Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 22, No. 1, 2026

A Review of Carbon Nanotubes' Effects on Plant Growth and Their Environmental Impact

Siyi Wang[1, a]

[1]Environmental Engineering (Sino-Foreign Cooperative Education Program), Hubei University, No. 368 Youyi Avenue, Wuchang District, Wuhan City, 430062, Hubei Province, China

[a]2506076633@qq.com

Abstract: Against the backdrop of global warming and rapid population growth, issues such as limited arable land and soil degradation and water pollution caused by the overuse of traditional chemical fertilizers are becoming increasingly severe. Developing new agricultural technologies to ensure food security has become a global consensus. Carbon nanotubes (CNTs), with their unique physicochemical properties—including high specific surface area, excellent conductivity, and environmental friendliness—offer innovative solutions to these challenges and serve as key materials for promoting sustainable agricultural development. Research indicates that CNTs can optimize plant growth in multiple dimensions, including promoting water transport and nutrient absorption, as well as regulating endogenous plant hormones and antioxidant systems. These beneficial effects can also significantly enhance crop resilience under adverse conditions such as drought and salinity. When faced with heavy metal or pesticide residue contamination, CNTs can alleviate stress by reducing the bioavailability of toxins. Furthermore, as novel carriers for fertilizers and pesticides, CNTs not only enable the slow release of active substances to enhance efficacy but also facilitate the construction of microsensors, supporting precision monitoring and virus control in smart agriculture. However, concerns remain regarding the ecological safety of CNTs. Their environmental degradation mechanisms are unclear, and they are prone to bioaccumulation; moreover, their effects on plants and soil microorganisms vary depending on type, concentration, and exposure duration. Compounding this complexity, CNTs may exhibit synergistic toxicity with environmental pollutants, and their long-term ecological risks urgently require assessment. This research focuses on the microscopic mechanisms by which CNTs promote the growth of major crops, their practical application efficacy, and their potential disruption of soil ecosystems. It aims to systematically evaluate the agricultural application potential of CNTs, providing a theoretical basis for maximizing their agronomic benefits while mitigating ecological risks, ultimately contributing to global food security and the green transformation of agriculture.

Keywords: Carbon nanotubes, agriculture, sustainable development, plant growth, environmental stress.

1. Introduction

Carbon nanotubes (CNTs) can be described as concentric cylindrical structures formed by the rolling of graphene sheets, with diameters at the nanoscale and excellent optical, electrical, thermal, mechanical, and chemical properties. Despite their high rigidity, CNTs exhibit outstanding flexibility; their electrical properties depend on structural features and can be either semiconducting or metallic. Furthermore, CNTs exhibit good stability under high-temperature conditions [1]. Consequently, CNTs are widely applied across various fields. Applications in agriculture include serving as carriers for pesticides or nutrients, promoting crop growth, preparing functional fertilizers, removing pathogenic microorganisms (bacteria/viruses) from water bodies, and eliminating chemical pollutants from soil. Against the backdrop of increasingly severe environmental issues such as global warming and a growing population, developing more arable land and increasing crop yields to address food supply challenges is of critical importance. As overreliance on chemical fertilizers leads to further environmental degradation, the various roles of nanomaterials throughout the plant life cycle offer new avenues for solving these problems and have the potential to become more sustainable and efficient agricultural practices to meet future food demands [2].

