



Enhancing Post-harvest and Fruit Quality of Capsicum Using Titanium Dioxide Nanoparticles

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

The impact of titanium dioxide nanoparticles (TiO₂ NPs) on a range of post-harvest and fruit quality metrics of capsicum under field experiments were examined in this study. At 50, 100, and 150 mg/L, TiO₂ NPs were sprayed on leaves and applied as seed treatments. Comparing the results to foliar treatments and the control, seed treatments, especially at 50 mg/L, considerably improved fruit quality parameters. The seed treatment with the greatest texture score (8.13), specific gravity (0.93), cuticle thickness (36.96 μm), penetration force (12.05 N), shearing force (78.18 N), moisture content (94.00%), shelf life (7.66 days), and capsaicin content (0.24%) were the 50 mg/L seed treatment. These improvements stemmed from enhanced photosynthesis, cellular structure, and nutrient uptake. Higher foliar concentrations (150 mg/L), on the other hand, demonstrated limited effectiveness and, under certain situations, negative effects that were probably caused by oxidative

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stress or metabolic imbalance. According to the results, TiO₂ NPs improve turgor pressure, encourage lignification, improve cuticle growth, and stimulate secondary metabolite pathways, all of which have an impact on plant physiology. Better fruit texture, firmness, water retention, and extended shelf life were the outcomes of these changes. The results of this study revealed that best method for improving the physical and biochemical characteristics of capsicum fruits was to apply seeds at low to moderate concentrations of TiO₂ nanoparticles. These findings provide a promising avenue for improving fruit quality and post-harvest performance through nano-enabled agricultural practices. Further studies are recommended to explore long-term environmental impacts and mechanistic pathways.

Keywords: Nanoparticles; titanium dioxide; capsicum; seed treatment; foliar spray.

1. INTRODUCTION

The concerns of sustainable agricultural production and food security have prompted significant technological advances and advancements in agriculture in recent years (Dwivedi et al., 2016; Kou et al., 2018). Because land and water supplies are limited, this objective can only be achieved by technical interventions to boost production. Since nanomaterials offer such remarkable and unique qualities, it is not unexpected that efforts have been made to employ them to enhance the agriculture sector (Grillo et al., 2015; Handford et al., 2014; Husen and Siddiq, 2014). Nanotechnological advancements may lead to new applications in the fields of biotechnology and agriculture. Nanotechnology is providing expanding research in the fields of electronics, energy, medicine, and life sciences, including reproductive science and technology, enzymatic nano bioprocessing that converts food and agricultural wastes into energy and other useful byproducts, chemical sensors, water purification, disease prevention, and plant treatment with various nanocides (Nair et al., 2010). Despite the fact that fertilizers are crucial for the growth and development of plants, leaching, photolysis, hydrolysis, and decomposition make the majority of fertilizers in use ineffective for plants. Therefore, it is essential to reduce fertilizer-related nutrient losses and boost crop output by experimenting with novel uses for nanotechnology and nanomaterials. According to DeRosa et al. (2010), nano fertilizers or nano-encapsulated nutrients may offer the following advantages: regulated release of compounds that affect plant development, increased target action, and the ability to release nutrients on demand. In order to improve the natural functions of plants, scientists and researchers are now working to create new methods. Nanoparticles may increase plant metabolism and have special physicochemical characteristics (Giraldo et al., 2014).

