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Review Article

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Recent Advancements on Coalesced Effects of Nanomaterials on Tomato Plant: A Review

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Abstract

Nanotechnology unlocks a prominent orbit of unique functions in the fields of agricultural industries and biotechnology. In nanotechnology, nanomaterials such as nanoparticles (NPs), quantum dots (QDs) and carbon nanotubes (CNTs) demonstrate exceptional physicochemical properties. The incorporation of nanomaterials into plant systems holds significant promise, with the ability to increase agricultural productivity as well as adaptability to both environmental and biological stressors. This can lead to a more efficient use of resources and reduced environmental impacts. Nanomaterials can serve as "magic remedies," controlling herbicides, fertilizers, genes, or nano-pesticides that target cell organelles in plants to unleash their payload. Despite the abundance of knowledge on NPs toxicity to plant systems, little research has been undertaken on the methods by which NPs regulate plant growth rate and maturity. Tomatoes are one of the world's most flavorful and extensively eaten vegetables. The current analysis emphasizes the significant contribution of NPs to cultivated tomato plants. The precise understanding of NPs biochemical mechanisms in tomato plants leads to improved plant growth as well as improvements in overall tomato plant quality. The current investigation also looked at the cumulative impacts of NPs on tomato plant life cycles. It is our hope that this detailed review will spark new proposals, leading to the invention of new NPs that will be extremely efficient at regulating tomato plant growth. These advancements may significantly increase the scope of different NPs in the fields of chemistry, biology, and food production.

Keywords

Nanotechnology, Plant growth, Phytotoxicity, Nanomaterials, Nanoparticles, Tomato plant

Introduction

The world population is expected to exceed 9.7 billion by the year 2050, expressing serious alarms about the global need for nourishment, livestock, fuel, and fiber. Growing crops fulfill the demand for nourishment and nutrition, while crude oil production provides fuel and fiber. As a result, there is a desperate need to improve farming capacity and production to assure the availability of food and build an ongoing supply of basic components [1-3]. Since a significant number of fertilizers originate from mining and their supply is restricted, their consumption must be improved. Plant nutrient needs vary during the life cycle, with notable rises during periods such as flowering and grain development. As a result, fertilizers should be formulated to satisfy the plant's nutritional requirements, delivering nutrients as required. When traditional fertilizers are applied to soils, a considerable fraction of the ionic chemical component is absorbed into the soil as colloidal particles, trapped by microbes, or leached away. As a result, plants absorb just a portion of these nutrients at the expense of their stored energy [4].

Therefore, there is an urgent need for an alternative scientific approach to minimize the above-mentioned constraints.

Nanotechnology has gained recognition as a promising area with applications in agriculture, food, and medicine [5]. NPs have nanoscale dimensions (1 - 100 nm) and may be designed to have unique features that may facilitate agricultural applications [6]. Without a doubt, nanotechnology is a rapidly evolving discipline with unique applications in electronics, energy, health, and life sciences. Plants exhibit morphological, physiological, and biochemical changes in response to stress. Plants face a wide range of problems, including drought, salt, heat, frost, and stress from heavy metals. It is critical to encourage the development of ecologically sensitive solutions that minimize these strains while also boosting agricultural production [7]. NPs can considerably affect plant development and yield. Different metal or metal oxides NPs such as iron oxide (Fe_3O_4) NPs, cobalt ferrite ($CoFe_2O_4$) NPs, cerium oxide (CeO_2) NPs, silicon oxide (SiO_2) NPs, zinc oxide (ZnO) NPs, titanium dioxide (TiO_2) NPs, selenium (Se) NPs, copper (Cu) NPs, silver (Ag) NPs, gold (Au) NPs, and other NPs have lately sparked substantial interest because of their benign application in agriculture [5, 8, 9]. NPs can be generated via an array of methods, including physical, chemical, and green synthesis [10], and are then administered to plants by foliar application, root application, branch injection, or seed treatment [11]. They have favorable influences on plant growth. However, the consequences vary depending on the origin, concentration, size, and timing of application to plants [12]. However, concerns have also been raised regarding the environmental and toxicological effects of NPs [13]. Excessive usage of NPs produces physiological irregularities and oxidative stress in plants, resulting in diminished respiration and antioxidant properties [14]. NPs also lower the mitotic index and disrupt cell division and root development processes [15]. Additionally, NPs cause indirect contamination by altering microbial activity in the soil [16]. Second-generation seeds taken from parent plants treated with CeO_2 NPs showed distinct variances. These seeds were found to be smaller as well as more sensitive, as evidenced by lower water perspiration, lower biomass, and a slightly higher amount of reactive oxygen species (ROS) [17].

Several research have found that NPs boost plant tolerance to abiotic and biotic stressors [10]. Hydrogel NPs and Fe_3O_4 NPs were shown to protect plants from oxidative damage by boosting antioxidant activity [9]. Furthermore, Ag NPs can mitigate toxic effects induced by drought by lowering the accumulation of malondialdehyde (MDA) and hydrogen peroxide (H_2O_2) while sustaining photosynthetic efficiency [8, 9]. NPs may get through plant chloroplasts and reach the reaction center of photosystem II, increasing electron transmission and absorption of light in chloroplasts under drought stress and therefore enhancing photosynthetic efficiency and plant development [18]. About Fe NPs, they have demonstrated a range of beneficial impacts on plants, depending on crop variety, concentration, and duration of interaction with plants [8, 19]. The administration of Fe NPs to lettuce plants boosted the root length and rate of germination [20]. Notably, multiple investigations have been performed to study the role of NPs in the germination of seed and plant growth, resulting in enhanced plant development and yield. One of these investigations discovered that introducing nano-silica to the soil elevated maize plant growth [21].