CNTs are currently the most extensively studied carbon nanomaterials. In research on the interactions between nanomaterials, plants, and the environment, studies on multi-walled carbon nanotubes (MWCNTs) account for 84% of the total [1]. Furthermore, CNTs possess advantages such as low cost and environmentally friendly, economical synthesis methods, which provide the fundamental conditions for their use as agricultural products to improve crop growth [1]. Current research indicates that the interaction between CNTs and plants and soil microorganisms allows for the incorporation of CNTs into fertilizers, pesticides, and plant growth regulators, thereby enhancing nutrient uptake, improving plants' adaptability to abiotic stress, and reducing the ecological footprint of agricultural activities. Within a certain concentration range, CNTs promote seed germination and plant growth. Bhattacharya et al. found that seed priming with MWCNTs significantly increased the germination rate of Caragana javanica seeds under drought conditions, while also increasing root length, stem length, and biomass accumulation. MWCNTs applied via air spraying can penetrate the seed coat, promote water absorption, and thereby significantly improve the germination rates of barley, soybeans, and corn [3]. At the same time, CNTs can interact with soil microorganisms, altering the microbial community structure in the rhizosphere and influencing natural carbon and nitrogen cycles. In some cases, this effect is positive. Jordan et al. found that applying 200 mg/L of CNTs during tomato cultivation increased soil microbial diversity and enhanced microbial interactions, thereby promoting tomato growth [4]. However, CNT regulation of community structure may affect community functions, including the degradation of aromatic compounds, the synthesis of antioxidants, and the biosynthesis of redox cofactors. Furthermore, these effects are influenced by factors such as the physicochemical properties of CNTs, plant species, soil conditions, exposure concentration, and biological responses. Given the complexity of microbial communities and the current lack of advanced quantitative methods, scientists have insufficient understanding of the long-term effects of these interactions, and it is difficult to ensure experimental standardization and reproducibility [5]. The unique structure of CNTs gives them sustained-release capabilities and targeted delivery, making them suitable carriers for nano-pesticides. By precisely delivering encapsulated fertilizers and pesticides, CNTs promote crop growth, reduce nutrient leaching, and lower the risk of water pollution [3]. Furthermore, their ability to be absorbed by plants and their precise targeted transport capabilities make it possible to modulate plant gene expression without causing damage. CNTs interact with the encapsulated substances, influencing the availability of genetic material; they transport small interfering RNAs (siRNAs) and other nucleic acid molecules to induce RNA interference, thereby regulating the expression of specific genes [5]. The high specific surface area and excellent conductivity of CNTs make them suitable for various sensing applications, including innovative use as sensing components in plants to monitor temperature, humidity, soil conditions, nutrients, and pests and diseases during plant growth, thereby supporting the development of smart agricultural systems. Given the aforementioned advantages of CNTs and their broad application prospects in agriculture, it is crucial to investigate and understand the mechanisms of interaction between CNTs and plants, as well as their environmental impacts [6].

Currently, there is limited research on the long-term environmental impacts and hazards of CNTs. Throughout their lifecycle, CNTs continuously disperse into the environment and undergo various physicochemical modifications during release; these modifications may influence their potential toxic effects in the future. Human exposure to CNTs via the lungs may pose health risks. Given that the fibrous morphology of CNTs is similar to that of asbestos, they have the potential to trigger global epidemics similar to those historically caused by asbestos. In soil, most CNTs are retained within soil components, and soil texture plays a dominant role in the migration of MWCNTs. Furthermore, the large specific surface area of CNTs allows them to interact with other pollutants, which may affect the behavior and toxicity of the CNTs, co-pollutants, or both, posing significant potential environmental hazards [1]. Based on the above findings, the objective of this study is to systematically evaluate the mechanisms, efficacy, and environmental implications of CNTs in agricultural applications, identifying knowledge gaps and future research priorities in plant growth associated with CNTs and their underlying mechanisms, and to conclude by addressing the cutting-edge applications and potential threats of CNTs, with the aim of providing a scientific reference for the application of CNTs in agricultural practice.

2. Mechanisms of Interaction Between Carbon Nanotubes and Plants

2.1. Carbon Nanotubes Enhance Water and Nutrient Uptake and Utilization

CNTs significantly enhance plant water and nutrient uptake and utilization through multiple mechanisms, including physical penetration, gene regulation, carrier functions, and ecological interactions, thereby improving plant growth by supplying energy resources.

CNTs can penetrate seed coats or root cell walls, inducing internalization—that is, forming nanoscale channels—within the cytoplasm, cell walls, cell membranes, and organelles such as chloroplasts and mitochondria, thereby facilitating the transport of water and nutrients through cells and tissues. This penetration occurs either through pores in the cell wall or via endocytosis. The hydrophobic surface and high aspect ratio of MWCNTs allow them to embed in intercellular spaces, creating additional water pathways. This promotes seed swelling and shortens germination time. Within cells, CNTs upregulate aquaporin gene expression through signal transduction pathways (such as NO/ROS signaling), enhancing cell membrane permeability and transmembrane water transport [3]. Previous studies using fluorescent probe imaging have demonstrated that CNTs are absorbed through the vascular system, potentially facilitating increased uptake and transport of water and assimilates by plants [7]. Furthermore, the increased levels of nutrients such as Mg, Fe, and C observed in MWCNT-treated samples may result from dipole-dipole interactions between MWCNT-bound ions, which may reduce their oxidation states and enhance their availability for plant uptake [8]. CNTs can also improve the bioavailability and accumulation cycles of nutrients in the environment. MWCNTs also influence soil microbial communities at the phylum level. At certain concentrations, CNTs can promote the enrichment of beneficial microbial populations, indirectly improving nutrient mineralization and thereby enhancing plant nitrogen use efficiency [9].

