

The effects of cobalt and titanium nanoparticles on plant health

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ABSTRACT

Plants are components of natural resources that have contributed in the maintenance of ecosystem. They are essential for human nutrition and rich sources of raw materials for other human needs and economic values. Over the years, nanoparticles have been essential in improving plants and making plant and plant products affordable and accessible for humans and animals. The nanomaterials consistently used include zinc, silver, gold, copper, and iron. Little attention has been paid to cobalt-based nanoparticles and titanium-based nanoparticles. These seemingly neglected nanoparticles surreptitiously get into the plant tissues and disrupt the morphology, metabolism, physiology, and growth processes of plants. The manipulations of cobalt oxide nanoparticles (Co₃O₄NPs) and titanium oxide nanomaterials (TiO₂NPs) can be beneficial or detrimental depending on the mode of formulations, concentration, particle size, and application process. The integration of the green-based biological molecules to Co₃O₄NPs and TiO₂NPs improved plants. These nanoparticles colonize the plant tissues and accumulate for a long time, thereby exerting certain effects on plants. Upon consumption, these materials transfer these accumulated deleterious effects to humans and animals, who are the consumers, subsequently affecting their respiratory, reproductive, excretory, and endocrinal systems. The study examines cobalt and titanium-based oxide nanoparticles and their roles in regulating plants based on effects on genetic makeup, growth, and physiological and metabolic processes. It establishes the roles of Co₃O₄NPs and TiO₂NPs in the food chain and the corresponding effects on humans. The study also compares the merits and demerits of the two nanoparticles and makes a feasible approach to maximise their potential for plant health.

Introduction

Plants are essential resources needed for their medicinal properties (Miransari et al., 2025; Rahman et al., 2022), ecstasy (Danquah et al., 2023), food and nutrient (Zhang et al., 2024), sources of raw materials (Boichuk et al., 2024), and maintenance of a healthy and green environment (Kachenchart and Panprayun, 2024). The functional assessment of plants is a veritable medium that provides necessary information for agricultural practices and the health status of humans (Pittol et al., 2017). Plants, during interactions with microbiomes in the soil, get colonized by pathogenic microbes and their metabolites, which interfere with nutrient absorption, increased disease spread, and heightened adverse environment-based effects (Olanrewaju et al., 2024).

Appropriate regulation of plant health is not only beneficial to plants but also essential to humans. Therefore, the processes that promote the upward development of plants should be encouraged since our health is indirectly linked to plant or their products. Plant health ensures food availability commensurate with the United Nations-approved standard safety. It protects lives and provides rapid economic upsurge in developing and developed nations (Gullino et al., 2024).

Nanoparticles are components with sizes of less than 100 nm. They exist in different sizes and structures, which subsequently contribute to their activity in plant development (Satya et al., 2024). They have been used in agriculture, medicine, water management, environmental assessment, dietary bolsters, and the development of antifungal, antibacterial, antiviral, and antiprotozoal agents (Altammar, 2023). In agriculture, the integration of nanoparticles is responsible for improving

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the nutrients of plants via fertilizer formulations, plant growth, upward maintenance of dry and fresh biomass, and photosynthesis (Joudeh and Linke, 2022). They have been used to improve the yield of crops, growth development, and metabolic processes. In another contrasting figure, they prolong their phytotoxicity status or improve the plants in all ramifications. Some nanoparticles promote optimum plant yields and do not develop any physiological dysfunction in plants (Alabdallah et al., 2024).

Titanium dioxide nanoparticles have been both beneficial and harmful to plants. At low concentrations, they promote the plants' developmental processes; at high concentrations, they become toxic. Their ability to exhibit dual characteristics is dependent on the types of plants, the nature of the particles, and the surrounding factors (Alabdallah et al., 2024). Cobalt oxide nanoparticles, in the same vein, share characteristics similar to those of titanium oxide nanoparticles; however, they provide more severe effects than titanium oxide nanoparticles (Alinovi et al., 2017). Due to the extent of their toxicity in both plants and the environment, they are hardly studied for potential benefits. For instance, at elevated concentrations, developmental processes in plants are inhibited; the growth process and food synthetic mechanism via a photosynthetic process are reduced. Plant metabolism, nutrient absorption, and product output are also affected (Wang et al., 2024).

Both titanium and cobalt oxide nanoparticles have their 'bad' and 'good' sides. However, there is no in-depth discussion on their role in regulating plant health. Attention has usually been paid to animals, humans, and microorganisms, with only a few studies on plants. Several published papers have evaluated their roles as drug carriers, treatment agents, and water treatment. Therefore, this review outlined the up-to-date effects of the nanoparticles of titanium and cobalt oxides in plants, provided solutions to improve their beneficial applications, and projected the best approaches to reduce their deleterious effects.

Plant health

Plants are living components of the ecosystem that do not exist independently of themselves (Harman et al., 2021). There are usually interactions between plants, animals, and other ecological factors components of the ecosystem (Rizzo et al., 2021). The meaning of 'plant health' is not entirely the same as that of human health due to the diversity of plant species and the fact that there is only one species for humans. It goes beyond linking it to mere free microbial contaminants or diseases in plants. The different conceptualized meanings of plant health are based on the specificity of naturalism and normativism, as reported by (Döring et al., 2012). The environmental, physiological, morphological, and growth assessment of different plant tissues are some parameters that determine the health of plants (Silva Filho et al., 2024; Zhang et al., 2023). Therefore, plant health is the maintenance of the functional capabilities in plants induced by sustained ecological and gene-based factors (Döring et al., 2012). Plants forms an integral part of "One Health" since they are co-contributors to the sustenance of humans and animals (Rizzo et al., 2021). The continued contact of plants with metallic ions (Ahmed et al., 2021; Bhat et al., 2024), nanoparticles (Rehman et al., 2025), chemicals, microbial pathogens, and mutagens (Ghosh et al., 2019) results in physiological and morphological damage to the overall well-being of plants. The contamination of soil, too, can promulgate deleterious effects on plants since plants benefit directly from soil through nutrient absorption, assimilation, and metabolism. The accumulation of trace nanoparticles, including TiO₂NPs, attacks the soil microbiomes that are beneficial to plants and degrades them, thereby denying plants their necessary nutrients (Gade et al., 2023).

Nanoparticles

Nanoparticles are molecules whose size is less than 100 nm. They vary in size, shape, and form, perhaps responsible for their surface area

and as drug carriers (Öztürk et al., 2024). These shapes could be regular or irregular (Joudeh and Linke, 2022). Their different structural forms determine their rate of reaction and durability (Khan et al., 2019) and contribute to their activity in plant health by improving soil quality, mineral assimilations, and disease control (Nandini et al., 2023). NPs are classified based on structure, chemical constituents, and physical attributes (Khan et al., 2019). Generally, NPs can be either organic or inorganic. Organic NPs are developed from biological matters with carbon content, while inorganic are formulated with ions, atoms, or metals. Inorganic NPs are water-soluble, well-matched with living cells, stable against chemical or physical changes, and have an increased surface area to volume ratio due to their small sizes. On the other hand, organic NPs are nontoxic and decomposable, producing a more suitable interface with living tissues than inorganic NPs (Abdel-Megeed, 2025). NPs can be grouped as metal-based NPs, ceramic-based NPs, carbon-based NPs, semiconductor-based NPs, polymer-based NPs, and fat-based NPs (Altammar, 2023; Khan et al., 2019). NPs of all types have been used as drug carriers, antimicrobial agents, disease detectors, and treatment enhancers due to their structures and sizes (Abdel-Megeed, 2025).

NPs have been massively mobilized to regulate nutrient and water absorption in plants (Sodhi et al., 2025), plant cell genetic and bimolecular compositions, growth processes (Satya et al., 2024), nutrient quality in the soil (Zhang et al., 2024), outburst of plant microbes and diseases (Verma et al., 2024), and phytotoxicity (Rajput et al., 2019). Recently, Gunasena et al. (2024) evaluated some metal-based nanoparticles and their roles in plant cell culture propagation, microbial sterilization, embryonic development, stimulation of induction of callus formation, and phytotoxicity. According to the authors, these roles are commonly used in agriculture to sustain lives and ensure food security.

