, and they are generally associated with nano-sized absorbents that provide a much slower release compared to conventional fertilizers. The slow-release mechanism of nanofertilizers ensures balanced and long-term nutrient supply, promoting better plant growth and productivity. Furthermore, it enhances nutrient-use efficiency while minimizing nutrient leaching into groundwater (Zulfiqar et al., 2019). Owing to their slow and controlled release, nanofertilizers are more easily absorbed by roots and shoots and are therefore preferred over traditional fertilizers (Mandal, 2021).

Several studies have reported the application of nanofertilizers in viticulture. In a study conducted to maintain grape yield and quality, calcium phosphate nanoparticles enriched with urea were applied under limited nitrogen concentrations to seven-year-old *Vitis vinifera* L. cv. 'Pinot Gris' grafted onto Kober 5BB rootstock. Four treatments were performed: (1) a control group, (2) conventional fertilizer (NH_4NO_3) applied to the soil, (3) urea-doped calcium phosphate nanoparticles applied via fertigation, and (4) a combination of conventional fertilizer applied to the soil and urea-doped calcium phosphate nanoparticles applied foliarly.

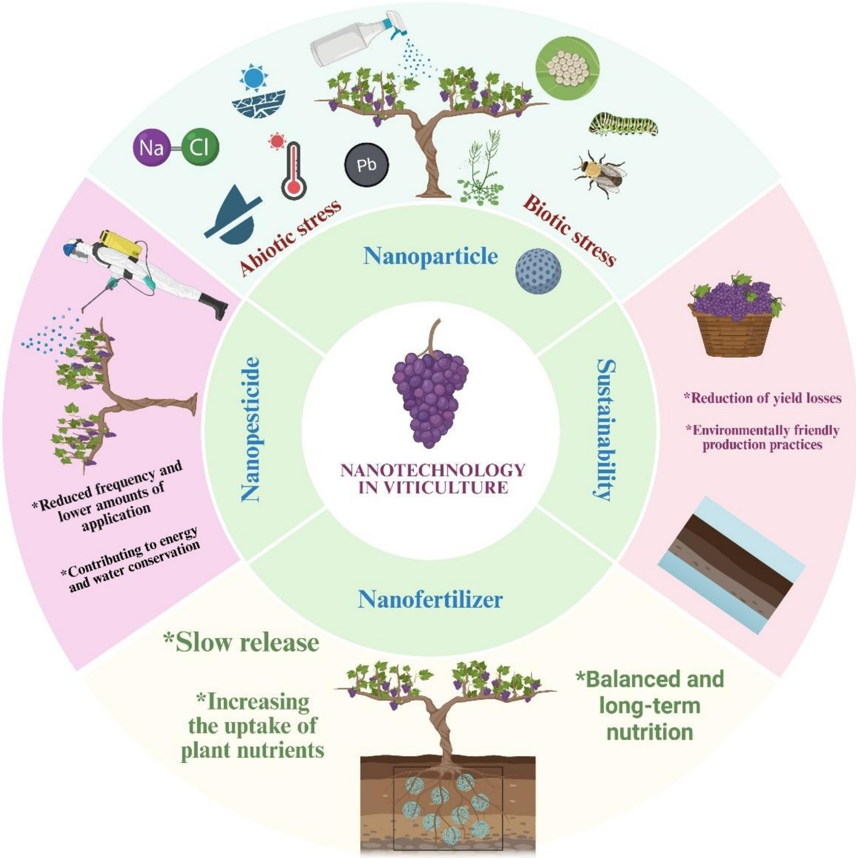

Figure 2. Applications of nanotechnology in viticulture.

In treatments involving urea-doped calcium phosphate nanoparticles, the nitrogen rate was reduced by 20% compared to the conventional fertilizer. The results indicated that despite the 20% reduction in nitrogen rate, plant nutrition, yield, and grape quality parameters were comparable to those obtained with conventional fertilization. The study also showed that urea-doped calcium phosphate nanoparticles can serve as an effective nitrogen source for grapevines (Gaiotti et al., 2021).