2.2. Carbon Nanotubes Affect Plant Gene Expression

CNTs exert multifaceted effects on the plant transcriptome and can influence the expression of various genes critical to cellular function. The growth and development of plant root architecture are highly influenced by environmental signals generated by various types of environmental stress. Through complex gene regulatory networks, plants respond to environmental stress by inducing or suppressing the expression of relevant genes to regulate morphology or growth rates. Plant hormones such as auxin (IAA), cytokinin (IPA), abscisic acid (ABA), gibberellin (GA), and ethylene collectively form a complex signaling network. CNTs can induce stress responses in plants; enzymes and their precursors in plant hormone synthesis pathways can be stimulated or inhibited by them, thereby helping plants maintain a balance between hormone levels and signaling dynamics, as well as between growth promotion and stress adaptation [6]. Stress-signal-driven gene expression typically depends on post-translational modifications of nucleosome histones, inducing changes in chromatin modifications throughout the genome. Previous studies have observed that CNTs may not only induce DNA methylation but also cause global or selective histone acetylation, which has been shown to be associated with gene transcription or expression [5]. Region-specific epigenetic modifications have been identified in rice and barley exposed to SWCNTs and MWCNTs, indicating that CNTs induce changes in chromatin modifications within gene promoter regions, leading to upregulation of gene expression. CNTs can also influence gene expression through the nitric oxide (NO) signaling pathway. CNT-induced increases in reactive oxygen species (ROS) lead to alterations in citrulline levels, which in turn affect NO levels, thereby influencing plant height, flowering, and fruit set. In tomatoes, MWCNTs increased citrulline and NO levels, thereby activating genes associated with growth and flowering [4].

The stress responses induced by CNTs also enhance plant stress tolerance. Nanomaterials improve agricultural productivity by regulating plant hormone signaling, enhancing stress tolerance, and strengthening defense mechanisms; they have been proven effective in agricultural systems for alleviating both biotic and abiotic stresses [6]. Changes in ABA and salicylic acid (SA) levels caused by increased ROS activate ABA- and SA-dependent stress-responsive transcription factors (TFs), which in turn activate stress-responsive genes, thereby enhancing plant stress tolerance [4]. Under drought conditions, SWCNTs can induce the coordinated expression of the plant antioxidant defense enzyme system, upregulating the activity of superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), and ascorbate peroxidase (APX) to scavenge excess hydrogen peroxide and malondialdehyde, thereby reducing electrolyte leakage and protecting cell membrane integrity. Furthermore, SWCNTs induce plants to activate secondary metabolic pathways, significantly increasing the levels of key osoregulatory compounds such as phenolic substances, soluble proteins, and proline. This stabilizes protein structures and cell membranes, helps plant cells withstand water loss, and acts as a non-enzymatic antioxidant to enhance overall oxidative stress tolerance [10]. However, there is currently a lack of in-depth molecular biological evidence regarding exactly how CNTs act as signaling molecules and through which receptors and transcriptional regulatory networks they activate these downstream defense genes.

Contrary to the assumption of universal efficacy, the phytotoxic potential of nanomaterials is highly context-dependent, governed by variables such as composition, size, dose, and surface functionalization. The heightened reactivity conferred by a high surface-area-to-volume ratio facilitates intensified interactions with plant biomembranes, exacerbating cytotoxicity. Additionally, prolonged exposure to high concentrations of certain nanomaterials has been shown to interfere with phytohormone signaling cascades, leading to significant growth retardation and hormonal dysregulation. Transcriptomic analysis indicates that nanomaterials may downregulate genes involved in IAA and ABA signaling pathways, as well as those associated with pathogen defense responses. This highlights the dual nature of the physiological effects of nanomaterials on plants [6].