A member of the Solanaceae family, capsicum, also known as Shimla Mirch (*Capsicum annum* L.), are high-value crops with non-pungent, green, yellow, or red fruit. Fruits in their green or immature stages are utilized for a variety of reasons. Both polyhouse and open field settings can be used to grow the crop. With nanotechnology, the experimental realm is gradually giving way to the practical. Nanotechnology has made it possible to use nanoscale or nanostructured materials as controlled-release vectors or fertilizer carriers to create so-called "smart fertilizer," which is a new facility that will increase the efficiency of nutrient use and lower environmental protection costs (Chinnamuthu and Boopathi, 2009). Nanofertilizers work with nutritious elements that are active at the nanoscale (1–100 nm). These engineered nanoparticles (ENPs) may carry chemicals and DNA into plant cells and penetrate plant cells and leaves (Galbraith, 2007). When compared to conventionally used pesticides and their formulations, the advantages of nanomaterial-based formulations include improved efficacy due to a higher surface area to volume ratio, which offers a better opportunity for interaction, higher solubility, induction of systemic activity due to smaller particle size and higher mobility, and lower toxicity due to the elimination of organic solvents (DeRosa et al., 2010). Novel materials made possible by nanotechnology offer significant and distinctive solutions to the shortcomings of other conventional materials. It is also predicted to become a major economic force in the near future with a high potential for achieving sustainable agriculture, particularly in developing nations. Nanomaterials are very new in the agricultural area and require more research. Furthermore, the concentration is on the latest advancements in plant science that concentrate on agricultural methods, plant growth, and output. Titanium dioxide nanoparticles (TiO₂ NPs) were selected due to their high frequency

of reference in the literature pertaining to the usage of NPs in agriculture (Gogos et al., 2012). One of the most common elements in the energy and agricultural industries, titanium dioxide (TiO₂) is thought to be good for plant growth and development (Singh and Chaudhary, 2020). There are few studies that primarily focuses on the benefits of nanoparticles for agriculture (Fraceto et al., 2016).

Increased yield, improved levels of some key elements in plant tissues, and increased chlorophyll content in paprika (*Capsicum annuum* L.) are the three main impacts of titanium on plants (Hrubý et al., 2002). In soybeans, the application of nano TiO₂ increased nitrate reductase activity, growth, and germination (Lu et al., 2002). Additionally, it has been discovered that TiO₂ nanoparticles promote the germination in spinach (*Spinacia oleracea*) seeds and the development of spinach plants (Zheng et al., 2005). Enhancing crop growth and reducing environmental risks are two major benefits of using nanoparticles as fertilizer (Vakhrouchev and Golubchikov, 2007). Engineered nanoparticles might act as a nutrition supply for the organisms by storing nutrients on their surfaces (Navarro et al., 2008). Cluster bean (*Cyamopsis tetragonoloba* L.) crop growth was even improved when used as a foliar spray (Raliya and Tarafdar, 2013). According to Rameshaiah and Jpallavi (2015), nano-formulated fertilizers are easily absorbed by plants and may have a longer effective duration of nutrient delivery in the soil or on plants. In this context, the current study was conducted to investigate the most effective concentration and application method of TiO₂ nanoparticles in capsicum which enhance various fruit properties.

2. MATERIALS AND METHODS

The two-year (2021-22) open field experiment was conducted at Experimental farms, Department of Soil Science and Water Management, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (HP). The experimental site was situated at 1260 meters above mean sea level, with an average slope of 7-8 percent and 30° 52' North latitude and 77° 11' East longitude represents mid-hills sub-humid (Agro-climate zone-II) region of Himachal Pradesh. About 75% of the region's 1115 mm of annual rainfall received during the monsoon season (mid-June to mid-September). The months of January and February get mild winter showers. The typical range of the coldest