In another study conducted on 30-year-old productive *Vitis vinifera* L. var. 'Tfiefihi' vines, the effects of foliar-applied nanofertilizers on plant growth, nutrient uptake, and yield were investigated. Six treatments were tested: (T1) conventional Ca fertilizer applied once at full bloom (0.5 L per 200 L water), (T2) conventional Ca fertilizer applied twice (at full bloom and 2 weeks later, 0.5 L per 200 L water each time), (T3) Lithovit®-Amino25 nanofertilizer applied once (5 g/L at full bloom), (T4) Lithovit®-Amino25 nanofertilizer applied twice (5 g/L at full bloom and 2 weeks later), (T5) Lithovit®-Standard nanofertilizer applied once (5 g/L at full bloom), and (T6) Lithovit®-Standard nanofertilizer applied twice (5 g/L at full bloom and 2 weeks later). The results revealed that nano calcium fertilizers, particularly when applied twice, improved the vegetative characteristics of the vines, and the Lithovit®-Standard formulation showed higher efficiency in most parameters compared to Lithovit®-Amino25 (El Masri et al., 2021).

Mahdavi et al. (2022) evaluated the effects of different zinc (Zn) sources on soil Zn availability, grape yield, and fruit quality in *Vitis vinifera* cv. 'Bidaneh Sefid'. Three Zn sources were tested: zinc sulfate ($ZnSO_4$, 30% Zn), nano zinc chelate (Zn-EDTA, 12% Zn), and nano zinc oxide (ZnO, 98% Zn). These were applied to the soil at concentrations of 0, 250, and 500 mg Zn kg^{-1} soil. Considering Zn content and 40 kg soil per pot, the required fertilizer amounts were calculated as 33.3 g for $ZnSO_4$, 83.5 g for Zn-EDTA, and 10.2 g for ZnO. The fertilizers were incorporated into 30 cm deep and 35 cm wide holes near the active root zone at the onset of the growing season (April). The highest Zn availability was observed in the nano Zn chelate treatment, which also increased grape yield, cluster weight, and berry weight. The application of nano Zn chelate at 500 mg Zn kg^{-1} soil was more effective than $ZnSO_4$ and nano ZnO in improving leaf and fruit nutrient contents, yield, and fruit quality.

In a recent study, Masoud et al. (2025) investigated the effects of foliar applications of mineral and nanofertilizers on yield and berry quality of 'Thompson Seedless' grapevines. Leaves were sprayed with zinc (250 and 500 ppm), nano zinc (25 and 50 ppm), boron (2000 and 3000 ppm), nano boron (1000 and 1500 ppm), micronutrients (450 and 1000 ppm), nano micronutrients (450 and 1000 ppm), and distilled water (control). The study reported that both mineral and nanofertilizer treatments improved grape yield and berry quality, with the best performance obtained from the 50 ppm nano zinc treatment.

Similarly, Sabir et al. (2014) studied six-year-old own-rooted 'Narince' grapevines and applied four foliar treatments: 0.5 g/L nano-sized calcite, 0.3 g/L *Ascophyllum nodosum* seaweed extract, a combination of both (0.5 g/L nano-calcite + 0.3 g/L seaweed extract), and a control. The results indicated that the nano-sized Ca-based fertilizer enhanced leaf development and chlorophyll concentration in vines grown in alkaline soils. The study concluded that nano fertilizer application under alkaline soil conditions plays a significant role in improving growth, yield, fruit quality, and leaf nutrient content in 'Narince' grapevines.

3.6. Disease and Pest Management

In viticulture, disease and pest control is generally achieved through the application of pesticides. Although chemical pesticides are effective against weeds, pathogens, and insect pests, their use often leads to residue accumulation on grapevines and in the environment. These residues contaminate soil and water resources, harm beneficial organisms, and consequently disrupt ecological balance, posing significant risks to human health (Yadav and Devi, 2017; Mwaka et al., 2024).