2.3. Carbon Nanotubes Enhance Photosynthesis

CNTs primarily improve plant photosynthetic efficiency through mechanisms such as increased leaf area and turgor, elevated chlorophyll content, enhanced carbon dioxide uptake efficiency, and improved photosystem efficiency.

The positive effects on photosynthesis are believed to stem from nanoparticle-induced changes in root hydraulic properties, which ultimately indirectly increase stomatal conductance, thereby promoting CO_2 uptake and enhancing the effective quantum yield of photosystems [11]. The improvement in plant leaf area and turgor by CNTs is primarily achieved through the activation of growth-related genes (such as expansion genes), which promote cell wall relaxation and division and enhance water transport efficiency [3]. CNTs enter leaf cells and interact with photosynthetic tissues to enhance plant photosynthetic efficiency. Existing studies have demonstrated that CNTs adsorb onto the outer membrane of chloroplasts and rapidly penetrate and localize to their internal structures within seconds [12]. Several studies have now shown that CNTs can increase the content of photosynthetic pigments in plants. Stevia stem cultures treated with 100 mg/L MWCNTs exhibited the highest levels of chlorophyll and β-carotene. The increase in carotenoid content stems from the induction of oxidative stress mechanisms; MWCNTs may promote increased carotenoid production by inducing oxidative stress [8]. The increase in photosynthetic pigment content induced by CNTs is also associated with the maintenance of chlorophyll stability. In addition to activating the plant's antioxidant defense system, research by Liu et al. indicates that CNTs can directly reduce ROS by lowering hydrogen peroxide and superoxide anion levels, thereby preventing ROS-induced chlorophyll degradation and thylakoid membrane damage, and maintaining or even enhancing the activity of photosynthetic systems and Rubisco under normal conditions [11]. Due to their unique optical and electronic properties, CNTs can also enable the chloroplast photosystems to capture a number of photons far exceeding the threshold required to convert them into an electron flow. Furthermore, their conductivity may enhance the electron transport rate within the chloroplasts, ultimately increasing the photosynthetic rate. Under non-saturated light conditions, the introduction of CNTs can maximize solar energy capture efficiency. SWCNTs can absorb light energy across a broad wavelength range—including ultraviolet, visible, and near-infrared spectra—that chloroplast pigments cannot capture. In other words, integrating CNTs into the chloroplast membrane expands the light-harvesting range to enhance overall photochemical efficiency [12].

2.4. Antibacterial Properties of Carbon Nanotubes

CNTs primarily resist microbial attacks through two main mechanisms: direct antibacterial activity and the induction of plant defense responses, thereby enhancing plant disease resistance and stress resilience. Their effects include inhibiting pathogen proliferation, disrupting microbial structures, and activating plant immune pathways.

CNTs can directly inhibit the proliferation of pathogenic microorganisms. The inherent stability and high biocompatibility of CNTs enable them to inflict physical and chemical damage on pathogenic microorganisms, thereby exhibiting significant antimicrobial activity, making them a subject of extensive research as potential antimicrobial agents. Direct contact between bacteria and CNTs causes physical damage to the cell membrane and alters cell morphology, leading to cytoplasmic leakage, the release of enzymes and electrolytes, and lipid degradation—all of which trigger microbial cell death. Kang et al. were the first to demonstrate that highly purified native SWCNTs possess significant antimicrobial properties. Aggregates of native SWCNTs with a narrow diameter distribution, when in direct contact with microorganisms, cause damage to their cell membranes, inducing cytoplasmic leakage, lipid degradation, and cell death. This is the most likely mechanism leading to bacterial cell death. Furthermore, due to their layered structure, they are able to interact with microorganisms by covering their surfaces, blocking active sites, and reducing pathogen survival rates, thereby trapping pathogens and rendering them inactive, thus inhibiting their proliferation [13]. Regarding antimicrobial activity against fungi, CNTs demonstrate significant effects such as inhibiting fungal hyphal growth and blocking spore germination. CNTs comes into close contact with the spore surface, forming aggregates and inhibiting water absorption by the spores. Contact is a key factor in the antimicrobial activity of CNTs; physical properties such as van der Waals forces and the state of dispersion can influence their contact with cells and, consequently, their antimicrobial activity. Van der Waals forces likely play a dominant role in the formation of cell-CNT aggregates. Furthermore, some existing studies indicate that these aggregates, in addition to causing the aforementioned damage to the cell surface and morphology, can also lead to the disruption of DNA or RNA replication and protein synthesis, thereby triggering cell death. The van der Waals forces of SWCNTs are sufficient to promote close contact between spores and CNTs, whereas the van der Waals forces of MWCNTs are weaker, inducing only loose contact, which results in significant differences in their antifungal activity [14].