Tomato (*Solanum lycopersicum* L.) is one of the world's most widespread and frequently ingested vegetables. In some countries, such as Saudi Arabia, high-quality production is a necessary condition for financial accomplishment [22]. Tomatoes have recently gained popularity in the fight against certain human illnesses. The fascination stems from the existence of carotenoids, including lycopene, an unsaturated alkylic molecule that looks to be a valuable ingredient in the protection of breast cancer, heart disease, and delaying the deterioration of cells [23]. Therefore, application of nanoparticles on tomato plant growth is an emerging area of research worldwide. It was found that certain nanoparticles, for instance, ZnO NPs, have been proven in studies to improve tomato yield and growth [4]. In addition to that, they boost root and stem biomass in tomatoes as well as in peanuts. Additionally, ZnO NPs have been demonstrated to positively improve photosynthetic efficiency in Arabidopsis. Furthermore, NPs have been discovered to improve the conditions of soil and the defense system in plants [24, 25]. The silica NPs were shown to be effective in lowering chromium (Cr) phytotoxicity in seedlings of *Pisum sativum* L. [26]. They were shown to be benign to plants [27], while a toxic impact was observed by some authors after the pH of the medium decreased after the addition of NP [28]. Cu NPs were observed to enhance the level of Cu in tomato plant tissues under salinity, which raised the content of phenols (16%) in the leaves and glutathione (GSH) (81%), vitamin C (80%), and phenols (7.8%) in the fruit in comparison to the control [29]. In addition to that, AuNPs exposure boosted free radical scavenging capability and antioxidant enzyme functioning, as well as changed microRNA expression, which governs various physiological, morphological, and biochemical reactions in plants. This process of modification stimulated the productivity and yields of the crops [30].

As a result, understanding the role of certain NPs is critical for the efficient application of nanotechnology in agriculture [31]. Furthermore, nanoscience adds innovative concepts that help us comprehend the appropriate mechanisms of NPs in cultivated tomato plants. Given the possible favorable impacts of various NPs, the goal of the focused review is to examine the influence of various NPs on tomato plants.

Effect of NPs in Tomato Plant

CeO_2 NPs are widely employed in consumer and commercial products due to their unique physicochemical characteristics. In terms of the effect of CeO_2 NPs on plants, they frequently serve as fertilizers at low concentration, however at higher concentrations, they develop chronic toxicity and accumulate in plant edible tissues, reducing plant yield. This raises concerns about the security and safety of our food. In view of expanding sector of nanotechnology and to examine the effect of CeO_2 NPs at comparatively lower concentrations than used in the previous studies, Wang et al. [32] in 2012 reported the long-term phenotypic reaction of tomato plants (Figure 1) after interaction with CeO_2 NPs (0.1 - 10 mg/L). The findings showed that the CeO_2 NPs at the doses used in this finding either had no effect or a very minor

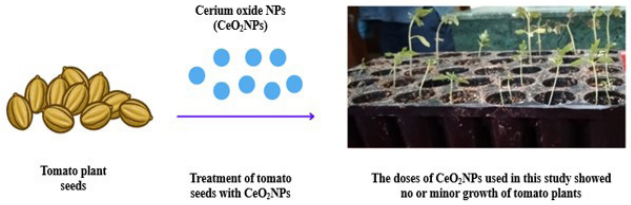


Figure 1: The schematic effect of CeO_2 NPs on tomato plants.

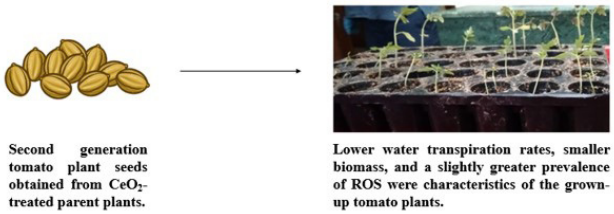


Figure 2: The schematic effect of CeO_2 NPs on tomato plants.

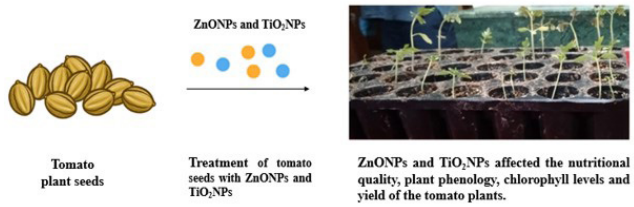


Figure 3: The schematic effect of ZnO NPs and TiO_2 NPs on tomato plants.

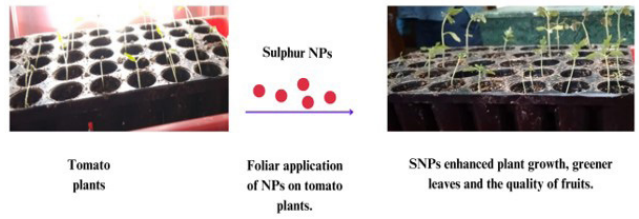


Figure 4: The schematic effect of SNPs on tomato plants.

favorable effect on tomato yield and plant development. The study demonstrated that the buildup of Ce in tomato fruits and the chronic effects of relatively modest concentrations of CeO_2 NPs on tomato production result in the absorption of CeO_2 NPs by the roots of tomato plants and their translocation to edible tissues and shoots, which allows for the detection of enhanced cerium content in plant tissues. For instance, noticeably greater Ce concentrations than controls were found in fruits that had been treated with 10 mg/L CeO_2 NPs. This finding clarifies the chronic effects of CeO_2 NPs on the health of plants and their consequences for the security and safety of our food supply [32].

Several prior experiments have proven that high concentrations of CeO_2 NPs are hazardous to plants, whereas low concentrations have long-term impacts on plants. Wang et al. [17] investigated the long-term impact of CeO_2 NPs on succeeding generations in 2013. The main objective of this work was to determine if nontoxic amounts of CeO_2 NPs exposure during the life cycle of tomato (*Lycopersicum esculentum*) parental plants harmed second generation plants generated from these seeds. The impact of exposing parent tomato plants (Figure 2) to non-toxic doses of CeO_2 NPs during their lifetime was investigated. The researchers wanted to know if the prolonged exposure would affect future generations of plants that grew from the treated seeds. It was observed that the second-generation seedlings (SGSs) developed from the seeds taken from parent plants treated with 10 mg/L CeO_2 NPs showed distinct variances. Lower water transpiration rates, smaller biomass, and a slightly greater prevalence of ROS were among them. Overall, the treated SGSs, which were grown from seeds extracted from parent plants that had been cultivated with CeO_2 NPs, were smaller and more fragile. One noteworthy finding from the investigation was that, independent of administration, SGSs produced from treated seeds grew considerably more root hairs than control next-generation seedlings generated from untreated parent plant seeds. Although these changes were not empirically significant, the treated SGSs absorbed more Ce than their control counterparts under the same circumstances [17].