and highest temperatures is 4°C to 36°C. The warmest months are May and June, while the coldest months are December and January. The soils of the research area belong to the order Inceptisol and subgroup Eutrochrept according to the soil taxonomy given by USDA. These soils are composed of dolomitic limestone and ferromagnesian shales. The initial soil sample was taken before the execution of the first trial for physio-chemical properties and the results revealed that soil was neutral in reaction, electrical conductivity was in safe limits, available NPK was also medium in range. The recommended dose of nutrients for the cultivation of capsicum in mid-hills condition of Himachal Pradesh is N: 100 kg ha⁻¹, P₂O₅: 75 kg ha⁻¹ and K₂O: 55 kg ha⁻¹ (Anonymous, 2014). The recommended dose of nutrients was supplied indiscriminatory to all treatments through chemical fertilizers (Urea, Single Super Phosphate and Muriate of Potash) at the time of field preparation. For the experiment, the nursery of capsicum was raised and one month old healthy seedlings with 4-5 leaves were selected for the experiment. The experiment comprised of seven treatments and three replication and was laid in randomized block design (RBD). The treatments were: T1-Control, T2-50 mg/L TiO₂ nanoparticles as seed treatment, T3-50 mg/L TiO₂ nanoparticles as foliar spray, T4-100 mg/L TiO₂ nanoparticles as seed treatment, T5-100 mg/L TiO₂ nanoparticles as foliar spray, T6-150 mg/L TiO₂ nanoparticles as seed treatment, T7-150 mg/L TiO₂ nanoparticles as foliar spray.

Titanium dioxide (TiO₂) (anatase) powder with particle size <25 nm with 99.7% purity, poorly water soluble and white in color, applied as seed treatment and foliar spray. For a full day prior to being sowing them for nursery raising, capsicum seeds were treated by immersing them in nano-anatase TiO₂ powder at varying concentrations (50, 100, and 150 mg). Nano-anatase TiO₂ powder weighing 50, 100, and 150 mg was mixed with 5–10 ml of ethanol then mixed in distilled water for making final volume of 1 litre to make 50, 100, and 150 mg/L solutions for foliar spray. Foliar spray was done fifteen days after transplantation.

Typically employed in post-harvest quality assessment, the texture score of capsicum is a sensory or instrumental evaluation of the fruit's texture characteristics. The texture score was estimated using only ripe, uniform, and healthy capsicum (*Capsicum annuum* L.) fruits. To

ensure consistency, the fruits were rinsed with distilled water, let to air dry, and then sliced into rectangular pieces measuring 2 x 2 cm. Prior to analysis, all samples were allowed to settle at room temperature ($25 \pm 2^\circ\text{C}$). Each attribute was scored using a 9-point hedonic scale, where 9 is considered outstanding while 1 is considered very poor. The mean of the ratings was used to determine the texture score. The fruit specific gravity was calculated by dividing the fresh weight of the pepper by its volume. A TMS-Pro texture analyzer testing frame (TMS-PRO, FTC, USA) was used to assess each fruit's maximum penetration and shearing forces. Fruit pericarp sections were cut, and the tissue was immediately preserved in a formalin-acetic acid alcohol buffer to measure the cuticle thickness. The samples were embedded, sectioned, dyed, and dried using a gradient ethanol series before being immersed in paraffin. Sections were examined under a microscope, and their thickness was calculated using Image J software (Liu et al., 2022). After estimating the fresh weight, the peppers were dried in an oven at 80°C until their weight remained constant. The dry weight was then calculated, and the moisture content was calculated as well. Based on treatment, sample fruits were selected one at a time, and the number of days between fruit harvest and the point at which the fruits shriveled and lost their firmness was recorded in order to determine shelf life. After then, shelf life was calculated in days. Using the Folin-Dennis method, the amount of capsaicin was determined. The blue complex that results from the reaction of the pungent principle with the Follin-Dennis reagent was calculated colorimetrically (Mathew et al., 1971).

The data generated for this two-year field observation were collected, tabulated and analyzed by Randomized Block Design (RBD) (Panse and Sukhatme, 2000) and analysis of variance (ANOVA) were used to determine significance at $P \leq 0.05$ using Microsoft Excel and OPSTAT packages (Sheron et al., 1998). The least significant difference (LSD) was used to determine significant differences among the means at $P \leq 0.05$. The significant difference between mean treatments were separated by using Duncan's Multiple Range Test (DMRT) at 5% level of significance. Superscript letters signify statistical difference between the mean. Means followed by the same letter do not differ significantly from one another and if the mean values have different letters, they are significantly different ($P \leq 0.05$).