3. The Application Potential and Potential Threats of Carbon Nanotubes

3.1. Smart Agriculture

In the development of smart agriculture, real-time, precise monitoring technologies that cause minimal damage to plants are of great importance. The development of carbon nanotubes and their composite systems provide new technical directions for its advancement and management. For the detection of heavy metal contamination, anodic stripping voltammetry is a highly promising approach due to its low cost, high sensitivity, and relatively simple operation. As this method is highly dependent on the characteristics of the working electrode material, MWCNTs—with their large specific surface area, excellent conductive network, and ability to increase active sites on the electrode—make them an ideal material for electrode modification. Salinas et al. developed an electrode modified with a composite nanomaterial based on MWCNTs and gold and bismuth nanoparticles, achieving highly sensitive simultaneous detection of trace cadmium and lead in various parts of rice plants and in soil [15]. In the field of smart agricultural management, microelectrodes enable non-destructive plant monitoring. The application of materials such as CNTs in microelectrode modification enhances their selectivity, stability, and sensitivity; their ability to respond in real time to changes in plant growth status is of great significance for the development and management of smart agriculture. Previous research has developed a micro-implantable electrochemical sensor for in vivo, in situ, and real-time monitoring of dynamic changes in L-tryptophan, an auxin precursor, in tomato fruits. The presence of MWCNTs improves electrode conductivity and effective surface area, accelerates electron transfer, and lowers the oxidation potential of L-tryptophan, endowing the sensor with high sensitivity [16].

3.2. Green Remediation and Breeding

Through modification and other methods, CNTs can be specifically engineered to enhance their physicochemical properties, thereby achieving better growth-promoting effects. Research by Mahmoud and Abdelhameed indicates that combining multiple nanomaterials with plant-growth-promoting effects may yield even more remarkable results. They developed and evaluated a novel nanocomposite of titanium dioxide-doped MWCNTs as a foliar spray for plant growth promotion and stress resistance induction. Field trial results showed that this treatment not only significantly improved the photosynthetic efficiency, antioxidant capacity, and seed yield of sesame but also simultaneously optimized seed quality, clearly demonstrating the synergistic effect of MWCNTs and TiO_2 NPs [17]. CNTs also hold immense application potential in plant gene delivery and genetic transformation. Due to their small size and biocompatibility, nanoparticles can traverse cell walls and membranes through mechanisms such as size exclusion, electrostatic interactions, and receptor-mediated endocytosis. During transport, CNTs protect nucleic acids from degradation and enhance transformation efficiency. CNTs with specially functionalized surfaces have been used to deliver various substances, including DNA, siRNA, and CRISPR/Cas ribonucleoprotein complexes, and can be directed to specific organelles such as the nucleus, chloroplasts, and mitochondria. Kwak et al. used chitosan-conjugated SWCNTs to deliver plasmid DNA into the chloroplasts of various plant species, achieving transient expression [18]. These findings highlight the potential of nanoparticles for metabolic engineering and the stable transformation of the mitochondrial genome.

3.3. Potential Threats

However, CNTs are highly persistent in the environment, and their degradation mechanisms remain unclear, posing risks of bioaccumulation; long-term exposure may lead to their transmission through the food chain. As mentioned earlier, CNTs exhibit dose- and species-dependent phytotoxicity, and their mechanism of action remains unclear. Long-term exposure of CNTs to the soil environment may alter various physicochemical properties of the environment, leading to the destruction of the original microbial community and changes in community structure, thereby affecting microbial balance and causing soil ecotoxicity [3]. CNTs may also produce synergistic effects with environmental pollutants, increasing the migration and bioaccumulation of pollutants, resulting in more severe harm. It has been reported that MWCNTs can act as carriers for organic pollutants, promoting their uptake by plants. However, the enhanced mobility of heavy metals such as cadmium in soil due to CNTs and the promotion of heavy metal uptake by plants may lead to serious issues regarding environmental pollution and food safety [2]. Further evaluation is needed regarding the impact of long-term use on soil ecosystems and the economic feasibility of large-scale application.