ZnO and TiO_2 NPs have been extensively used in agriculture to improve crop yield without disturbing the concentrations of bio-compounds. To verify the effects of these NPs on tomato plants, Raliya et al. [33] determined that the application of TiO_2 and ZnO NPs via aerosol and soil mediated pathways had varied impacts on fruit and biomass output, plant phenology, nutritional quality, and chlorophyll levels in tomato plants (Figure 3). It was observed that once the NPs are absorbed by the plant, the vascular network bio-distributes them throughout the plant. However, the rate of accumulation in tissue differs between foliar and soil treatments. When the same dosage of TiO_2 and ZnO (250 mg/kg) NPs was applied, it stimulated the maximum plant height, root length and biomass regardless of NPs type. Also, the fruit yield and lycopene content were highest after 100 mg/kg NPs treatment, while 750 mg/kg NPs exposure enhanced chlorophyll content. The findings indicated that TiO_2 NPs boosted the plant's chlorophyll content and light absorption [33].

The accumulation of heavy metals has chronic effects on the edible plant and is thus harmful for animals and human beings. In contrast to other nanomaterials which consist toxic heavy metals such as Zinc [Zn(II)], Cobalt [Co(II)], Silver [Ag(I)], etc. Sulfur (S) is recognized as a friendlier element owing to its capacity to create organo-sulfur compounds in plant tissue, which are required for healthy development of plants, as well as its antimicrobial action. Keeping in mind the well-being of the living system, Salem et al. [34] effectively produced sulfur nanoparticles (SNPs) by adopting a green approach using sodium thiosulfate in the environment of an aqueous extract of peels of *Punica granatum* at ambient temperature. Foliar application of highly crystalline synthesized SNPs (200 mg/L) was done on tomato plants (Figure 4). The results showed that foliar spraying on tomato plants with 200 ppm SNPs is extremely favorable to plant development and produces robust plants with greener leaves and healthy tomato fruits than the controlled one. In addition, following foliar spraying with SNPs, the potassium content of tomato fruits was shown to be higher than the controlled one [34].

Magnetite NPs are often used for the remediation of water with heavy metals or metalloids. $CoFe_2O_4$ NPs have magnetic characteristics that make them appropriate for usage as nanomagnets, microwaves, and high-density information storage devices. They can be used in cancer therapy, magnetic resonance imaging, and exhibit antibacterial action against microorganisms. Because of the anticipated widespread usage of $CoFe_2O_4$ NPs in medicine and electronics, uncontrolled leakage of these NPs into the surroundings is unavoidable. In continuous improvement of tomato plant quality and fruit yield, López-Moreno et al. in 2016, examined the tolerance of tomato plants (Figure 5) against cobalt ferrite NPs. The tomato plants were cultivated in a hydroponic medium containing $CoFe_2O_4$ NPs in concentrations ranging from 0 - 10^3 mg/L. It was noted that plant germination and growth were unaffected by $CoFe_2O_4$ NPs exposure. The quantity of $CoFe_2O_4$ NPs in the medium enhanced the acceptance of cobalt and iron into plant tissues. Furthermore, magnesium absorption in plant leaves was highest at low $CoFe_2O_4$ NPs concentrations (125 mg/L) and reduced at high $CoFe_2O_4$ NPs concentrations. Calcium absorption in leaves followed a similar trend, with the greatest concentration obtained at low $CoFe_2O_4$ NPs levels (125 mg/L) [35].

Plant exposure to carbon NPs can increase plant production, however the dangers of using carbon nanomaterials (CNMs) as growth regulating agents must be measured. To assess this, McGehee et al. [36] reported that prolonged farming in a water-based nutrient system supplemented with multiwalled carbon nanotubes (MWCNTs) can increase the tomato fruit yield of exposed plants (Figure 6). The precise quantity of MWCNTs deposited inside fruits taken from MWCNTs-exposed plants was determined by means of an improved microwave-induced heating approach. It was discovered that MWCNTs absorption by the fruits of tomato plant had a considerable impact on the whole fruit metabolome. The study emphasizes the significance of conducting a full toxicological risk measurement of plants contaminated with carbon NPs [36].

Cu NPs have received the greatest attention in plant development. Chitosan + Cu NPs are less hazardous to plants than $CuSO_4$ and free Cu NPs. Earlier investigations on the usage of Cu NPs in conjunction with chitosan yielded promising results in the development and activation of bioactive chemicals in plants. Chitosan is used for agricultural purposes as a growth stimulant and as the trigger of the defense system in plants in response to both biotic and abiotic stress. Based on these studies, Hernandez-Hernández et al. [37] determined that the impact of Cu NPs and chitosan-polyvinyl alcohol hydrogels (Cs-PVA) on tomato plants (Figure 7) enhanced height and stem diameter. Additionally, studies suggest that the use of Cs-PVA and Cs-PVA + Cu NPs increases the transcription of genes that regulate enzymatic antioxidants, either in the existence or nonexistence of salt exposure. This result clearly showed that treatment with Cs-PVA and Cu NPs stimulates plant's antioxidant defense mechanisms, which are carried out through the jasmonate octadecanoid pathway. The use of Cs-PVA and Cu NPs showed promise for improving plant tolerance to salt adversity and perhaps other kinds of

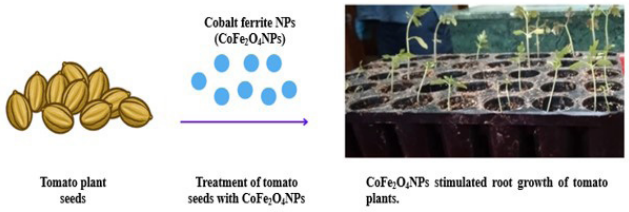


Figure 5: The schematic effect of $CoFe_2O_4$ NPs on tomato plants.