3. RESULTS AND DISCUSSION

3.1 Texture Score

The texture score of capsicum fruits was considerably improved by the application of TiO_2 NPs as given in Table 1. 50 mg/L seed treatment had the highest texture score (8.13), followed by 100 mg/L seed treatment (7.98) and 150 mg/L seed treatment (7.13). When it came to foliar sprays, 100 mg/L foliar spray shown a moderate improvement (6.58), while 150 mg/L foliar spray had the lowest score (5.22), which was comparable to the control (5.48). Nutrient availability and enzyme activity both affect turgor pressure and cell wall stiffness, which in turn affect fruit texture. TiO_2 NPs boost metabolic processes by increasing photosynthetic efficiency and nutrient absorption. Because of the more reliable systemic absorption of nanoparticles through roots, seed treatments performed better than foliar sprays. The decreasing impact at greater doses (150 mg/L foliar spray) might be due to metabolic imbalance or oxidative damage brought on by nanoparticles. In present study, the most effective seed treatments for TiO_2 NPs are 50-100 mg/L, which increased fruit texture. Overly high foliar concentrations could reverse this advantage, highlighting the significance of proper dosage and delivery technique. These results are similar with the results of Soliman et al. (2021) and Servin et al. (2012), who concluded in their studies that by strengthening the cell wall and controlling turgor pressure, TiO_2 nanoparticles improved the texture of the fruit. TiO_2 NP exposure was also found to improve fruit firmness and texture because it changed metabolism and boosted nutrient absorption.

3.2 Specific Gravity

The perusal of data presented in Table 1 revealed that use of TiO_2 NP considerably enhanced specific gravity. The 50 mg/L seed treatment had the highest value (0.93), followed by the 100 mg/L seed treatment (0.90) and the 150 mg/L seed treatment (0.84). With the lowest values in the control (0.43) and 150 mg/L foliar spray (0.47), foliar sprays demonstrated very slight improvements. Fruit density and internal quality, such as dry matter and solute content, can be determined by specific gravity. Improved nutrient transport and assimilate accumulation in fruits may be caused by increased specific gravity under seed-applied TiO_2 NPs. This may be the result of enhanced root activity and

effective mineral and water absorption brought on by the photocatalytic qualities of TiO₂. In our results, applying TiO₂ NPs as a seed treatment, particularly at 50 mg/L, significantly increased fruit density, suggesting superior quality and more storage capacity. The preference for seed-based distribution at lower concentrations was further supported by the less successful foliar sprays at higher dosages. These results are in conformity with the results of Khot et al. (2012). They reported increased dry matter content, solute accumulation and increased fruit density by the application of TiO₂ nanoparticles. Similarly, another study carried out by Raliya and Tarafdar (2013), concluded that nanoparticles improved physiological activities and solute concentration in the plant tissue.

3.3 Maximum Penetration Force (N)

As given in Table 1, with TiO₂ NP treatments, the maximum penetration force which is a qualitative indicator of fruit firmness, increased. The treatment containing 50 mg/L seed treatment produced the greatest force (12.05 N), which was followed by the 100 mg/L seed treatment (11.02 N). Moderate values were obtained from foliar treatments; the least effective foliar spray among treated samples was 150 mg/L (8.22 N). The least amount of force (6.72 N) was shown by the control. Fruit's shelf life and mobility depend heavily on its firmness. Firmer fruits result from TiO₂ NPs' involvement in boosting photosynthesis and strengthening cellular structures. Stronger fruit tissues are developed as a result of seed treatment, which guarantees extended exposure to nanoparticles throughout crucial developmental stages. Incomplete absorption of nanoparticles or phytotoxic reactions may be the cause of reduced outcomes at high foliar dosages. In the results, the positive effect of 50-100 mg/L TiO₂ NP seed treatments on fruit structural integrity are highlighted by improved penetrating force. This directly affects consumer demand and mechanical handling. Similarly, studies carried out by Rameshaiah et al. (2015) and Tripathi et al. (2017) revealed that cell wall structure is enhanced by nanoparticles like TiO₂, which also increase hardness and resistance to penetration. TiO₂ increases mechanical strength and lignin production, which raises penetrating force values.