4. Conclusion

CNTs possess a high specific surface area, excellent electrical conductivity, optical properties, mechanical properties, modifiability, biocompatibility, and controlled release targeting capabilities, making them promising materials for applications such as plant growth regulation. CNTs can penetrate plant tissues through micropores in seed coats, root hairs, or stomata and are transported to various plant organs via the vascular system. Their effects on plant growth exhibit significant concentration and species dependence. At low concentrations, CNTs can form transmembrane water channels through physical perforation, regulate gene expression, and activate antioxidant enzyme systems to scavenge ROS, thereby promoting growth and alleviating abiotic stress; at high concentrations, however, aggregation and ROS bursts lead to cell damage and DNA breaks, resulting in inhibitory effects. The sustainability of CNTs lies in their ability to be produced with low pollution and at low cost using agricultural waste such as crop straw, thereby contributing to the resource utilization of agricultural waste. The application potential of CNTs extends across multiple agricultural sectors. CNT-based sensors enable highly sensitive on-site detection of heavy metals, pesticide residues, plant hormones, and pathogen markers, while their functionalized surfaces can facilitate targeted delivery of genetic material (DNA/siRNA) to organelles, thereby overcoming breeding limitations. CNTs can also serve as nanocarriers for delivering fertilizers and pesticides, enhancing both crop yield and quality. However, due to their high environmental persistence and unclear degradation mechanisms, CNTs may alter soil microecology, exhibit synergistic toxicity with pollutants, and cause bioaccumulation through the food chain. Future research should focus on structure-activity relationships and risk assessment to balance agronomic benefits with environmental safety.

References

[1] Liné, C., Larue, C., & Flahaut, E. (2017). Carbon nanotubes: Impacts and behaviour in the terrestrial ecosystem-A review. Carbon, 123, 767–785. https://doi.org/10.1016/j.carbon.2017.07.089

[2] Safdar, M., Kim, W., Park, S., Gwon, Y., Kim, Y.-O., & Kim, J. (2022). Engineering plants with carbon nanotubes: A sustainable agriculture approach. Journal of Nanobiotechnology, 20(1), 275. https://doi.org/10.1186/s12951-022-01483-w

[3] Singh, M. P., Gazali, A., Prakash, O., Pal, P., Singh, A. K., Prakash, A., Sarangi, P. K., Sahoo, U. K., Prasad, R., & Sonkar, S. (2025). Harnessing carbon nanotubes for enhanced plant growth and sustainable agriculture: Opportunities and challenges. Plant Nano Biology, 13, 100178. https://doi.org/10.1016/j.plana.2025.100178

[4] Jordan, J. T., Oates, R. P., Subbiah, S., Payton, P. R., Singh, K. P., Shah, S. A., Green, M. J., Klein, D. M., & Cañas-Carrell, J. E. (2020). Carbon nanotubes affect early growth, flowering time and phytohormones in tomato. Chemosphere, 256, 127042. https://doi.org/10.1016/j.chemosphere.2020.127042

[5] Wani, A. K., Khan, Z., Sena, S., Akhtar, N., Alreshdi, M. A., Yadav, K. K., Alkahtani, A. M., Wani, A. W., Rahayu, F., Tafakresnanto, C., Latifah, E., Hariyono, B., Arifin, Z., & Eltayeb, L. B. (2024). Carbon nanotubes in plant dynamics: Unravelling multifaceted roles and phytotoxic implications. Plant Physiology and Biochemistry, 210, 108628. https://doi.org/10.1016/j.plaphy.2024.108628

[6] Dhiman, V. K., Rana, G., Dhiman, V. K., Subbarayan, R., Sharma, M., Singh, D., Jabir, M., Ghotekar, S., & Chauhan, A. (2025). Nanomaterials for sustainable agriculture: Plant physiology and environmental resilience. Physiological and Molecular Plant Pathology, 139, 102824. https://doi.org/10.1016/j.pmpp.2025.102824