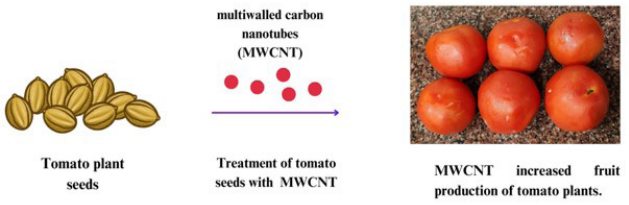


Figure 6: The schematic effect of MWCNTs on tomato plants.

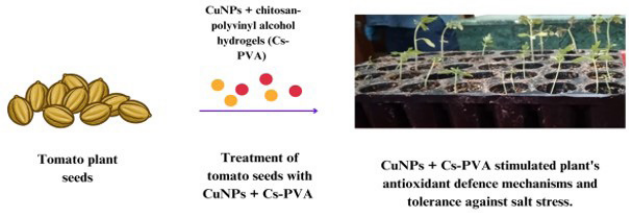


Figure 7: The schematic effect of Cu NPs and Cs-PVA on tomato plants.

abiotic stress as well. It was discovered that the use of Cs-PVA and Cs-PVA + Cu NPs improved the rate of growth of plants. The researchers claimed that the effects of Cs-PVA + Cu NPs and Cs-PVA on saltwater stress are mediated by regulating oxidative and ionic stress mechanisms [37].

ZnO NPs are known to affect growth of plants and help in root elongation. To find better methods for the development of tomato plants, the effect of ZnO NPs on tomato plants (Figure 8) was investigated in 2018. 35-day-old plants were studied for their growth, photosynthetic traits, chlorophyll fluorescence indices, and antioxidative enzyme activities. The ZnO NPs treatments greatly slowed the development of tomato shoots and roots, reduced the amount of chlorophylls a and b, and, in a concentration-reliant way, lowered photosynthetic efficiency and various other chlorophyll fluorescence indices. Despite the presence of trace levels of Zn^{2+}, tomato growth was unaffected by the ZnO NPs suspension supernatant. The findings showed that low concentrations of ZnO NPs (0 and 200 mg/dm^3) had no significant effect on tomato plant development. This was likely due to ZnO NPs' low toxicity at low concentrations as well as tomato plants' moderate tolerance to ZnO NPs treatment. As a result, high ZnO NPs concentrations (400 and 800 mg/dm^3) are thought to be phytotoxic to tomato plants because they inhibit growth. They affected chlorophyll concentration and photosynthesis, which decreased plant growth and biomass output. The ZnO NPs improved the transcription of the corresponding genes as well as the antioxidant activity of enzymes [14].

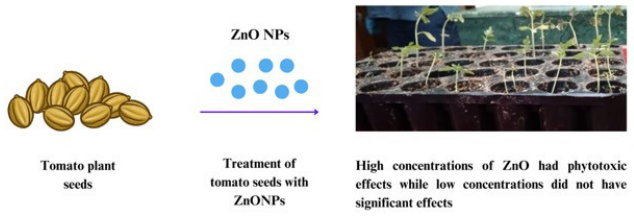


Figure 8: The schematic effect of ZnO NPs on tomato plants.

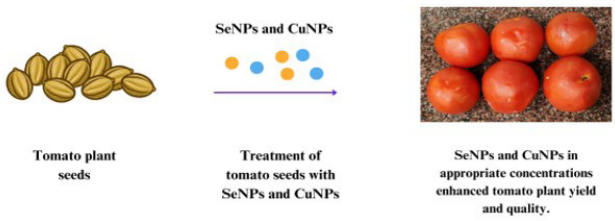


Figure 9: The schematic effect of Se NPs and Cu NPs on tomato plants.

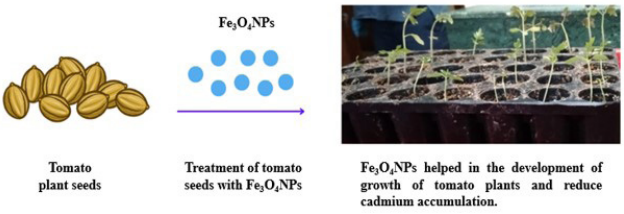


Figure 10: The schematic effect of nano-Fe_3O_4 on tomato plants.

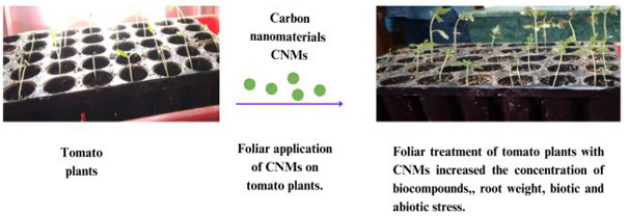


Figure 11: The schematic effect of CNMs on tomato plants.

Selenium, being chemically identical to sulfur, is hard to distinguish by plants. Selenium administration at low concentrations has been proven to improve plant growth, fruit quality, and tolerance to various stress situations. Selenium is hazardous to plants at higher concentrations and alters plant morphology and anatomy. Cu NPs, on the other hand, have received great attention in terms of their effects on plants and have been shown to have beneficial effects at low doses. To employ both Cu NPs and Se NPs at different concentrations to examine their effect on tomato fruit yield, quality, and antioxidant capacity (Figure 9). Se NPs increase tomato plant yield, but when combined with Cu NPs, they have the opposite effect and, in certain cases, may even lower the yield. The administration of Se NPs and Cu NPs boosts the non-enzymatic (GSH, flavonoids, and vitamin C) and enzymatic antioxidant systems as well as the chlorophyll content in tomato plant leaves. Additionally, they improve the firmness, titratable acidity, and total soluble solids, as well as the commercial and nutraceutical quality of fruits. To increase the productivity of tomato crops, particularly for producing higher-quality tomatoes, Se NPs and Cu NPs may be an effective choice. According to the studies, 10 mg/L of Se NPs boosted the yield of tomatoes by up to 21%. The concentration of important components in the leaves and fruits of the tomato plants was enhanced by Se NPs and Cu NPs. To increase tomato productivity and quality, a blend of Se NPs and Cu NPs at appropriate concentrations may be a feasible option [38].