Cobalt-based nanoparticles and formulations

Cobalt-based nanoparticles are nanoformulations produced majorly by reacting certain concentrations of cobalt salts commonly referred to as initiator compounds such as cobalt (II) nitrate hexahydrate (Co(NO₃)₂·6H₂O) (Alshareef and Albalawi, 2024; Talib al Alawi et al., 2024; Tatarchuk et al., 2024), cobalt diacetate tetrahydrate (Co(CH₃COO)₂·4H₂O) (Rasool et al., 2025; Tamil Thendral et al., 2024), and oxide of cobalt (Co₃O₄) with distilled water or other chemicals like ethyl alcohol, manganese diacetate tetrahydrate and sodium sulfide nonahydrate (Na₂S·9H₂O) depending on the cobalt salt used. Followed by alkalization, drying, calcination, grinding, and storage (Alshareef and Albalawi, 2024). The resultant products usually are Co₃O₄NPs and CoFe₂O₄NPs, and they are used as sources of nanoformulations based on the research interests of the researcher. Bagdeli et al. (2024) synthesized CoFe₂O₄NPs by combining CoCl₂·6H₂O with FeCl₃·6H₂O, while López-Luna et al. (2018) formulated it by precipitating Co(NO₃)₂ with Fe(NO₃)₃·9H₂O and later reacted the mixture with FeSO₄·7H₂O before dissolving the content in water. In some instances, other transition elements like manganese could be added in the form of manganese ions to improve the outcome of the nanoparticle, MnCo₂O₄NPs (Tamil Thendral et al., 2024), or the addition of iron and silver as we have in CoFeAgNPs (Abdelsattar et al., 2023), which is dependent on the interest of the researcher and the experimental design.

Cobalt is a transition element with variable oxidation states of Co²⁺ and Co³⁺ (Banerjee and Chattopadhyay, 2019). They constitute vitamin B12 and can be found in the environment in small quantities (Huang et al., 2021). A small concentration can elicit changes in plant health and affect other natural agricultural pathways. Their presence in soil regulates plant development, nutrient absorption, and metabolism (Hu et al., 2021). They serve as cofactors or coenzymes to basic enzymatic and metabolic processes in plants (Minz et al., 2018).

The Co₃O₄NPs have consistently been used in biological-based studies at low concentrations due to their benefit. Their availability makes them the most sought-after cobalt-based nanoformulations, and

their efficacy against pathogens has been confirmed (Alshareef and Albalawi, 2024). Based on the interest of a researcher, cobalt-based nanoparticles can be modified into several ions, forms, and sizes (Kong et al., 2020; Ma et al., 2024). The efficacy of cobalt-based nanoparticles is improved by adding plant extracts (Blessymol et al., 2024; Din et al., 2024), plant-based products (Abbas et al., 2021), microbial components (El-Wahab et al., 2025), and synthetically modified biological products like chitosan (Kiani et al., 2021). For instance, chitosan has improved the efficacy of Co₃O₄NPs (Kiani et al., 2021) or CoFe₂O₄NPs. In the study of Tatarchuk et al. (2024), prepared extracts of plants like *Solanum lycopersicum*, *Diospyros virginiana*, and *Gingko biloba* were specifically added to the formulation to produce green-based nanoparticles. Interestingly, the nature of surface area determines the level of their interactions with biological surfaces and would further enhance their efficacy (Ma et al., 2022).

Titanium-based nanoparticles and formulations

The formulation of titanium-based nanoparticles is necessary to provide a holistic approach for future researchers and probably set opportunities for improvement. The preparation of titanium dioxide nanoparticles has been reported by Öztürk and Çitak (2022) and Seman et al. (2022) in their studies. Öztürk and Çitak (2022) outlined the 'sol-gel method, hydrothermal method, solvothermal method, direct oxidation method, chemical vapor deposition, physical vapor deposition, electrochemical anodization, and biological syntheses as the groups, while Seman et al. (2022) reported six (6) techniques, namely 'sol-gel method, instantaneous synthesis method, solvothermal method, microwave-assisted synthesis, simple mixing, and precipitation methods.' All the methods outlined earlier are encapsulated in chemical, physical, and biological processes (Al-darwesh et al., 2024). All reactions of sol-gel, precipitation, emulsion, and colloid formation that involve chemical formulations with required solvents are chemical-based.

The integration of green synthesis into the reaction process is biological-based, and another process that requires sound, photobleaching, and thermal is physical-based (Al-darwesh et al., 2024). Although Öztürk and Çitak (2022) and Seman et al. (2022) reported their methods differently, they emphasized that the sol-gel method is the most widely used (Sakka, 2013). Ninety per cent of the authors of the articles evaluated centred their titanium dioxide nanoparticle synthesis on the chemical process. Therefore, since the chemical process has been widely adopted in most studies, we shall briefly assess the process. In titanium dioxide nanoparticles, the initiator compounds used in most studies include titanium tetraisopropoxide (Ti(OCH(CH₃)₂)₄) (Blessymol et al., 2024), titanium chloride (TiCl₄) (Rajkumari et al., 2019), tetra-n-butyl Orthotitanate (CH₃CH₂CH₂CH₂O)₄Ti (Öztürk and Çitak, 2022), titanil hydroxide (Ti(OH)₂), titanium oxysulphate (TiOSO₄) (Aslam et al., 2021) and titanium dioxide (TiO₂) (Abbas et al., 2021). These chemical compounds are formulated with deionized water or alcohol (Aslam et al., 2021). Some authors (Chahardoli et al., 2025; Ma et al., 2024; Rehman et al., 2025), instead of synthesizing the titanium oxide nanoparticles, preferred to purchase them from manufacturers, probably to ascertain absolute purity. Blessymol et al. (2024) dissolved Ti(OCH(CH₃)₂)₄ in distilled water for about half an hour until white pigmentations were formed. The water was removed at 70 °C before calcination occurred at 200 °C. The same procedure of titanium dioxide nanoparticle preparation of titanium dioxide initiator compound dissolution, drying, and calcination was carried out by Pittol et al. (2017).

As discussed earlier on the formulation model of cobalt-based nanoparticles with supplemental biological molecules, the efficacy of titanium-based nanoparticles can also be improved by formulating the titanium nanoparticles with microbes and plant extracts. Aslam et al. (2021) reported that using green-based phytoconstituents as biomolecules provided plants with improved 'health' processes in all

ramifications.

Green synthesis versus chemical-based synthesis

The green synthesis model has been used over the years for cobalt oxide-based (Govindasamy et al., 2022) and titanium oxide-based nanoparticles (Singh Jassal et al., 2022) due to their huge advantages over the chemical process model. These conventional nanoparticles have been identified by Saberi Riseh and Gholizadeh Vazvani (2024) in agriculture to enhance plant development, eliminate plant diseases, and provide resistance to toxic chemicals and metallic substances. The green synthesis model is the conventional approach that incorporates biomolecules onto the surface of nanoparticles for enhancement (Annu et al., 2024). The green synthesis model has been implicated in the synthesis of cobalt and titanium nanoparticles. Plants, microorganisms, animals and their products are major bio-components of the green synthesis model (Alsaiaari et al., 2023). Tatarchuk et al. (2024) in one of their studies synthesized CoFe₂O₄NPs using a green synthesis model, particularly a plant-based approach. They identified the availability of raw materials, cost effectiveness, easy preparation and safety in the green conventional model as comparative benefits over the chemical method. They identified plants like tomato, Ginkgo biloba, flax and huge phytoconstituents present in their leaves, seeds, fruits, stems and roots as major and useful green synthesis methods. According to them, the phytoconstituents are biomolecules that provide stability to the nanoparticles and eliminate or decrease harmful effects associated with the CoFe₂O₄ chemicals. Singh (2022) reported that the synthesis of CoO-NPs using the plant-based green method is a promising area of research that provides less toxic effects to target cells and the environment. They can be sustained over a period of time with minimal energy. The author inferred that due to the surface area and structural patterns of CoO-NPs created by the plant biomolecules, antimicrobial attributes were enhanced. Among the group of microorganisms that have been used in green synthesis model, fungi are the most preferred for cobalt-based nanoparticles because of their quick growth process and ability to produce huge nanoparticles. The most commonly used fungi are *Aspergillus* species, *Fusarium* species and *Cladosporium* species (Alsaiaari et al., 2023). These attributes were associated with rich proteinous compositions on the fungal cell and the intracellular enzymes. Singh Jassal et al. (2022) reaffirmed that biomolecules from biological sources that constitute the green synthesis model can also be integrated into titanium oxide (TiO₂) to develop nanoparticles with antimicrobial characteristics. Santiago et al. (2023) in an experiment to synthesize titanium oxide nanoparticles using a green synthesis model, extracts of Aloe vera, hibiscus and orange peels were used as biological agents. The result of the study showed that the nanoparticles were effective with strong purity and limited emission of any toxic substance. The study also identified that the efficacy of the nanoparticles, especially those produced from orange peel and hibiscus, was based on their well-defined particle size of 100 nm and round shape. Aravind et al. (2021) compared the efficacy of TiO₂ nanoparticles synthesized chemically and by the green synthesis model. The authors used alcohol as the reducing agent for the chemical process and extracts from the *Jasmine officinale* flower for the biological process. They used the antimicrobial efficacy index as a criterion to grade the performance of the nanoparticles from these two methods. From the result of the study, it was observed that the TiO₂ nanoparticles from the green synthesis model displayed stronger antimicrobial effects than the nanoparticles. Apart from being used in agricultural settings, the authors recommended the green-synthesized TiO₂ nanoparticles to be applied in the environment and biomedicine.