3.4 Maximum Shearing Force (N)

With TiO₂ NP treatment, the shearing force increased noticeably. Among the seed

treatments, 50 mg/L had the maximum shearing force (78.18 N), followed by 100 mg/L (70.53 N) and 150 mg/L (68.15 N). Of the treated samples, 150 mg/L foliar spray had the lowest force (53.67 N), whereas the control had the lowest (49.98 N) as shown in Table 1. TiO₂ mediated enhancements in enzymatic and hormonal balance are associated with improved lignification and cell wall integrity, which are implied by higher shearing force. Strong tissue growth is facilitated by zinc, a recognized regulator of auxin production, and TiO₂, which increases chloroplast activity. In contrast to foliar sprays, which may offer limited translocation and so reduce efficacy, seed treatments have a long-lasting impact. The findings show that the best way to increase fruit tissue strength and increase post-harvest utility and market value is to treat seeds with 50-100 mg/L TiO₂ NPs. Similarly, Mahajan et al. (2011) and Singh et al. (2017) reported that the internal structure of plants is strengthened by nanoparticles increased tissue hardness and resistance to shearing force and improved post-harvest characteristics, such as tissue strength.

3.5 Cuticle Thickness (µm)

The data shown in Table 2 indicated that treatments with TiO₂ nanoparticles had a substantial impact on the cuticle thickness of capsicum fruits. 50 mg/L TiO₂ seed treatment produced the maximum thickness (36.96 µm), which was followed by 100 mg/L seed treatment (34.30 µm) and 150 mg/L seed treatment (29.48 µm). The control had the minimum cuticle thickness, measuring 16.57 µm. Among the treated samples, the 150 mg/L foliar spray recorded the lowest (21.16 µm), although foliar sprays displayed values that were somewhat lower than those of comparable seed treatments. TiO₂ application, particularly at 50 mg/L via seed treatment, resulted in an increase in cuticle thickness, which suggests that nanoparticles had a beneficial effect on the development of protective epidermal layers. Reduced water loss, postponed senescence, and enhanced resilience to infections and environmental stresses are all linked to thicker cuticles. Early root absorption and systemic dispersion throughout plant growth are probably the reasons why seed treatments were more successful. Similarly, studies carried out by Servin and White (2016) and Raliya et al. (2015) reported that plant surface characteristics can be changed by nanoparticles such as TiO₂, which can also improve cuticle production by changing the growth of epidermal cells. thicker

Table 1. Effect of TiO₂ nanoparticles on texture score, specific gravity, maximum penetration force and maximum shearing force in capsicum

Treatments	Texture score	Specific gravity	Maximum penetration force (N)	Maximum shearing force (N)
T1: Control	5.48±0.03 ^f	0.43±0.07 ^b	6.72±0.20 ^g	49.98±0.87 ^d
T2: 50 mg/L TiO ₂ nanoparticles as Seed treatment	8.13±0.04 ^a	0.93±0.05 ^a	12.05±0.11 ^a	78.18±1.49 ^a
T3: 50 mg/L TiO ₂ nanoparticles as Foliar Spray	6.08±0.03 ^e	0.57±0.07 ^b	9.13±0.02 ^d	65.34±3.61 ^{bc}
T4: 100 mg/L TiO ₂ nanoparticles as Seed treatment	7.98±0.04 ^b	0.90±0.05 ^a	11.02±0.30 ^b	70.53±3.55 ^b
T5: 100 mg/L TiO ₂ nanoparticles as Foliar Spray	6.58±0.03 ^d	0.53±0.07 ^b	8.67±0.03 ^e	60.78±2.42 ^c
T6: 150 mg/L TiO ₂ nanoparticles as Seed treatment	7.13±0.04 ^c	0.84±0.05 ^a	9.58±0.03 ^c	68.15±3.05 ^b
T7: 150 mg/L TiO ₂ nanoparticles as Foliar Spray	5.22±0.03 ^g	0.47±0.07 ^b	8.22±0.25 ^f	53.67±3.27 ^d
LSD (P≤0.05)	0.01	0.20	0.42	5.64