Nanotechnology has emerged as one of the most important scientific advances contributing to agricultural transformation and the reduction of health and environmental problems associated with the intensive and widespread use of conventional pesticides (Kapelaka and Mwema, 2024). Nanopesticides, in the presence of suitable nanomaterials, ensure the slow degradation and controlled release of active ingredients, providing long-lasting pest control. They represent an effective and sustainable tool for the management of different pest species, with the potential to reduce the use of synthetic chemicals and their associated environmental risks (Figure 2).

Compared to conventional pesticides, nanopesticides are applied in smaller quantities and at longer intervals, leading to significant energy and water savings. They also reduce waste and labor costs while enhancing pesticide efficiency and agricultural productivity, resulting in higher crop yields and lower input costs (Chhipa, 2017; Usman et al., 2020; Yin et al., 2023).

Several studies have investigated the use of nanopesticides in grapevine disease management. In one study, nanopesticide applications were evaluated as an alternative to chemical pesticides to control grapevine trunk diseases and to reduce chemical pesticide use. Over a two-year experiment, four chemical compounds and silver–selenium nanoparticles were tested for their inhibitory effects on three major pathogens responsible for grapevine trunk diseases. The study revealed that while all chemical compounds exhibited varying degrees of inhibition, silver–selenium nanoparticles showed 55–88.9% inhibitory activity, particularly against *Diaporthe eres* and *Eutypa lata* (Štůsková et al., 2025).

In another study, Falsini et al. (2024) designed nanoparticles based on biopolymers such as lignin and tannin to encapsulate and deliver neem oil and capsaicin against *Verticillium dahliae*, *Phaeomoniella chlamydospora*, and *Phaeoacremonium minimum* pathogens. The results showed that the highest antifungal effect was observed against *Phaeoacremonium minimum*, and the encapsulated form of neem oil and capsaicin significantly enhanced antifungal efficacy compared to their non-encapsulated forms.

3.7. Biotic and Abiotic Stress Tolerance in Plant

Plants are continuously exposed to various environmental stress factors that negatively affect agricultural productivity. Stress is defined as any internal or external constraint that limits photosynthetic activity and reduces the plant's ability to convert energy into biomass. Plants experience stress as a result of their physiological responses to changing environmental conditions, and these responses can manifest in different forms, such as alterations in gene expression, cellular metabolism, growth and development rates, and yield performance. Environmental stresses are generally classified into two main categories: biotic and abiotic. Abiotic stresses include factors such as temperature fluctuations, soil salinity, alkalinity, drought, ultraviolet radiation, and heavy metals, while biotic stresses are caused by insects, nematodes, fungi, bacteria, and weeds (Figure 2) (Umar et al., 2021; Kumari et al., 2022; Gonzalez Guzman et al., 2022; Manghwar and Zaman, 2024).

Numerous ways have been established to improve stress tolerance in plants, and recent research indicates that nanotechnology possesses considerable potential in addressing both biotic and abiotic challenges (Zhao et al., 2020; Silva et al., 2022). Nanoparticle applications under stress conditions have been shown to provide substantial benefits in terms of growth, development, and yield performance (Zain et al., 2023). Several studies in viticulture have reported the use of nanotechnological approaches to mitigate the adverse effects of biotic and abiotic stresses on grapevines.

Bidabadi et al. (2023) evaluated the effects of iron oxide (Fe_2O_3) nanoparticles on oxidative stress in the seedless grapevine cultivar *Vitis vinifera* L. cv. 'Asgari' subjected to polyethylene glycol (PEG)-induced drought stress. The treatments included Fe nanoparticles at 0, 5, 10, 20, 30, and 40 μM concentrations added to a half-strength Hoagland solution. Fe-EDDHA was excluded from all treatments except for the control (0 µM). PEG-6000 was used at a 7% (a/h) concentration to induce drought stress. The results showed that drought stress increased H_2O_2 and MDA levels, negatively affecting the physiological integrity of the vines and reducing relative leaf water content, chlorophyll concentration, and chlorophyll fluorescence. However, Fe nanoparticle treatments, particularly at 30 and 40 µM concentrations, effectively mitigated these adverse effects.