Effects of cobalt-based nanoparticles on plants

Cobalt-based nanoparticles have not been properly studied, especially in their roles in plant health, which encapsulates plant growth, morphology, physiology, and genetic compositions. Data are lacking to

provide an evidence-based study to the agriculturists and botanists properly. For some papers assessed (Balu et al., 2023; Gowtham et al., 2024; Santás-Miguel et al., 2023), the majority of them omitted cobalt oxide nanoparticles in their discussions, as they might have considered them less important. The few that discussed cobalt nanoparticles often focused on the impacts of nanoparticles on animals and humans. Studies with cobalt-based nanoparticles have shown great potential in the overall plant performance and the generality of human and animal health. A study conducted by Govindasamy et al. (2022) showed that *Psidium guajava*-Co₃O₄NPs disrupted the proliferation of mutated HCT 116 and Michigan Cancer Foundation-7 (MCF-7) human cell lines, providing antimicrobial effects against harmful bacterial pathogens that colonize the body surface while becoming harmless to normal human cells. Since our study focuses on plant health, only a few studies will be reviewed between the selected 50 and 200 µg/ml concentrations, Ogunyemi et al. (2023) identified the positive effects of *Hibiscus rosa-sinensis*-based cobalt oxide nanoparticles on the morphology and physiology of *Oryza sativa* plants. In their study, it was confirmed that *Xanthomonas oryzae* pv. *Oryzae* that colonized the plant were eradicated,

the lengths of both roots and stems increased, and the dry and fresh weights of the plant were optimally maintained. Similarly, the photosynthetic roles of PSII of *Arabidopsis thaliana* were evaluated with the interaction of *Hibiscus rosa-sinensis*-based cobalt oxide nanoparticles. The outcome showed that the photosynthetic pathway of PSII was effectively enhanced. The effects of Co₃O₄NPs on the expression of genetic factors virulence B1 (*virB1*) and beta-glucuronidase (*gus*) genes on cell culture of *Catharanthus roseus* grown with *Agrobacterium tumefaciens* was evaluated by Fouad and Hafez (Fouad and Hafez (2020). *A. tumefaciens* was introduced to *C. roseus* to mediate the genetic transformation process in the cell culture. However, the effects of Co₃O₄NPs at 2.5, 5, 7.5, and 10 mg/l enhanced the expression of the *gus* gene while reducing the synthesis of ethylene, an inhibitor of the *virB1* gene. In another study, El-Wahab and colleagues infected potato plants with *Rhizoctonia solani* and exposed them to cobalt *Fusarium solani*-based nanoparticles at 250 and 500 mg/l. Their study identified specific parameters that were improved by the cobalt nanoparticles. The sizes of the plant shoots and roots, including the leaves, increased; photosynthetic pigments optimally improved, and the dry and fresh weights of

Table 1
Effects of cobalt oxide nanoparticles on the health of plants.

Plants	Group of nanoformulation	Concentration of nanoformulations	Conditions	Effects on plant health	References
<i>Oryza sativa</i> <i>s</i> <i>Arabidopsis thaliana</i>	<i>H. rosa-sinensis</i>	50, 100 and 200 µg/ml	The <i>Oryza sativa</i> plant was exposed to <i>Xanthomonas oryzae</i> pv. <i>Oryzae</i> was contaminated, and the rice plant was treated with Co ₃ O ₄ NPs	Co ₃ O ₄ NPs reduced the biofilm formations and inhibited the proliferation of the pathogens. The nanoparticles increased the sizes of the shoots and roots and the dry and fresh weights of <i>H. rosa-sinensis</i> . Increased the photosynthetic process of the photosystem II (PSII) in <i>Arabidopsis thaliana</i>	(Ogunyemi et al., 2023)
<i>Acacia jacquemontii</i> and <i>Acacia nilotica</i>	cobalt oxide nanoballs (Co ₃ O ₄ Nbs)	25, 50, 75, and 100 ppm	The soil where planting <i>Acacia jacquemontii</i> and <i>Acacia nilotica</i> seeds were planted were initially treated with zinc before planting. During germination, the seedlings were later exposed to Co ₃ O ₄ -Nbs and zinc at different concentrations by foliar spray.	At 100 ppm, the root and shoot lengths of both plant species increased significantly, compared to the control. The fresh and dry weights of the plants also increased. The total chlorophyll, chlorophylls a and b increased. Their water and soluble sugar contents enhanced significantly.	(Mahmood et al., 2023)
<i>Catharanthus roseus</i>	ND	2.5, 5, 7.5 and 10 mg/l	The cell culture of <i>Catharanthus roseus</i> was incubated with <i>Agrobacterium tumefaciens</i> to mediate the genetic transformation process.	Co ₃ O ₄ NPs enhanced the genetic transformation of <i>gus</i> and <i>virB1</i> genes in the cell culture of <i>Catharanthus roseus</i> mediated with <i>Agrobacterium tumefaciens</i> .	(Fouad and Hafez, 2020)(Fouad and Hafez, 2020)
<i>Solanum tuberosum</i>	Co ₃ O ₄ .carbendazim-NPs	250 and 500 mg/l	The <i>Solanum tuberosum</i> tubers infected by <i>Fusarium solani</i> were exposed to Co ₃ O ₄ .carbendazim-NPs	Co ₃ O ₄ NPs enhanced the sizes of the shoots and roots; tuber yields improved significantly. The dry and fresh weight of the plant increased.	(El-Wahab et al., 2025)
<i>Triticum aestivum</i>	None	500, 1000, 2000, 4000 and 8000	Wheat plants were treated with cobalt ferrite nanoparticles (CoFe ₂ O ₄ NPs)	CoFe ₂ O ₄ NPs produced deleterious effects on the sizes of the shoots and roots of the wheat plants. They decreased the antioxidant effects (catalase, glutathione, ascorbate, and peroxidase), chlorophylls a and b, carotenoids, and insignificant growth rate differences.	(López-Luna et al., 2018)
<i>Brassica napus</i> L.	None	50, 100, 250, 500, 1000, and 4000 mg/l	The <i>Brassica napus</i> L seeds were treated with Co ₃ O ₄ NPs.	The glutathione, ascorbate, and peroxidase increased. DPPH increased. Chlorophylls a and b and carotenoid reduced. The phytoconstituents increased significantly.	(Jahani et al., 2019)
<i>Glycine max</i> L.	None	0, 0.17 and 16.7 mg/kg	The DT26 <i>Glycine max</i> L. was treated with nanoscale zerovalent cobalt (NZVC).	Increased photosynthetic processes of photosystem II at 0.17 mg/kg. Increased seed development and growth. Improved the chlorophylls a and b; carotenoids remained unchanged compared to control. Increased peptide and fat composition and reduction in starch components.	(Hong et al., 2019)

Key: ND =Not determined

the plants were significantly enhanced. Most enzymes responsible for metabolic and physiological processes in the potato plants increased their activities. In another development, López-Luna et al. López-Luna et al. (2018) examined the effects of dry and fresh $\text{CoFe}_2\text{O}_4\text{NPs}$ in wheat plants. They compared the toxic effects resulting from differences in the morphological characteristics, photosynthetic process, and antioxidants of the plants. Their study confirmed the decrease in the sizes of the shoots, roots, and leaves with dry nanoparticles, the antioxidant effects, and photosynthetic pigments. However, comparing the nanoparticles, fresh $\text{CoFe}_2\text{O}_4\text{NPs}$ produced a more deleterious impact on the wheat than the dry nanoparticles. The results obtained by López-Luna and colleagues were similar to those of Jahani et al. (2019), with a few exceptions. Both authors reported the accumulation of remarkable toxicity instead of improving the morphology and physiological characteristics of *Brassica napus* L. For instance, at high concentrations of $\text{Co}_3\text{O}_4\text{NPs}$, the growth process of the plant is significantly reduced, as are the photosynthetic pigments. The antioxidants like glutathione, ascorbate, and peroxidase are also reduced except for antioxidant capacity (DPPH). However, the sugar contents and proline and phytochemical constituents of the plant increased (Table 1).