Using various concentrations of magnetic NPs nano-Fe_3O_4, Zadeh et al. [39] aimed to examine their impact on tomato plants (Figure 10) under cadmium exposure. The findings suggest three possible routes for NPs to contribute to the decrease in cadmium-induced stress: (i) minimizing cadmium accumulation in both root and shoot structures; (ii) reducing oxidative stress due to reduced cadmium buildup; and (iii) governing the assimilation of nutrients with antioxidant characteristics. Exposure to cadmium increased MDA, proline, and H_2O_2 levels while decreasing critical nutrients, photosynthetic efficiency, and growth metrics in tomato plants. On the contrary, the use of 20 mg/L nano-Fe_3O_4 exhibited the ability to reduce cadmium buildup while increasing nutritional absorption, alleviating the negative consequences of cadmium toxicity. However, it is vital to keep in mind that this concentration of 20 mg/L nano-Fe_3O_4 may simultaneously boost plant growth while also altering the plant's defensive systems in response to cadmium-induced toxicity [39].

Another fascinating study was done by Garcia et al. [40]. Instead of conventional metal NPs, they developed a new tactic for stress relief in tomato plants (Figure 11) utilizing CNMs in 2019. Their research looked at the effects of foliar and drench sprays of different doses (10 - 1000 mg/L and a control) of CNTs and graphene on the antioxidant reactions of tomato saplings. The findings revealed that employing CNMs increased both dry and fresh root weights. CNMs boosted the amounts of many chemicals in tomato seedlings, including proteins, enzymes, phenols, flavonoids, ascorbic acid, and photosynthetic pigments. There was also a hike in the amounts of antioxidant enzymes and proteins. The findings imply that tomato seedlings' antioxidant defense system may be increased, which could contribute to improved immunity to various types of abiotic or biotic stress. Furthermore, because there were no negative effects on biomass production, no toxicity was seen for any amount of CNMs administered. As a result, using carbon-based nanomaterials to induce resilience to diverse stressors in tomato plants might be a potential alternative [40].

Several studies on the applications of Cu NPs in plants show that they stimulate the antioxidant system and tolerance to saline stress in plants. Following this, it was investigated that biochemical and agronomic responses of tomato plants (Figure 12) to salt stress, with a particular focus on the impacts of Cu NPs administered to the leaves. The study discovered that variations in the Sodium (Na^+)/Potassium (K^+) ratio were associated with decreased growth and development in tomato plants exposed to salt stress. The negative effects of salt stress on tomato plant development were severe. However, the nega-

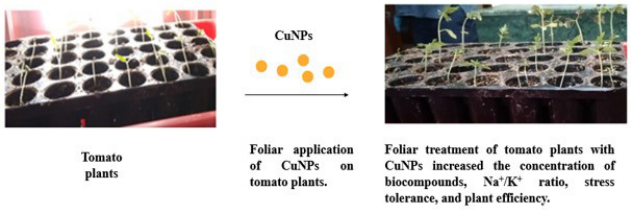


Figure 12: The schematic effect of Cu NPs on tomato plants.

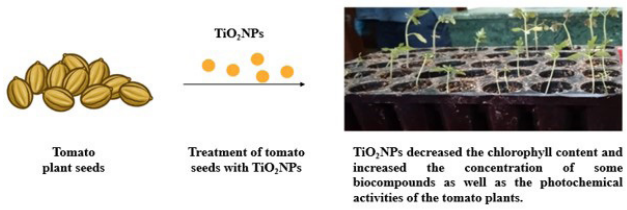


Figure 13: The schematic effect of TiO_2 NPs on tomato plants.

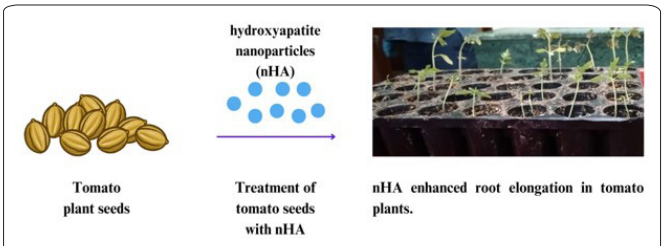


Figure 14: The schematic effect of nHA on tomato plants.

tive effects were minimized by the foliar spray of Cu NPs (250 mg/L), which enhanced efficiency as well as the Na^+/K^+ ratio. The introduction of Cu NPs resulted in increased copper levels in the tissues of salt-stressed tomato plants. As a result, the increased copper concentration increased the phenol content in the leaves while also increasing the amounts of glutathione, phenols, and vitamin C in the fruit as compared to the placebo group. Similarly, enzyme activity for glutathione peroxidase (GPX), superoxide dismutase (SOD), phenylalanine ammonia lyase (PAL), catalase (CAT), and ascorbate peroxidase (APX) increased in leaf tissues. Cu NPs applied by spraying onto the leaves seemed to improve stress tolerance in tomatoes encountering salt issues by boosting antioxidant systems inside the plant. The results of these findings clearly suggest that foliar spraying of Cu NPs is a promising technique for regulating and perhaps minimizing the negative effects of salt stress on tomatoes [29].

The photochemical and physiological effects of exposure of tomato plants to nano-TiO_2 (Figure 13) were examined. In a hydroponic system, tomato plants were subjected to 100 mg/L nano-TiO_2, and physicochemical changes brought on by high irradiance on nano-TiO_2 were observed. A detailed verification of nano-TiO_2 presence on leaves was undertaken utilizing a variety of electron microscopy techniques to produce strong confirmation of nano-TiO_2 accumulation within plant cells and subsequent translocation from the roots. The evaluation included phenotypic and physiological characteristics such as pigment quantity, rate of growth, fruit production, colour change, and enzyme activity. A rapid decrease in chlorophyll content, increased carotenoid, and anthocyanin concentrations, increased enzymatic action, and an astounding eight-fold rise in fruit output were all seen because of the combination of high irradiance with nano-TiO_2 exposure. An ultraviolet-visible light spectrometer revealed that the photochemical activities of the nano-TiO_2-treated tomato plants increased. This increase in photochemical activity is most likely due to the amplification of natural pigments functioning as sensitizers, thereby increasing the absorption process [41].