In another study, Daler et al. (2025a) investigated the effects of silicon dioxide (SiO_2) nanoparticles on morphological, physiological, and biochemical parameters of *Vitis vinifera* L. 'Crimson Seedless' grafted onto rootstocks Kober 5BB, 41B, and 1103 Paulsen, representing low, moderate, and high drought tolerance, respectively. The vines were grown under well-watered (90–100% field capacity) and drought-stressed (40–50% field capacity) conditions, and SiO_2 nanoparticles were foliar-applied at 0, 1, 10, and 100 ppm. The results indicated that SiO_2 nanoparticle treatments enhanced the antioxidant defense system and provided strong oxidative stress protection, with 10 ppm identified as the optimum concentration.

Gohari et al. (2021) examined the effects of cerium oxide (CeO_2) nanoparticles on mitigating the adverse effects of salinity stress in *Vitis vinifera* L. cv. 'Flame Seedless' cuttings. The vines were exposed to 25 and 75 mM NaCl salinity stress, and foliar applications of CeO_2 nanoparticles were performed at 25, 50, and 100 mg L^{-1} concentrations. The results showed that CeO_2 nanoparticles significantly improved chlorophyll integrity and provided protection against salinity-induced damage under high salinity conditions.

Daler et al. (2025b) studied the effects of iron oxide (Fe_3O_4) nanoparticles in mitigating lime-induced stress in the American grapevine rootstock 1103 Paulsen. The vines were exposed to lime concentrations of 0%, 20%, 40%, and 60% $CaCO_3$, and Fe_3O_4 nanoparticles were foliar-applied at 0, 0.01, 0.1, and 1 ppm concentrations to the green plant surfaces. The results indicated that increasing lime stress inhibited vine growth, while the application of 1 ppm Fe_3O_4 nanoparticles under high lime stress (60%) provided significant improvement. Under low and moderate lime stress conditions, 0.1 ppm Fe_3O_4 nanoparticles were found to be most effective in mitigating stress effects.

Panahirad et al. (2025) investigated the effects of chitosan–selenium nanoparticles on lead (Pb) stress in *Vitis vinifera* cv. 'Sultana'. The soil was supplemented with 0, 50, and 100 mg kg^{-1} $Pb(NO_3)_2$ concentrations at planting. Foliar applications included 0.1% chitosan, 20 mg L^{-1} selenium, and 10 and 20 mg L^{-1} chitosan–selenium nanoparticles at the eight-leaf stage. The results indicated that chitosan–selenium nanoparticle treatments increased leaf and root biomass, photosynthetic rate, proline and phenolic contents, and major antioxidant enzyme activities, while significantly reducing Pb accumulation and cellular stress markers in the plants.

In another experiment, Daler et al. (2024) evaluated the effects of titanium dioxide (TiO_2) nanoparticles on morphological, physiological, and biochemical characteristics of *Vitis vinifera* L. cv. 'Crimson Seedless' grafted onto rootstocks 5BB, 41B, and 1103 Paulsen under well-watered and drought-stressed conditions. TiO_2 nanoparticles were foliar-applied at 0, 1, 10, and 100 ppm concentrations. The 10 ppm TiO_2 treatment significantly enhanced growth traits and SPAD index values under both well-watered and drought conditions, while reducing oxidative stress parameters, demonstrating its effectiveness in improving stress tolerance in grapevines.

4. Conclusion

Nanotechnology represents one of the most promising innovations of the twenty-first century, offering unique opportunities for sustainable agricultural transformation. In viticulture, where environmental sensitivity and production quality are closely linked, nanotechnology provides effective, environmentally friendly, and economically viable alternatives to conventional practices. The ability to manipulate materials at the nanometer scale has opened new avenues for improving nutrient-use efficiency, controlling pests and diseases, and enhancing grapevine tolerance to abiotic and biotic stress factors.