Roles of cobalt nanoparticles in mutagenic effects in plants

Plant growth and development are determined by some internal and external conditions. These conditions determine the safety of the consumers of the plants or their products. The integration of nanoparticles in agricultural practices is one of the conditions that determine the health of plants. The chemical constituents of the nanoparticles and the colonization of plants by pathogenic microbes like viruses, protozoans, and bacteria are the major contributors to plants' mutagenicity and toxicity. Some chemicals used for the formulation, like hypochlorite,

NaOH , and cobalt salts, could be responsible. Generally, the disruptions of the genetic makeup of plant cells are dependent on the zeta potential, size, and ionic compositions of the nanoparticles (Marmioli et al., 2022). The disruptions of the plant genes would result in the development of epigenetics, a change in protein regulatory molecules and overall modification of RNA and DNA molecules (Fig. 1).

Furthermore, modification of DNA methylation could result in permanent changes in the chromosomal chromatids and expression of the chromosomal locus of the plant cells (Marmioli et al., 2022). Karami Mehrian and De Lima (2016) identified the potentials of nanoparticles of silver, copper oxide, zinc oxide, titanium oxide, copper, and other known nanoparticles except cobalt oxide nanoparticles. The absence of cobalt-based nanoparticles in their study is a grave concern since the deleterious effects of cobalt nanoparticles at the genetic and molecular levels are high. Thus, the study attracted our interest. Though the research period is over a decade, novel research on the effects of cobalt nanoparticles on the genetic manipulation of plant cells or tissues is necessary even now. Srivastava, in 2015, examined the impact of cobalt nanoparticles, cobalt oxide nanoparticles, and ethanol on the genetic toxicity and pathways in the *Sesbania cannabina* plant. The activities of the three compounds were compared. The result identified several disruptions in the chromosomal arrangements of the roots and seed at the embryonic levels. The author identified several genetic disruptions in the chromosomes; however, according to them, the most probable disruptions with prominent effects include the formation of fragments and disruption plates at the metaphase. Others include uneven segregation and formation of cross walls at the anaphasic phase and scattering at the metaphasic phase. It was further discovered that cobalt oxide nanoparticles were the most virulent among the three compounds used against the root tissues of the *S. cannabina* plant.

In a relatively recent study by Kong et al. (2020), the researchers

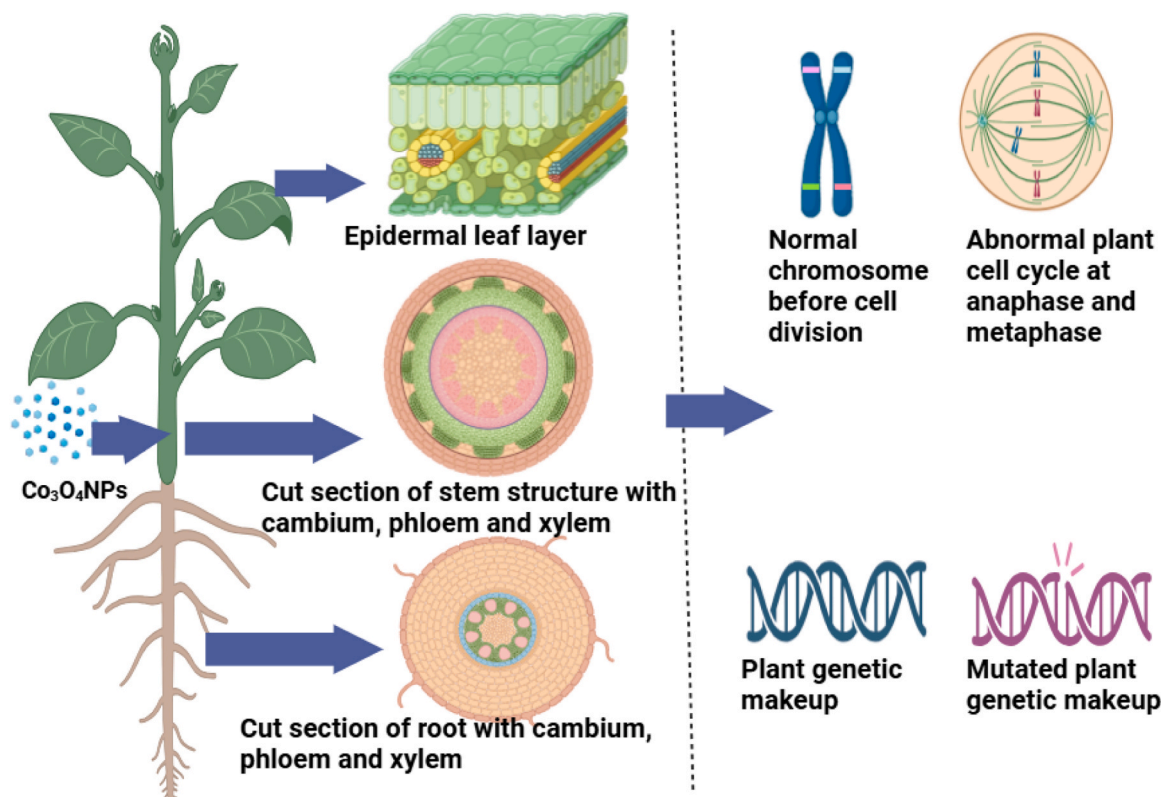


Fig. 1. The mutagenic effects of cobalt oxide nanoparticles in plant tissues. When plants are exposed to the $\text{Co}_3\text{O}_4\text{NPs}$ -based nanofertilizer, the nanoparticles colonized the roots, and leaves and spread throughout the parts of plants. The anaphase and metaphase of chromosomes are aligned improperly. The chromatids might be destroyed making cell division very impossible. The genetic makeup of plant tissues in the stem, roots, and leaves are mutated when exposed to cobalt oxide nanoparticles in the nanofertilizer.

evaluated the efficacy of the particle size of two cobalt oxide nanoparticles integrated with microorganisms, plants, and green algae. The genetic disruptive processes of the different particle sizes were compared. Although the authors assessed the effects of the cobalt oxide NPs on microbes, plants, and algae using nine different parameters, our interest is only in the effects on the genetic variations of plants since the genetic variations were conducted on *Chlorella vulgaris* and *Lactuca* species, a flowering plant, we did not proceed further. Wang et al. (2024) reported that Co₃O₄NPs downregulated the genetic processes that regulate cell formation mechanism, metabolism, and biological growth processes in soybeans. The authors linked the effects to the cobalt ions and not necessarily all the components of the nanoparticles. In their argument, the constituents of the NPs in Co₃O₄NPs do not in any way affect the soybean roots other than the cobalt ions used in the comparative study.

When the nanoparticles are translocated alongside plant nutrients, they interfere with the biological processes and structural plant components responsible for nutrient assimilations and metabolism (Faisal et al., 2016). While the mutagenic effects of cobalt nanoformulations are notable and have produced genetic disruptions in the metabolic processes in plants, their mutagenicity depends on the model and method of the formulations (Uboldi et al., 2016). In humans, the simple process of plant genetic mutations involves the identification of nanoparticles and absorption into the system through a clathrin-dependent process into the lysosomes, where cobalt ions are released after being dissolved in the lysosome. The cobalt ions circulate through the blood and cause genetic disruptions, chromosome destruction, and superoxide release (Ma et al., 2022). The extent of mutagenicity in plants is dependent on the size of the particles. Small-sized NPs tend to exert more effects than large-sized NPs (Kong et al., 2020).

In a contrasting report from Ogunyemi et al. (2023), cobalt oxide nanoparticles have been effectively used to protect plants at low concentrations (Ogunyemi et al., 2023) from environmental factors. The plant growth process can be influenced by the atmospheric conditions, aquatic sources surrounding the plants, and sources of nutrients within the ecosystems. Cobalt nanoformulations provided the medium for promoting the expression of *gus* genes in *Catharanthus roseus* cell culture. This study validates the genetic protection of *C. roseus* by blocking the ethylene synthesis pathway (Fouad and Hafez, 2020).