[7] Wang, X., Han, H., Liu, X., Gu, X., Chen, K., & Lu, D. (2012). Multi-walled carbon nanotubes can enhance root elongation of wheat (Triticum aestivum) plants. Journal of Nanoparticle Research, 14(6), 841. https://doi.org/10.1007/s11051-012-0841-5

[8] Sorcia-Morales, M., Mancilla-Álvarez, E., Baltazar-Bernal, O., Spinoso-Castillo, J. L., & Bello-Bello, J. J. (2024). In vitro physiological and biochemical response of Stevia rebaudiana exposure to carbon nanotubes: Hormetic and photomixotrophic effect. Industrial Crops and Products, 220, 119168. https://doi.org/10.1016/j.indcrop.2024.119168

[9] Hao, Y., Yu, F., Lv, R., Ma, C., Zhang, Z., Rui, Y., Liu, L., Cao, W., & Xing, B. (2016). Carbon nanotubes filled with different ferromagnetic alloys affect the growth and development of rice seedlings by changing the C:N ratio and plant hormones concentrations. PLOS ONE, 11(6), e0157264. https://doi.org/10.1371/journal.pone.0157264

[10] Hatami, M., Hadian, J., & Ghorbanpour, M. (2017). Mechanisms underlying toxicity and stimulatory role of single-walled carbon nanotubes in Hyoscyamus niger during drought stress simulated by polyethylene glycol. Journal of Hazardous Materials, 324, 306–320. https://doi.org/10.1016/j.jhazmat.2016.10.064

[11] Tran, T. L. C. (2026). Nanoparticle-enabled enhancement of plant photosynthesis: Mechanisms and applications.

[12] Giraldo, J. P., Landry, M. P., Faltermeier, S. M., McNicholas, T. P., Iverson, N. M., Boghossian, A. A., Reuel, N. F., Hilmer, A. J., Sen, F., Brew, J. A., & Strano, M. S. (2014). Plant nanobionics approach to augment photosynthesis and biochemical sensing. Nature Materials, 13(4), 400–408. https://doi.org/10.1038/nmat3890

[13] Kang, S., Pinault, M., Pfefferle, L. D., & Elimelech, M. (2007). Single-walled carbon nanotubes exhibit strong antimicrobial activity. Langmuir, 23(17), 8670–8673. https://doi.org/10.1021/la701067r

[14] Yang, C., Mamouni, J., Tang, Y., & Yang, L. (2010). Antimicrobial activity of single-walled carbon nanotubes: Length effect. Langmuir, 26(20), 16013–16019. https://doi.org/10.1021/la103110g

[15] Salinas, T. A. O., Natividad, M. T., & Palisoc, S. T. (2023). Determination of heavy metals in rice (Oryza sativa L.) and soil using AuNP/BiNP/MWCNT/Nafion modified glassy carbon electrode. Heliyon, 9(11), e21271. https://doi.org/10.1016/j.heliyon.2023.e21271

[16] Yang, L., Ma, Y., & Ye, J. (2021). In vivo detection of L-tryptophan in tomatoes using multi-walled carbon nanotubes and poly (sulfosalicylic acid) film modified graphite rod electrode. Biosensors and Bioelectronics: X, 9, 100086. https://doi.org/10.1016/j.biosx.2021.100086

[17] Mahmoud, N. E., & Abdelhameed, R. M. (2023). Use of titanium dioxide doped multi-wall carbon nanotubes as promoter for the growth, biochemical indices of Sesamum indicum L. under heat stress conditions. Plant Physiology and Biochemistry, 201, 107844. https://doi.org/10.1016/j.plaphy.2023.107844

[18] Kwak, S.-Y., Lew, T. T. S., Sweeney, C. J., Koman, V. B., Wong, M. H., Bohmert-Tatarev, K., Snell, K. D., Seo, J. S., Chua, N.-H., & Strano, M. S. (2019). Chloroplast-selective gene delivery and expression in planta using chitosan-complexed single-walled carbon nanotube carriers. Nature Nanotechnology, 14(5), 447–455. https://doi.org/10.1038/s41565-019-0375-4