Traditional viticultural practices often rely heavily on chemical fertilizers and pesticides, which can reduce soil fertility and increase environmental pollution through leaching and residue accumulation. In contrast, nanofertilizers and nanopesticides offer controlled and slow-release mechanisms that improve nutrient absorption, reduce application frequency, and minimize ecological impact. These nanoenabled inputs also enhance plant photosynthetic performance, boost antioxidant defenses, and contribute to the overall resilience and productivity of grapevines. Moreover, specific nanoparticles such as Ag, Cr_3O_4, Fe_3O_4, ZnO, SiO_2, and CeO_2 have demonstrated the ability to mitigate drought, salinity, and calcareous soil stress by improving physiological balance and metabolic adaptation mechanisms.

Beyond plant nutrition and pest control, nanotechnology is poised to transform the concept of sustainable viticulture through innovations in precision farming and smart monitoring systems. Nanosensors integrated with precision viticulture platforms can enable real-time assessment of soil nutrients, water availability, and pathogen presence, facilitating site-specific management decisions. Furthermore, the use of nanoencapsulation for biofertilizers, growth regulators, and biocontrol agents offers potential for reducing chemical dependency while maintaining ecological stability and fruit quality.

To fully harness the benefits of nanotechnology in sustainable viticulture, the following recommendations are proposed.

4.1. Encouraging Applied and Field-Based Research

Long-term, large-scale field trials should be conducted to confirm laboratory findings and to establish optimal nanoparticle concentrations, application timings, and delivery methods under real vineyard conditions.

4.2. Developing Safe and Green Nanoformulations

Future research should focus on the synthesis of biodegradable and plant-based nanomaterials to ensure environmental and human safety while maintaining high efficacy.

4.3. Integrating Nanotechnology into Precision Viticulture

Combining nanosensors with digital vineyard management tools will support data-driven decision-making, allowing efficient use of fertilizers, pesticides, and water resources.

4.4. Evaluating Long-Term Ecotoxicological Effects

Continuous monitoring programs should be developed to assess nanoparticle persistence and potential risks to soil microorganisms, beneficial insects, and the surrounding ecosystem.

4.5. Supporting Education, Policy, and Collaboration

Governments and research institutions should provide training and establish regulatory frameworks that ensure the safe application of nanomaterials in agriculture. Collaborative projects between agronomists, materials scientists, and environmental experts should be encouraged to accelerate the adoption of nanoenabled sustainable viticulture practices.

4.6. Biofortification

In addition to improving grapevine productivity and stress tolerance, nanotechnology-based fertilization strategies offer significant potential for the biofortification of grapevines and grape berries with essential nutrients. Recent studies have demonstrated that nutrient-enriched nanofertilizers, particularly magnesium, zinc, and iron-based formulations, can enhance the accumulation of micronutrients in edible plant organs while simultaneously improving the biosynthesis of bioactive compounds and antioxidant capacity. Magnesium deficiency, which is associated with various metabolic and cardiovascular disorders in humans, represents a widespread global health concern. The application of magnesium-based nanofertilizers in viticulture may therefore contribute not only to improved grapevine nutrition but also to the production of nutritionally enriched grape products with added health value. From a broader perspective, nanoenabled biofortification strategies in viticulture can support consumer awareness of functional foods and provide complementary benefits for human nutrition, thereby strengthening the link between sustainable agricultural practices and public health.

In conclusion, nanotechnology has the potential to redefine viticulture as a more resilient, resource-efficient, and environmentally responsible production system. By enhancing grapevine productivity, improving stress tolerance, and minimizing environmental harm, nanotechnological innovations align perfectly with the global vision of sustainable agriculture and climate-smart viticulture. The integration of science-driven nanotechnological solutions into vineyard management will not only improve grape production efficiency but also ensure ecological harmony for future generations.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	N.Ş.	G.Ö.
C	50	50
D	50	50
S	50	50
DCP	50	50
DAI	50	50
L	50	50
W	50	50
CR	50	50
SR	50	50
PM	50	50

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management.

Conflict of Interest

The authors declared that there is no conflict of interest.

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