Hydroxyapatite [$Ca_{10}(PO_4)_6(OH)_2$] nanoparticles (nHA) have advantages over other nanoparticles due to their inherent biodegradability and biocompatibility since it is the basic component of human teeth and bones. Thus, when contemplating open-field NPs applications, the safe biologic profile of nHA should not cause worry for human or environmental health. Yet, no comprehensive investigations on the impact of nHA on plants have been conducted, in the year (2019), Marchiol et al. [42] used tomato plants as a model to explore the functions of various nHA solutions stabilized with carboxymethylcellulose. Their research looked at how various treatments affected germination, seedling development, and the metabolic activities of tomato plant life (Figure 14). It was shown that whereas root elongation is greatly encouraged by increasing nHA concentrations, the percentage germination of the plant is unaffected. In hydroponics, tomato plants exposed to nHA did not experience phytotoxic effects. The study indicated that carboxymethylcellulose-stabilized nHA may serve as a multipurpose asset, acting as a supply of phosphorus and a carrier for many other compounds and elements. Notably, even at extremely high doses, this chemical combination was found to be favorable for the model plant [42].

QDs have been extensively utilized in the electronics sector, cell imaging, and targeted delivery of drug in recent years, and they may be introduced to the surroundings through waste disposal. Mung bean (*Vigna radiata* L.) is an economically significant food legume, while tomato (*S. lycopersicum* L.) is a globally important vegetable. Due to lack of research on the effects of graphene quantum dots (GQDs), Feng et al. [43] investigated the different biochemical and physiological responses in tomato plant seedlings and mung bean (*V. radiata* L.) caused by GQDs at 250 - 1500 mg/L. The outcomes demonstrated that both exposed seeds may still germinate normally (Figure 15). The GQDs did, however, negatively affect the seedlings' development after germination, with mung bean being more susceptible than tomato. Following a two-week exposure period in hydroponic studies, the right concentration of GQDs resulted in a spike in chlorophyll deposition inside tomato and mung bean seedlings. GQDs (1000 - 1500 mg/L) increased the concentrations of H_2O_2, MDA, proline, GSH, CAT, and glutathione reductase, as well as the enzyme activity of CAT and glutathione reductase, in seedlings of both species. Moreover, GQD penetration into plants was detected. The findings revealed that both kinds of plants responded negatively to increased GQD concentrations, with mung bean seedlings being more susceptible than tomato seedlings. Additionally, the issue of nano-contamination was raised, and the consequent issues with food safety call for more research [43].

Since Se NPs are proven to have outstanding biological

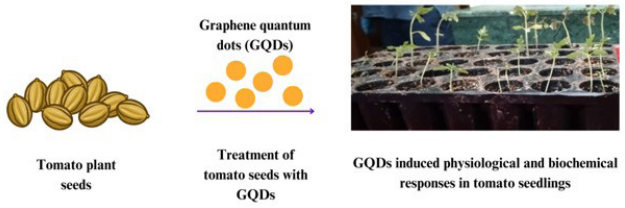


Figure 15: The schematic effect of GQDs on tomato plants.

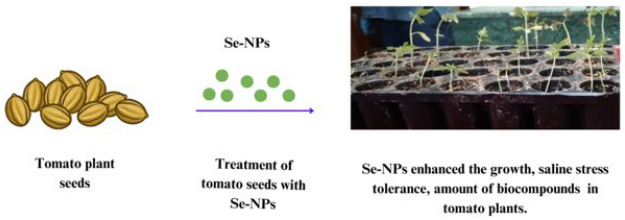


Figure 16: The schematic effect of Se NPs on tomato plants.

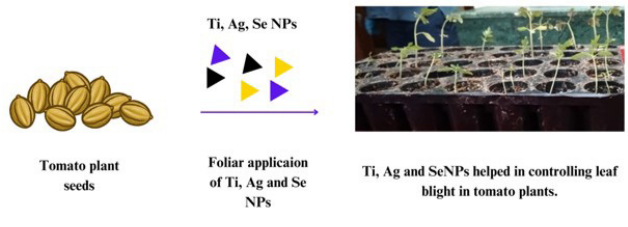


Figure 17: The schematic effect of Ti NPs, Ag NPs, and Se NPs on tomato plants.

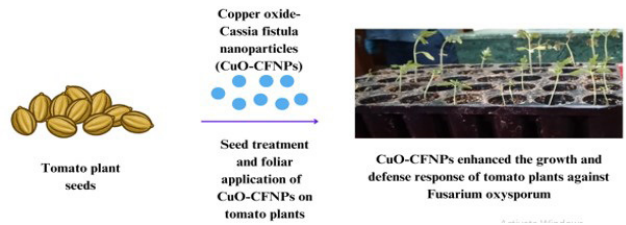


Figure 18: The schematic effect of CuO-CFNPs on tomato plants.

characteristics and are less toxic to plants. They serve as a favorable option for their application to the crops. Considering this, Morales-Espinoza et al. [44] evaluated the impact of Se NPs (1, 5, 10, and 20 mg/L) on tomato growth (Figure 16), fruit quality, and antioxidant responses while cultivated in a salt environment. The results showed that using Se NPs had an effective effect on tomato plant salinity. Furthermore, aerial biomass and production were boosted. The percentage of phenol content in the leaves grew, as did the amounts of antioxidant substances present in tomato fruits (including lycopene, carotene, flavonoids, and phenols). Furthermore, Se NPs improved enzymatic activity in tomato plant fruits and leaves, indicating that Se NPs could boost a plant's tolerance towards salt-induced stress [44].

In the following year, El-Gazzar and Ismail. [45] investigated the potential use of NPs, especially those containing TiO_2, Ag, and Se, for treating a disease of leaves in tomatoes caused by the fungus *Alternaria alternata*. Various quantities of these NPs were employed and evaluated against *A. alternata*, with promising results as antifungal agents against the illness. These NPs were probed for their effect on fungal growth and morphology, as well as their capacity to hinder spore germination and impede mycelial growth. The researchers also looked at how these NPs affected the severity of leaf blight in tomato plants (Figure 17). These NPs effectively inhibited spore germination and mycelial growth in tomato plants, reducing disease symptoms. The NPs were also shown to have no phytotoxic effects on tomato plants, indicating that they may be employed to prevent leaf infection [45].