Table 2. Effect of TiO₂ nanoparticles on cuticle thickness, moisture content, shelf life and capsaicin content in capsicum

Treatments	Cuticle thickness (µm)	Moisture content (%)	Shelf life (Days)	Capsaicin content (%)
T1: Control	16.57±1.35 ^e	78.50±1.33 ^d	5.31±0.06 ^d	0.17±0.00 ^c
T2: 50 mg/L TiO ₂ nanoparticles as Seed treatment	36.96±2.76 ^a	94.00±2.69 ^a	7.66±0.05 ^a	0.24±0.02 ^a
T3: 50 mg/L TiO ₂ nanoparticles as Foliar Spray	26.69±1.47 ^{bc}	87.41±1.70 ^{bc}	6.23±0.06 ^b	0.17±0.00 ^c
T4: 100 mg/L TiO ₂ nanoparticles as Seed treatment	34.30±1.66 ^a	92.59±2.16 ^{ab}	7.59±0.14 ^a	0.20±0.01 ^b
T5: 100 mg/L TiO ₂ nanoparticles as Foliar Spray	23.74±1.31 ^{cd}	83.90±1.56 ^{cd}	6.38±0.07 ^b	0.21±0.02 ^b
T6: 150 mg/L TiO ₂ nanoparticles as Seed treatment	29.48±2.45 ^b	88.23±2.44 ^{bc}	6.46±0.14 ^b	0.15±0.00 ^d
T7: 150 mg/L TiO ₂ nanoparticles as Foliar Spray	21.16±0.86 ^d	81.76±4.07 ^d	5.80±0.15 ^c	0.14±0.01 ^d
LSD (P≤0.05)	3.39	5.01	0.24	0.03

leaf and fruit epidermis as a result of TiO₂ NPs, most likely as a result of increased cuticle and wax deposition, enhancing post-harvest quality and drought resistance. The most effective method across all parameters examined was seed treatment with 50-100 mg/L TiO₂, indicating that early nanoparticle exposure permits more reliable internal control and systemic augmentation.

3.6 Moisture Content (%)

The data in Table 2 revealed that moisture content was recorded highest in treatment that consisted of 50 mg/L ranging from 78.50% in the control to 94.00%. The 100 mg/L seed treatment (92.59%) and the 150 mg/L seed treatment (88.23%) were both effective treatments. Foliar treatments, particularly at the highest dosage, showed reduced moisture retention. TiO₂ nanoparticle-promoted increased root activity and water absorption efficiency may be the cause of treated fruits' improved moisture retention. It is well recognized that nanoparticles can improve water conservation by influencing stomatal behavior and modifying aquaporin expression. A greater relative moisture balance was maintained by the seed treatments, especially at 50 and 100 mg/L. This is important for maintaining fruit quality after harvest. These results are similar with the results of Hong et al. (2005) and Faisal et al. (2021), they noted that TiO₂ NPs improve stomatal control and photosynthesis, which indirectly increases plant water retention. TiO₂ increases root function and water absorption efficiency under stress, assisting in maintaining a greater relative water content.