Effects of titanium-based nanoparticles on plants

Panahirad et al. (2024) studied the effects of Pb on *Echinacea purpurea* plants and the soil components. The researchers initially treated the plant with Pb. They compared the roles of TiO₂ NPs on the leaves and inflorescence of the plants based on antioxidative characteristics, essential oil contents, proline quantification, light-absorbing pigments, sugar contents, and morphological characteristics. Equal concentrations of 50 mg/l of TiO₂ NPs were used for the experiment and compared with the control. For instance, the essential oils of the plant were significantly improved when TiO₂NPs were added. However, when the plant was treated with Pb, the addition of TiO₂NPs inhibited the significant expression of some metabolites; this process is a precautionary measure of the plant to protect itself from the deleterious effects of Pb. The TiO₂NPs reduced the sugar and EOs of the plant. The chlorophylls a and b of the plants increased significantly while the sugar content decreased. In addition, the antioxidant effects of ascorbate peroxidase of the plant-treated Pb improved significantly, while the superoxide dismutase decreased. It was also discovered that the proline amino acid content of the plant increased. Chahardoli et al. (2025) evaluated the effects of TiO₂NPs on the developmental process, phytoconstituents, metabolic, antioxidant, and physiology of *Dracocephalum kotschy* Boiss. The nanoparticles were formulated into 0, 50, 100, 1000, 2500 ppm concentrations. Analysing the microscopy report, the root cells had mechanical disruptions at 1000 ppm due to the excess bioaccumulation of the nanoparticles. Still, at 100 ppm, no observable difference was seen

in the root cells when compared with the control. The growth process of the plant witnessed changes at different concentrations. At 50 ppm, the stem weight and length of the plant improved considerably. However, at 100 ppm, the root biomass and length were reduced.

The effects produced on the pigmentation profile of the plant indicate that at 2500 ppm, chlorophylls a and b increased, while at 100 ppm, the chlorophyll pigments reduced considerably. The carotenoids remained unaffected in all concentrations except at 100 ppm, where it decreased. At 50 ppm and 100 ppm, the proteins increased and decreased, respectively, while high concentrations of 1000 and 2500 ppm proline and the sugar content of treated plants showed great improvement. There was also an increase in Peroxidase, superoxide dismutase (POD), catalase (CAT), ascorbate peroxidase (APX) superoxide dismutase (SOD) in the plants. In their study, it was observed that the degree of performance is dependent on the concentrations of the nanoparticles. In a study to determine the effects of titanium oxide nanoparticles on plants exposed to nickel, Rehman and colleagues in 2025 identified several parameters in *Zea mays* that were affected. The nickel-treated plants had a significant reduction in root size and fresh and dry biomass. Moreover, the TiO₂NPs have been effectively utilized to curtail the effects of lead-treated plants. They promote growth and photosynthetic evolutions with strong microbial protections (Panahirad et al., 2024). When the nickel-treated rice plant was exposed to constant 40 mg/l titanium oxide nanoparticles, the reversal process observed was significant in all the growth, physiological, and morphological parameters. The root size and biomass increased considerably compared to the control. The assessment of antioxidant and photosynthetic processes was not left out. The nanoparticle reduced the reactive oxidative products induced by the nickel, increased the chlorophylls a and b, and increased the glutathione, SOD, POD, CAT and APX. The stomata responsible for the exchange of fluids in plants during photosynthesis were enhanced after treatment with TiO₂NPs.

Abbas et al. (2021) reported that the biochar-based TiO₂NPs increased the total chlorophyll a and b content of *Triticum aestivum* L and the photosynthetic pathways at 100, 200, and 500 mg/l concentrations. They were responsible for improving the morphological appearance of the roots and shoots by increasing their sizes to 500 mg/l. The role of biochar is to reduce the accumulation of titanium ions in the roots and stems of the studied plant. This reduction is to reduce phytotoxicity and subsequently enhance the efficacy of titanium oxide nanoparticles (Table 2).

Roles of cobalt oxide nanoparticles in plant growth and developmental processes

Cobalt oxide nanoparticles play a major role in the growth and developmental processes of plants (Table 3). Earlier, we discussed the roles of cobalt genetic mutations on the plants in a research by (Faisal et al., 2016; Kong et al., 2020). The authors evaluated the growth and developmental processes in *Chlorella vulgaris* and *Lactuca* species in these parameters and compared the two-sized nanoparticles. In their study, the smaller cobalt oxide nanoparticles were more effective in toxicity inflictions in *C. vulgaris* than the large-size cobalt oxide nanoparticles. At 100 and 200 mg/l, the small-size cobalt oxide nanoparticles produced between 96 % and 98.5 % toxicity in cell counts, a situation associated with high toxic conditions of the nanoparticles. A similar trend was observed in the chlorophyll content, with 74.8 % and 79.7 % chlorophyll toxicity. The seed germination rate was compared in *Lactuca* species at the same concentrations in the study. At 200 mg/ml, by comparing their sizes after treatment and incubation, the small-size nanoparticles produced a more significant percentage inhibition of root and shoot developments. Similarly, Co₃O₄NPs improved the nutritional contents of phosphorus, iron, and manganese in *Glycine max*, especially at high concentrations of 100 and 500 mg/kg. In a study, López-Moreno et al. (2016) reported that at 125 mg/ml, Co₃O₄NPs enhanced the absorption of Ca and Mg by the roots of the growing

Table 2
Effects of titanium oxide nanoparticles (TiO₂ NPs) on the health of plants.

Plants	Attaching molecules	Formulations	Conditions	Effects on plant health	References
<i>Echinacea purpurea</i>	None	50 mg/l of TiO ₂ NPs and the combinations of TiO ₂ NPs	The <i>Echinacea purpurea</i> was treated with lead (Pb).	Decreased essential oils of Pb-treated <i>E. purpurea</i> . Increased the proline concentration. TiO ₂ NPs increased the phenol content while reducing the sugar concentrations. Increased the antioxidant effects of ascorbate peroxidase (APX) and reduction in the antioxidant effects of superoxide dismutase (SOD) under 100 mg/kg. Increased the morphological (leaf weight, inflorescence weight, leaf length, and plant height) characteristics of the plant. Increased the photosynthetic pigments (carotenoids, chlorophyll a and b) of the plants	(Panahirad et al., 2024)
<i>Triticum aestivum</i> L.	Biochar	100, 200, 500, 1000 mg/l	The effects of activities of TiO ₂ NPs on <i>Triticum aestivum</i> L. The effects were compared with those of TiO ₂ NPs +Biochar	Increased plant morphological changes in the sizes of roots and shoots. Total biomass improved at 500 mg/l. Photosynthetic and transpiration processes slightly improved at 500 and 200 mg/l, respectively. At 200 and 500 mg/l, chlorophyll a and b content and the accumulated major nutrients increased. At 1000 mg/l, the photosynthetic and assimilation process decreased.	(Abbas et al., 2021)
<i>Zea mays</i>	None	40 mg/l	The effects of TiO ₂ NPs on <i>Zea mays</i> treated with nickel (Ni)	TiO ₂ NPs increased the chlorophyll a and b contents. Increased the photosynthetic and transpiration processes. Increased the glutathione (GSH), peroxidase (POD), catalase (CAT), ascorbate peroxidase (APX), and superoxide dismutase (SOD) of the plants. Significantly improved the nutrient absorption mechanisms in the plant. Increased the plant morphology (root and shoot size)	(Rehman et al., 2025)
<i>Dracocephalum kotschyi</i> Boiss	None	0, 50, 100, 1000, 2500 ppm	The phytotoxicity of <i>Dracocephalum</i> species was considered when treated with TiO ₂ NPs.	Increased phytoconstituents. Enhanced proline and sugar components. Increased Peroxidase, superoxide dismutase (POD), catalase (CAT), ascorbate peroxidase (APX) superoxide dismutase (SOD) of the plants. Increased sugar, proline. Enhanced the phytoconstituents of the plant (flavonoids, anthocyanins, and saponins). Considerably improved the chlorophyll a and b at 250 ppm; carotenoids are unaffected in concentrations except at 100 ppm, where it decreased. Increased the sizes of roots and shoots and height of the plants at 50 ppm. Increased the physiology of plant characteristics.	(Chahardoli et al., 2025)
<i>Coriandrum sativum</i> L.	None	50, 100, 250, 400 mg/l		The nanoparticles significantly enhanced the water content of the roots at 50 mg/ml by almost 5%. Increased slightly, the shoot and root lengths. The dry and fresh weights of the roots and shoots increased by 13.2% and 12.3% at maximum level respectively.	(Hu et al., 2020)
<i>Allium cepa</i> <i>Raphanus sativus</i>	None	0.001, 1, 100, 10000 mg/l	The roots and shoots of <i>Allium cepa</i> and <i>Raphanus sativus</i> were exposed to TiO ₂ NPs for phytotoxicity.	The TiO ₂ NPs reduced and inhibited the root size at 100 and 10000 mg/l. The nanoparticle inhibited the growth of the root system of <i>R. sativus</i> .	(Pittol et al., 2017)