Cu NPs are advantageous in plant development. They attract a lot of interest when they are synthesized using a plant-mediated technique since it is a cheap and environmentally friendly way to generate them. Inspired by this, Ashraf et al. [46] developed CuO-*Cassia fistula* NPs (CuO-CFNPs) using an ecologically friendly approach, demonstrating remarkable efficiency as antifungal agents against the soil-borne phytopathogen *Fusarium oxysporum*. The research confirmed the fungicidal capabilities of CuO-CFNPs in a dose-dependent manner using *in vitro* studies. The association between the produced NPs and fungal cells caused notable changes in the shape of the fungal mycelia as well as the formation of ROS at the outermost layer of the fungal cell membrane. Furthermore, by improving the growth factors, these NPs applied to tomato plants (Figure 18) in a greenhouse greatly decreased the incidence of *Fusarium* wilt on those plants. Tomato fruits increased in size and quantity after treatment with CuO-CFNPs (5 - 350 µg/ml), which also boosted the storing of bioactive substances. Additionally, there were no obvious negative effects on plant productivity or yield from the uptake of these NPs. Because of their competitive advantage, these innovative nanoscale materials have the potential to improve food security through sustainable agriculture [46].

Ag NPs are popular antibacterial agents in medicine. However, data on the impact of Ag NPs on the most prominent phytopathogenic agents is scarce. Zakharova et al. [47] investigated the effect of aqueous distribution of sodium tallow amphopolycarboxyglycinate (STAPCG) stabilized Ag NPs at a dosage level of 100 ppm on tomato plants (Figure 19) development, growth, and efficiency. The study found that four times the amount of Ag NPs applied to plants throughout the growth season improves the surface area of the leaves, which leads to an improvement in photosynthetic efficiency. Therefore, tomato plants administered Ag NPs produced more tomatoes than tomato plants in the control trial. It has been discovered that nano-Ag treatment increases the activity of enzymatic antioxidants. The research on plant tissues revealed that Ag bioaccumulation was identified in tomato leaves but not in tomato fruits. These findings might be utilized to create novel plant protection solutions based on colloidal Ag [47].

Malandrakis et al. [48] studied the influence of CuO NPs, Cu NPs, ZnO NPs, and Ag NPs (Figure 20) on tomato plant development, physiological parameters, and symbiotic interactions with the endophytic FsK (*Fusarium solani*) strain. Metal NPs had a substantial detrimental impact on tomato plant physiology and growth, as measured by dry mass, photosyn-

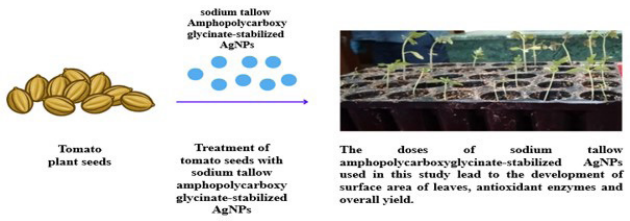


Figure 19: The schematic effect of STAPCG-stabilized Ag NPs on tomato plants.

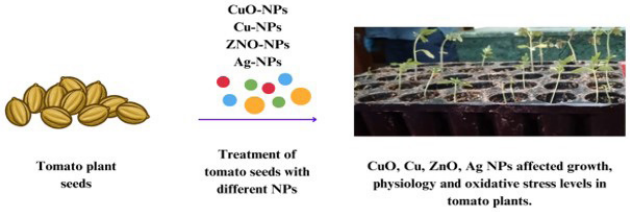


Figure 20: The schematic effect of CuO NPs, Cu NPs, ZnO NPs, and Ag NPs on tomato plants.

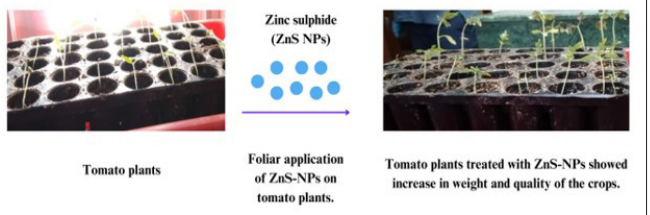


Figure 21: The schematic effect of ZnS NPs on tomato plants.

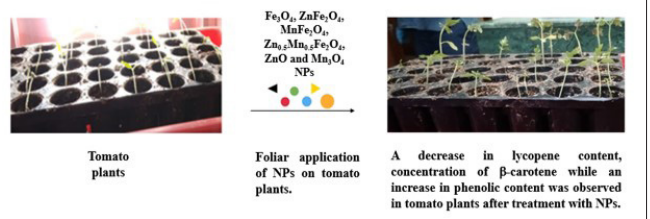


Figure 22: The schematic effect of Fe_3O_4, $ZnFe_2O_4$, $MnFe_2O_4$, $Zn_{0.5}Mn_{0.5}Fe_2O_4$, ZnO, and Mn_3O_4 NPs on tomato plants.

thetic pigment levels, and oxidative stress responses. Sublethal doses of NPs and their counterparts had no effect on *F. solani* colonization of tomato roots. Nonetheless, earlier study has revealed that intimacy of *F. solani* with chemicals such as zinc sulphate ($ZnSO_4$), ZnO NPs, and CuO NPs may result in a possible decrease in metallic toxicity [48].

Zinc sulfide (ZnS) NPs exhibit non-toxic behavior and a non-oxide exhibiting exceptional properties. Kanwal et al. [49] decided to address the synthesis, characterization, features, and foliar application (Figure 21) of ZnS NPs as a nano-fertilizer in tomato plant development. Plants treated with nano-fertilizer boosted the quality and weight of the crops they produced. This study proved the capability of foliar treatment with ZnS nano-fertilizer for tomato plant growth up to the optimum applied dosage. Tomato fruit yield and nutritional level were significantly boosted by a nano-calcium treatment at a dose of 0.5 g/L. However, if the concentration exceeds the optimized level, it imposes an inhibitory effect on agricultural plants, limiting crop development and yield [49].