3.7 Shelf Life

Among the various treatments as shown in Table 2, it is recorded that treatment containing 50 mg/L seed treatment had the longest shelf life (7.66 days), followed by 100 mg/L seed treatment (7.59 days). Compared to the control (5.31 days), all treatments increased shelf life. Although to a lesser extent, foliar treatments also extended shelf life; among treated plants, 150 mg/L foliar spray had the shortest shelf life (5.80 days). The physiological effects of thicker cuticles reducing transpiration, increased moisture content retaining fruit firmness, and the antibacterial activities of TiO₂ reducing decay are all responsible for benefits in shelf life. Delays in ethylene-mediated ripening and reduced levels of

oxidative stress in plants treated with TiO₂ may also contribute to longer shelf life. Similar results of Raliya and Tarafdar (2013) and Lee et al. (2008) also revealed similar outcomes. The longer fruit storage potential results from better physiological health by the application of TiO₂ nanoparticles (Palanisamy et al., 2025). They reported that nanoparticle exposure may postpone ripening and senescence, extending shelf life. The findings show that when used sparingly, nanoparticle-based therapies can greatly improve fruit quality and post-harvest physiology.

3.8 Capsaicin Content (%)

TiO₂ nanoparticle treatments considerably increased the amount of capsaicin. 50 mg/L seed treatment produced the greatest value (0.24%), followed by 100 mg/L foliar spray (0.21%). However, capsaicin decreased with increasing TiO₂ concentrations, particularly when applied through foliar application, with the lowest dosage being 0.14% in 150 mg/L foliar spray as shown in Table 2. Moderate amounts of TiO₂ appear to increase capsaicin production, presumably as a result of secondary metabolite pathways being activated by stress. However, a suppressive impact was observed at larger doses (particularly when given through foliar application), most likely as a result of oxidative imbalance or nanoparticle toxicity. To improve nutritional quality attributes like pungency, it is therefore essential to optimize the dosage and application technique. These results are similar with the results of Taha et al. (2017) and Khodakovskaya et al. (2011). They reported that low to moderate doses, nanoparticles can activate the formation of capsaicin through metabolic pathways triggered by stress. The generation of secondary metabolites, such as capsaicin, is extremely dose-dependent when exposed to nanoparticles, being stimulated at low concentrations and inhibited at high ones.

4. CONCLUSION

When applied as a seed treatment at lower concentrations (50-100 mg/L), titanium dioxide (TiO₂) nanoparticles (NPs) dramatically improved the quality parameters and post-harvest features of capsicum fruits. The 50 mg/L TiO₂ seed treatment continuously performed better than the others across the majority of metrics. Texture score (8.13), specific gravity (0.93), penetration force (12.05 N), shearing force (78.18 N), cuticle

thickness (36.96 μm), moisture content (94.00%), shelf life (7.66 days), and capsaicin content (0.24%) were all highest with this treatment. More efficient systemic uptake through roots, which improves nutrient absorption, photosynthetic efficiency, cell wall integrity, and water retention, is responsible for the better performance of nanoparticles applied to seeds. In contrast, foliar sprays showed only modest increases and were often less effective, especially at higher levels (150 mg/L), which frequently resulted in decreased performance because of possible oxidative stress or phytotoxicity. For instance, the lowest values for texture (5.22), specific gravity (0.47), cuticle thickness (21.16 μm), and capsaicin concentration (0.14%) were obtained with foliar spray containing 150 mg/L. These results highlight the significance of dosage and application technique because high concentrations of nanoparticles can cause metabolic abnormalities and reduce their positive effects. Overall, TiO_2 NPs increased the fruit's density, hardness, and resistance to mechanical stress—all of which are critical for increasing shelf life and marketability. The results are consistent with earlier research indicating that TiO_2 promotes secondary metabolism, including the manufacture of capsaicin, controls turgor pressure, and improves cuticle formation. Consequently, the best method for enhancing the quality and storage capacity of capsicum fruits in field settings is to treat seeds with 50-100 mg/L TiO_2 NPs. To optimize benefits and minimize side effects, however, careful concentration and delivery technique optimization is essential. Future studies should examine the long-term effects of using nanoparticles on crop productivity as well as the molecular mechanisms behind their interactions.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models and text-to-image generators have been used during writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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