Solanum lycopersicum L seedlings. They reported that the nanoparticles influenced the development of the roots and shoots above that obtained in the control. Although, at concentration above 125 mg/ml, the nutrient absorption was affected as well as the length of the shoots, however at the roots were not affected even at 1000 mg/ml the germination rate of the *S. lycopersicum* L were observed. According to Wang et al. (2025), the development of *Zea mays* seedlings was observed when the seedlings were treated with *Withania coagulans*-based-Co₃O₄ NPs. The positive effects of the nanoparticles triggered an increase in plant growth markers and identifiers, such as, total chlorophyll, chlorophylls a and b. The developmental process happened at 25 and 50 mg/ml. However, at 100 mg/ml, the chlorophyll b was reduced significantly.

Relationships between cobalt and titanium oxide nanoparticles and human health

Nanoparticles can accumulate the parts that are consumable by plants either as NP formulations or the different ionic states of the metals (Rajput et al., 2020). One major application of nanoparticles is the synthesis and use of nanofertilizers for crop improvement (Fig. 2). Nanofertilizers have improved what were customary deficiencies of normal fertilizers. In agriculture, they have been utilised to improve

crop yields and reduce nutrient loss associated with normal fertilizers (Zulfiqar et al., 2019). The NPs from nanofertilizers are absorbed through the leaves and roots. In the soil, the NPs are absorbed through the xylem tissues in the roots to other parts of the plant, while the stomatal openings on the leaves absorb the NPs and spread them through the phloem tissues (Zulfiqar et al., 2019). They have improved the development of plants within a constant environmental condition. Heavy metals used as pesticides or biofertilizers contaminate the terrestrial and aquatic environment, accumulating and interfering with the food chain and affecting humans and other animals (Ahmed et al., 2021). Plants absorb both cobalt and titanium oxide nanoparticles and, when consistently used as constituents of nanofertilizers, can easily enter the food chain and constitute major health hazards. Trela-Makowej et al. (2024) argued that since the Titanium oxide nanoparticles tend to persist for a long time in the food chain and interfere with the products of the plants, the safety of the supply chain is endangered, especially for prolonged contact with the nanoparticles. Therefore, conscientious efforts are needed in the study. TiO₂NPs can serve as a food preservative, which has the potential to generate superoxide species and irritation of various organs within the tissues of mammals. A prolonged effect leads to cell death and misalignment of the chromosomes. These NPs can induce colorectal cancer in a living host

Table 3

Positive roles of cobalt oxide-based and titanium-based nanoparticles in disease control, plant growth.

Nanoformulations	Disease control	Plant growth process	Concentration	References
Cobalt-based nanoparticles				
Co-NPs	The mycelia of <i>Pseudocercospora fijiensis</i> that covered the entire space of about 1.12 cm ² were eliminated after 30 days of incubation. The nanoparticle produced the highest antifungal growth	ND	2000 ppm	(Caguana et al., 2025)
Co-NPs	The black scurf disease (<i>Rhizoctonia solani</i>) that attacked <i>Solanum tuberosum</i> Co ₃ O ₄ .carbendazim-Nwas reduced when treated with Co ₃ O ₄ .carbendazim, but at 500 mg/ml, the disease was significantly reduced compared to the control.	The nanoparticles enhanced the growth and yields of <i>Solanum tuberosum</i>	500 mg/ml	(El-Wahab et al., 2025)
Co ₃ O ₄ NPs	Infected seeds of Zea mays were treated with Co ₃ O ₄ NPs to eliminate pathogens before planting.	The seeds achieved an approximately 97 % germination, influenced by the ability of the nanoparticles to enter the treated seed coat. The shoot and root lengths increased.	80 mg/ml	(Almeida Junior et al., 2024)
CoFe ₂ O ₄ NPs (<i>in vitro</i>)	The mycelia of <i>Colletotrichum gloeosporioides</i> , <i>Fusarium oxysporum</i> , and <i>Dematophora necatrix</i> were eliminated, and fungal growth was inhibited	ND	400 and 500 mg/ml	(Sharma et al., 2017)
CoFe ₂ O ₄ NPs (<i>in vivo</i>)	The growing seedlings exposed to <i>Fusarium oxysporum</i> -contaminated soil were almost eliminated at 500 mg/ml (90.5 %).	Treatment of the seedlings with CoFe ₂ O ₄ NPs enabled the growth of the crop without manifesting any physical changes like wilt or necrosis on the leaves.	500 mg/ml	(Sharma et al., 2017)
Titanium-based nanoparticles				
Ti ₂ ONPs	The nanoparticles eliminated only bacteria and fungi <i>in an in vitro</i> study at 20, 30 and 40 mg/ml.	Influenced the growth of <i>Chrysanthemum indicum</i> and the development of seedlings by increasing their height, as well as the quantity of roots and leaves.	10 and 20 mg/ml	(Pavasupree et al., 2023)
TiO ₂ NPs	ND	The nanoparticles enabled the <i>Solanum melongena</i> seedlings subjected to saline-based toxic conditions of 75 and 150 mM NaCl to grow by the development of all the growth parameters like shoots, roots and leaves at 200 ppm.	200 ppm	(Khalid et al., 2024)
TiO ₂ NPs	ND	At 1, 2 and 10 ppm, the nanoparticles enhanced seed germination rate and seedlings development and growth by increasing the size of shoots and roots	<i>Triticum. aestivum</i> L. var. Pishtaz	(Feizi et al., 2012)

(Bhardwaj et al., 2022). Genchi et al. (2023) asserted that at low concentrations, Co₃O₄NPs were effective against human cancer cells and showed great potency against human pathogens. However, they argued that these nanoparticles have deleterious effects on humans (Fig. 3). Through contact with Co₃O₄NP-contaminated water, either by directly drinking it or consuming seafood that is already contaminated, the cobalt oxide nanoparticles get to the human body. At accumulated and concentrated doses, vital tissues like the cardiac and blood-producing tissues with irritation of the lungs (Genchi et al., 2023).

Discussion, recommendations, and projections

From all the studies, both cobalt and titanium oxide nanoparticles affect plant growth, development, and genetic changes. The effects could be either beneficial or harmful based on their concentrations (Table 4). The phytotoxic effects they possess overwhelm their benefits. Different studies by Wang et al. (2024), Marmioli et al. (2022), and Panahirad et al. (2024) confirmed our assertions. However, in all fairness, comparing the severity of cobalt and titanium-based nanoparticles on plants, cobalt oxide nanoparticles produced more deleterious effects than titanium oxide nanoparticles. For instance, from the entire literature obtained from different databases for this study, Marmioli et al. (2022) and Pittol et al. (2017) reported in their research the deleterious effects of titanium oxide nanoparticles in plant growth and development, while several studies reported the improvement of plant antioxidant capabilities (Blessymol et al., 2024; Chahardoli et al., 2025), enhanced metabolic processes, protective genetic enhancement, and improvement in the morphological structures and phytoconstituents of plants of titanium oxide nanoparticles (Chahardoli et al., 2025). Other studies also reported that titanium oxide nanoparticles significantly reduced those negative factors or constituents, such as sugar content and proline, which affect the plant's morphological and physiological

health. Cobalt oxide nanoparticles did not produce any significant reducing effects on sugar, protein, and starch contents of *Glycine max*, but at low concentrations, protein content was considerably increased (Wang et al., 2024).