A substantial body of research has emerged that evaluates the possible uses and effects of diverse metal-based nanomaterials. There has been limited research into the impact of hybrid ferrite materials on tomato plant growth and fruit yield. Considering this, Cantu et al. [50] synthesized Fe_3O_4, $ZnFe_2O_4$, $MnFe_2O_4$, $Zn_{0.5}Mn_{0.5}Fe_2O_4$, ZnO, and Mn_3O_4 NPs and delivered them at 250 mg/L to tomato plants (Figure 22) by foliar process to examine their impacts on tomato fruit dietary value. After administration of NPs, there was a reduction in lycopene content in tomato plants, but no significant differences were identified after 15 days of storage when compared to the control. Moreover, the carotene level decreased while the overall phenolic content increased along with the increase in sugar content in fruits. This study shows that NPs can have both favorable and negative impacts on the nutritive content of fruits of tomato. This emphasizes the need for safety in such efforts, as well as more extensive investigations to examine and understand the underlying genetic basis of these effects [50].

Some previous research explored the phytotoxicity of rare earth oxide nanoparticles (REONPs) on tomato root elongation. However, there has been little focus on the REONPs adsorption by the plants. These investigations provided a vague insight into the interaction of Y_2O_3 (yttrium oxide) NPs with other plants (rice and maize) and the influence of soluble yttrium (Y^{3+}) released from the Y_2O_3 NPs. As a continuation of studies, Wang et al. [51] studied the anatomical toxicity, absorption, and transfer of Y_2O_3 NPs in tomato seedlings in various hydroponic conditions (1 - 100 mg/L) (Figure 23). Y_2O_3 NPs had a phytotoxic consequence on the physiology, morphology, germination, and free radical stress of tomato seedlings. With increasing concentrations, Y_2O_3 NPs (> 10 mg/L) and soluble Y^{3+} (19.2 mg/L) decreased elongation in root, bud activity, soluble proteins, chlorophyll amount, and superoxide dismutase while accelerating malondialdehyde and proline in the plant. Y_2O_3 NPs demonstrated greater adverse effects on tomato seeds than soluble Y^{3+} in all treatments. The addition of Y_2O_3 NPs drastically reduced root and shoot biomass in tomato seedlings, with a marked propensity to concentrate inside the root system. Furthermore, PLS-SEM demonstrated that NPs concentration has a considerable detrimental impact on plant shape and physiology, resulting in a change in plant biomass. This work identified a potential mechanism for Y_2O_3 NPs absorption, phytotoxicity, and translocation in tomato seedlings [51].

Early blight disease triggered by *Alternaria solani* is a big concern for tomato farmers, resulting in considerable crop losses. Because of their potential antifungal efficacy, Ag NPs have lately acquired popularity. Considering this, Ansari et al. [52] investigated the potential of environmentally friendly synthesized Ag NPs to improve tomato plant growth, fruit output, and immunity to early blight infection. Ag NPs synthesized from neem tree leaf extract were shown (Figure 24) to be helpful in serving plant development, as demonstrated by a considerable increase in the height of the tomato plant,

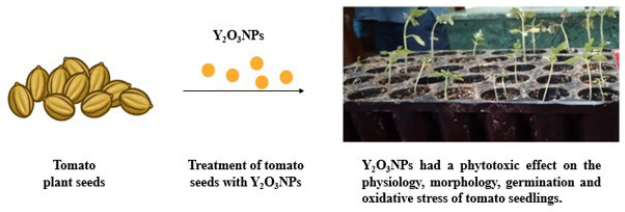


Figure 23: The schematic effect of Y_2O_3 NPs on tomato plants.

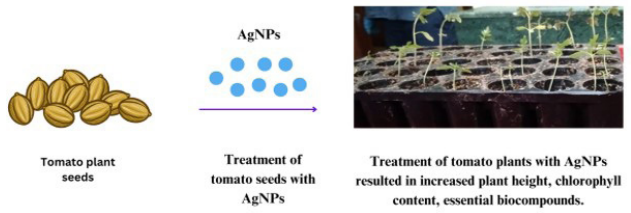


Figure 24: The schematic role of Ag NPs on tomato plants.

chlorophyll content, dry and fresh weight, and other important bioorganic compounds. Furthermore, as compared to control plants, those exposed to Ag NPs showed a substantial decrease in disease incidence and disease severity index, while simultaneously magnifying the antioxidants' enzymatic activity of PAL, CAT, PO, PPO, SOD, and APX, demonstrating that they can be used as an ecological plant protection solution. These outcomes imply that employing green synthesized Ag NPs is a potential technique for increasing tomato plant growth and output while being defensive for them against the early blight disease [52].

The NPs influence several morphological, physiological, and genotoxic alterations in the life cycle of plants. Furthermore, it is clear from this review that various NPs have been formulated and successfully utilized for tomato plants to improve their stem, leaf, and fruit quality. Notably, balancing growth rate and phytotoxicity in tomato plants remains a difficulty in the design of NPs, as a very promising remedy may occasionally lack the required uniqueness. Hence, more research is necessary to fully understand the processes behind the connection between NPs effects and plant growth. Transitioning from lab-scale investigations to practical usage necessitates resolving difficulties such as sample complexity and phytotoxicity. It is critical to ensure the nanoparticles cost of production, stability, and activity over long periods of time, especially for outdoor usage.

Conclusion

Only a few studies have been executed to demonstrate that NPs exert a beneficial role on plant growth and development. Additionally, current research has shown that using NPs can have greater benefits for plant phenology, fruit yield, chlorophyll contents, and nutritional quality than soil-mediated applications. It is also clear from previous studies that minimum concentration of NPs can induce significant effects on tomato plant life cycle. Hence, NPs incorporation in commercial fertilizer might not change over all cost of production of fertilizer. Furthermore, it is worthwhile to note that the efficacy of NPs may vary based on the chemical composition and concentration of NPs used, as well as the method of implementation. To ensure the safe and successful usage of NPs in plants, the dose and method of application must be thoroughly evaluated. Nevertheless, because of their extraordinary capabilities, several research have been executed to scrutinize the toxicological effects of NPs on plants. Interestingly, research on the beneficial effects of NPs on plants is still in its early stages. Therefore, the generation and application of new NPs with improved chemical and biological properties could serve as a 'magic remedy' in plants to regulate their growth and fruit quality, which is a potential area of research.

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Conflict of Interest

None.

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