In contrast to titanium oxide nanoparticles, cobalt oxide nanoparticles reduce the growth and developmental index of *Glycine max* plants, and the phytotoxic effects are capable of being transmitted to humans when consumed at high concentrations (Wang et al., 2024). Hong et al. (2019) provided a contrasting report against Wang and other colleagues. Hong and colleagues' study asserted that cobalt-based NPs of NZVC enhanced the morphology, physiology, and metabolism of *Glycine max*. Moreover, Mahmood et al. (2023) reported that at 100 ppm, green-based cobalt oxide nanoparticles enhanced the sizes of roots and stems of *Acacia jacquemontii* and *Acacia nilotica* initially exposed to zinc ions. Aside from the morphology of the plants, the physiology of the plants also significantly improved. From the studies of Hong and Mahmood and their colleagues, one thing was remarkable. All the authors integrated certain molecules into the NPs to increase the efficacy.

Several studies reported that cobalt oxide nanoparticles could disrupt the genetic and chromosomal arrangements of plant cells (Karami Mehran and De Lima, 2016; Marmioli et al., 2022; Srivastava, 2015), but only Fouad and Hafez (2020) provided evidence that cobalt oxide nanoparticles can also enhance the genetic compositions of plants, in this case, *Catharanthus roseus* cultures. Since the advantages of titanium nanoparticles in maintaining the integrity of plant health are considerably remarkable, we recommend that more studies be performed to ascertain the veracity of our claims.

From the few studies evaluated, green-based titanium and cobalt nanoparticle synthesis is encouraged as part of the nanoparticles in plant treatment. They reduce toxicity in plants, the surrounding environment, and humans. They also enhance the overall plant development. During synthesis, the plant extracts in the plant-based nanoparticles usually

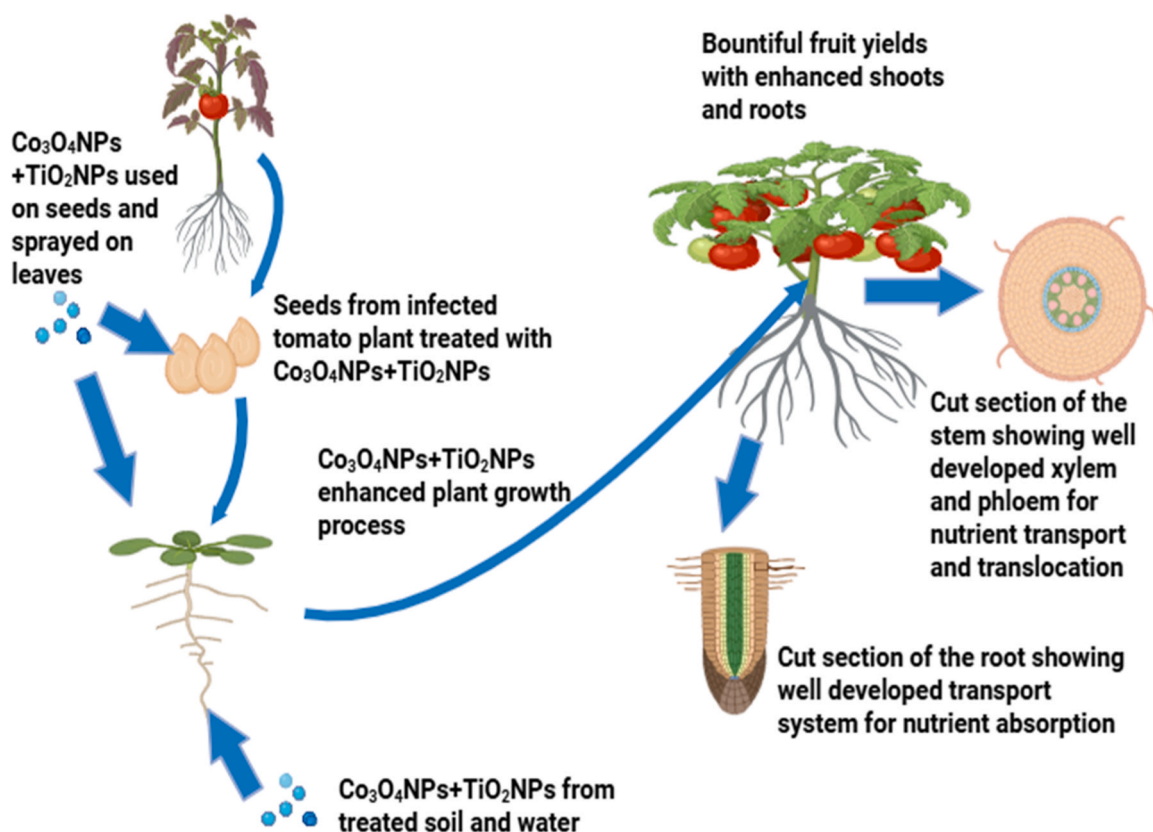


Fig. 2. The benefits of cobalt oxide and titanium oxide nanoparticles to the growth process of a plant (tomato). The seeds infected with microorganisms treated with the nanoformulations developed into seedlings. The shoots and roots of the plant were further exposed to the nanoformulations in a controlled environment (monitored room temperature, light/darkness, pH, relative humidity and water) until seedlings complete the growth cycle into a plant. The tomato plant yields bountiful fruits with well-developed leaves for translocation, as well as roots and stems for nutrient absorption.

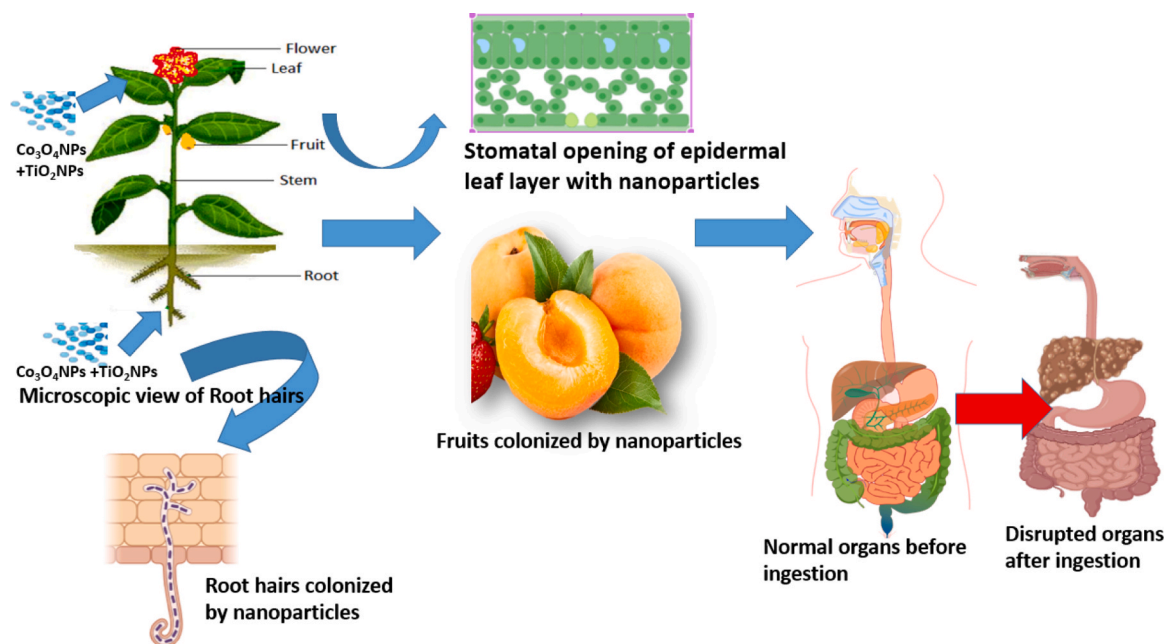


Fig. 3. The accumulated cobalt-oxide nanoparticles (Co₃O₄NPs) and titanium oxide nanoparticles (TiO₂NPs) in plant tissues produce deleterious effects in humans upon consumption. The Co₃O₄NPs and TiO₂NPs that colonize the leaves and roots of the plants accumulate edible parts of the plants. When consumed the infested edible parts are capable of destroying the vital body organs.

Table 4

Effects of differences in concentrations of cobalt oxide-based and titanium oxide-based nanoparticles on plant health.

Plants	Nanoformulations	Beneficial concentrations	Harmful concentrations	References
Cobalt oxide-based nanoparticles				
<i>Solanum tuberosum</i>	Co ₃ O ₄ .carbendazim-NPs	(At 250 and 500 mg/l). Co ₃ O ₄ .carbendazim-NPs enhanced the sizes of the shoots and roots; tuber yields improved significantly. The dry and fresh weight of the plant increased.	There was no reduction or decrease in the growth parameters of the plant even at the highest concentrations of 500 mg/ml.	(El-Wahab et al., 2025)
<i>Vigna radiata</i> L.	Co ₃ O ₄ NPs	(At 50 mg/ml). Increased the synthesis of chlorophyll a; enhanced the photosynthetic ability of the plant	(At 100 mg/l). Decreased the length of the shoots and roots of the seedlings. Reduced the synthesis of chlorophyll b	(Joshi et al., 2025)
<i>Solanum lycopersicum</i> L.	CoFe ₂ O ₄ NPs	(At 125 mg/ml). Increased the absorption of magnesium and calcium in the roots and leaves of growing plants. Increased the germination of the <i>Solanum lycopersicum</i> L. seedlings by enhancing the lengths of roots and stems.	(At 250, 500 and 1000 mg/ml). Decreased the transport of magnesium and calcium ions to the roots and leaves. At 1000 mg/ml, the stem decreased compared with the control, with no effects on the roots.	(López-Moreno et al., 2016)
<i>Brassica napus</i>	Co ₃ O ₄ NPs	(At 50, 100 mg/ml). Increased the growth of the plants by enhancing the fresh and dry weight of the <i>Brassica napus</i> leaves.	(At 4000 mg/ml). Decreased the fresh and dry weights of the leaves. Reduced the chlorophyll content in the leaves	(Jahani et al., 2020)
<i>Zea mays</i>	<i>Withania coagulans</i> formulated-Co ₃ O ₄ NPs	(At 25 and 50 mg/ml). Increased the length of the shoot. Increased chlorophylls a and b, and the total composition of the leaves.	(At 100 mg/ml). Decreased chlorophyll b	(Wang et al., 2025)
Titanium-based nanoparticles				
<i>Triticum vulgare</i> L.	TiO ₂ NPs	(At: 5 mg/ml). Increased the total chlorophyll content of the seedlings. Significantly increased the length of the shoots at all the concentrations	(20 and 40 mg/ml). Decreased chlorophyll content and reduced the absorption of potassium	(Dağhan et al., 2020)
<i>Vitex agnus - Castus</i> L	TiO ₂ NPs	(At: 600 and 800 ppm). Increased the dry weight of the stem and root. Increased chlorophyll a and the total chlorophyll composition. Increased the sugar content of and significantly improved the antioxidants of the plant seedling.	(At 600 and 800 ppm). Decreased chlorophyll b and reduced soluble sugar levels in the plant.	(Moshirian Farahi et al., 2023)
<i>Dracocephalum moldavica</i>	TiO ₂ NPs	(At 50 and 100 mg/ml). Increased the fresh and dry weights of the plant at 100 mg/ml after exposing the plant to saline conditions. Increased the lengths of the shoots and roots at 50 mg/ml. Increased the number of leaves in the growing plant	(At 200 mg/ml). The plants' fresh and dry weights decreased after exposure to salty conditions. Decreased dry and fresh weights of the plants	(Gohari et al., 2020)
<i>Chrysanthemum indicum</i>	TiO ₂ NPs	(At 10 and 20 mg/ml). Increased root and shoot length showed a significant difference when compared to the control, in the fresh and dry weights. The root numbers increased considerably.	(At 30 and 40 mg/ml). Decreased fresh and dry weights of roots and stems. Reduced the root and stem lengths significantly when compared to the control.	(Pavasupree et al., 2023)
<i>Vicia faba</i> L.	TiO ₂ NPs	(At 0.01 %). Increased plant growth by enhancing root and shoot lengths, dry and fresh weight by 40 % and 77 % respectively. Increased the size of leaves by 29 % and improved chlorophylls a and b and carotenoids. Increased the total soluble sugars and amino acids	(At 0.03 %). Reduced the shoot and root size compared with the control. Decreased the chlorophylls and b contents of the leaves.	(Abdel Latef et al., 2018)
<i>Zea mays</i>	Nano-TiO ₂	(At 0.2 %, 1 % and 2 %). The germination rate of <i>Zea mays</i> increased for 48 and 72 h treatment periods, but was slightly lower than the control.	(At 2 % and 4 %) Increased mitotic aberration of the chromosomal fragments of the root cells.	(Castiglione et al., 2011)

serve as a strong reducing medium and improve their antioxidant effects (Aslam et al., 2021). The microbe integrated into titanium nanoparticles provides a robust surface area for interaction, simple extraction methods, huge replicable products, easy accessibility, and ecologically safe (Alabdallah et al., 2024). This is to enhance their efficacy. The green-based nanoparticles produce more remarkable benefits in plants than ordinary nanoparticles. Therefore, the green-based nanoparticles are suggested to be consistently integrated into the various plant treatment processes to enhance the overall well-being of the plant. Using green-based nanoparticles, including plant extracts, biomolecules, and microbes, provides unique advantages over using only nanoparticles in plant treatments. They are stable to changes in environmental factors (Aslam et al., 2021). There have been studies, as reported by Ilyas et al., 2021, that integrated plant extracts and microorganisms into the formulation of nanoparticles. However, these studies focused on applications of green-based titanium nanoformulations in biomedicine. The authors outlined the uses of green-based titanium nanoformulations as good antimicrobial agents and drug carriers without their applications or roles in plant development. Only a few studies have been able to

evaluate the effects of green-based titanium and green-based cobalt oxide nanoparticles on plant development, growth, genetic and metabolic processes (El-Wahab et al., 2025; Ilyas et al., 2021; Ogunyemi et al., 2023). Though the studies were few, they are still relevant. The deleterious effects of cobalt oxide NPs have been considered to result from the cobalt ions (Hu et al., 2021) in the NPs and not necessarily the entirety of the NPs. Using green-based components as strong reducing agents will go a long way in enhancing the positive effects while reducing or inhibiting the negative roles in cobalt oxide NPs.

Generally, titanium and cobalt-based nanoparticles share common limitations. Since the particle sizes of these green based-nanoparticles are similar to the shapes of biomolecules like nucleic acids, peptides, and enzymes, they can easily pass through the membrane barrier to penetrate and disrupt the biomolecules within the cells (Aslam et al., 2021). These disruptions affect the overall development of plants. As carrier molecules, they take advantage of the process to inflict their toxicity.

In humans and other animals, since the genetic mutations of plants can occur in the edible parts of plants, there is a tendency for easy

genetic transmission from plants to humans. Specific organs can be affected upon consumption, and systemic impacts can persist for a long time. Nanofertilizers are risky for plants since their use in soil treatment can trigger certain hormonal changes in humans. Heavy metals can be translocated alongside plant nutrients to interfere with the normal function of the human hosts. The optimal performance of the two nanoparticles is dependent on their concentrations and nature, notwithstanding the type and constituents of the formulations. The nanoparticles perform optimally at certain conditions and concentrations; when they are exceeded, the aforementioned demerits might be perpetrated.

From the review conducted on the roles of cobalt oxide nanoparticles in the genetic manipulations of plant cells, it was discovered that no new research has been conducted. The genetic and cellular compositions of plants influence the overall biological, physiological, and metabolic processes that occur in them. There should be deliberate efforts in undertaking novel molecular research to provide up-to-date data on the genetic influence of cobalt nanoformulations.

Conclusions

Cobalt and titanium-based nanoformulations provide double roles as both enhancing and deleterious agents. Comparably, cobalt oxide nanoparticles have negative implications, but their positive effects on plant growth, morphology, antimicrobial roles, photosynthetic process, and physiology are huge. The significant improvements in the aforementioned parameters of cobalt oxide nanoparticles in plants generally compete and adverse effects. Cobalt nanoformulations have been used in the study of plant health, aside from a few studies. So far, cobalt nanoformulations are recommended for the progressive treatment of plants before cultivation and prior to harvest. From the study, titanium nanoformulations have not provided a holistic improvement in plant growth and physiology compared to cobalt oxide nanoparticles. While suggestions are rife for moderate titanium nanoformulations in plants and plant products, consistent and continuous use might become deleterious to humans who eventually consume the products.

CRedit authorship contribution statement

Sameerh Alsaifi: Resources, Formal analysis. **Kingsley Chukwuemeka Nwachukwu:** Writing – original draft. **Ositadinma Chinyere Ugbogu:** Writing – review & editing, Supervision. **Happy Uchendu Ndom:** Software, Data curation. **Oluwafemi Adebayo Oye-wole:** Writing – review & editing, Supervision.

Ethical approval

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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