



International Journal of Research in Agronomy

E-ISSN: 2618-0618

P-ISSN: 2618-060X

© Agronomy

www.agronomyjournals.com

2025; 8(1): 564-568

Received: 14-10-2024

Accepted: 25-11-2024

Alagesan Arumugam

Associate Professor (Agronomy),
Indian Council of Agricultural
Research-Krishi Vigyan Kendra,
Tamil Nadu Agricultural
University, Pudukottai, Tamil
Nadu, India

Jesupriya Poornakala Selvaraj

Associate Professor (FSN), Indian
Council of Agricultural Research-
Krishi Vigyan Kendra, Tamil
Nadu Agricultural University,
Pudukottai, Tamil Nadu, India

Thukkaiyannan Palaniappan

Associate Professor (Agronomy),
Indian Council of Agricultural
Research-Krishi Vigyan Kendra,
Tamil Nadu Agricultural
University, Tiruppur, Tamil Nadu,
India

Application of carbon nano tubes for sustainable agriculture

Alagesan Arumugam, Jesupriya Poornakala Selvaraj and Thukkaiyannan Palaniappan

DOI: <https://doi.org/10.33545/2618060X.2025.v8.i1h.2464>

Abstract

The integration of carbon nanotubes (CNTs) in sustainable agriculture offers a transformative opportunity to boost crop productivity while mitigating environmental harm. These nanomaterials possess unique properties such as high electrical conductivity and increased surface area, enhancing nutrient absorption in plants. CNTs serve as efficient carriers for fertilizers and pesticides, ensuring precise application and reducing wastage and environmental runoff. Moreover, their incorporation into soil improves aeration and water retention, supporting robust root growth and resilience to drought conditions. Current research highlights the role of CNTs in promoting sustainable agricultural practices and advancing nano-bioelectronics innovations. These developments aid in environmental monitoring and agricultural productivity, addressing food security challenges and aligning with sustainable development objectives. Harnessing CNTs in agriculture equips the sector to meet the growing population's needs while safeguarding essential ecological resources.

Keywords: Carbon nano tubes, agriculture, CNTs

1. Introduction

In the pursuit of sustainable agriculture, innovative materials and technologies play a pivotal role in addressing contemporary challenges such as soil degradation, water scarcity, and the detrimental effects of chemical fertilizers. Among these advancements, carbon nanotubes (CNTs) have emerged as a promising solution, given their unique physical and chemical properties. These cylindrical nanostructures, characterized by their high surface area, electrical conductivity, and mechanical strength, offer numerous applications that can enhance crop productivity and resource efficiency. By facilitating nutrient delivery, improving soil structure, and promoting plant growth through enhanced water retention, CNTs hold the potential to revolutionize agricultural practices. As the global population continues to rise, necessitating increased food production, the integration of carbon nanotubes into agricultural systems presents a strategic pathway towards achieving sustainable and eco-friendly farming solutions. Understanding their applications and implications is essential for fostering a resilient agricultural future.

2. Definition of Carbon Nanotubes (CNTs)

Carbon nanotubes (CNTs) are an essential class of nanomaterials characterized by their unique cylindrical structure composed of carbon atoms arranged in a hexagonal lattice. Typically measuring 1 to 100 nanometers in diameter, CNTs can be either single walled (SWCNTs) or multi-walled (MWCNTs), with distinct properties that enhance their utility in various applications, including sustainable agriculture. Their extraordinary mechanical strength, high electrical conductivity, and large surface area make CNTs particularly promising for enhancing soil health, improving nutrient uptake, and offering eco-friendly pest control solutions. As a novel nanotechnology, CNTs contribute to the development of smart agricultural practices, serving as delivery systems for fertilizers and biopesticides, thus fostering environmentally sustainable farming. The exploration of CNTs for such applications is crucial as society faces increasing challenges related to food security and environmental degradation.

Corresponding Author:

Alagesan Arumugam

Associate Professor (Agronomy),
Indian Council of Agricultural
Research-Krishi Vigyan Kendra,
Tamil Nadu Agricultural
University, Pudukottai, Tamil
Nadu, India

3. Importance of Sustainable Agriculture

The significance of sustainable agriculture extends beyond mere food production; it encompasses environmental preservation, economic viability, and social equity. By adopting practices that protect ecosystems and biodiversity, sustainable agriculture seeks to mitigate the adverse effects of conventional farming techniques, such as soil degradation and water pollution. Emerging innovations, particularly in nanotechnology, have shown tremendous potential to enhance agricultural practices. Carbon nanotubes, for instance, can improve nutrient delivery systems in crops, resulting in higher yields with reduced chemical inputs. As noted, nanomaterials can positively impact various sectors, including agriculture through their reactive properties and larger surface area, enabling efficient resource utilization (Assey *et al.*, 2021) ^[3]. Furthermore, the integration of advanced nanotechnology into agricultural practices reinforces food security and sustainable development, ultimately fostering resilience against climate change and ensuring the longevity of agricultural systems (Kim *et al.*, 2024) ^[13]. This holistic approach underlines the critical role sustainable agriculture plays in shaping a viable future.

4. Overview of CNT applications in agriculture

Carbon nanotubes (CNTs) have emerged as transformative tools in the field of sustainable agriculture, owing to their unique properties that effectively enhance plant growth and protect against pests. Their high surface area and excellent electrical conductivity allow for improved nutrient delivery and enhanced photosynthesis in crops. Moreover, CNTs can significantly fortify plants against biotic and abiotic stressors by facilitating targeted delivery systems that minimize phytotoxicity, as highlighted in recent studies. The versatility of CNTs in the formulation of fertilizers, pesticides, and other agricultural inputs represents a breakthrough in precision farming, allowing for controlled application while reducing environmental impact (Bokhad *et al.*, 2024) ^[5]. Furthermore, with the potential for harnessing CNTs in water purification and soil remediation, their applications extend beyond immediate agricultural needs, addressing broader challenges such as water scarcity and pollution in agricultural systems (Assey *et al.*, 2021) ^[3]. This underscores the growing importance of nanotechnology in achieving sustainable agricultural practices.

5. Properties of Carbon Nanotubes

The properties of carbon nanotubes (CNTs) position them as transformative materials in the pursuit of sustainable agriculture. Characterized by their exceptional mechanical strength, electrical conductivity, and high surface area, CNTs enhance the efficiency of various agricultural applications, such as improving soil quality and increasing crop yields. Their nanoscale dimensions facilitate the efficient delivery of nutrients and pesticides, thus minimizing the environmental impact often associated with traditional agricultural practices. Furthermore, the reactivity of CNTs allows for modifications that can tailor their functionality to specific agricultural needs, fostering eco-friendly practices that align with the principles of sustainable development. As identified in recent reviews, the application of nanomaterials, including CNTs, is critical for addressing challenges in agriculture and environmental sustainability, demonstrating their potential to mitigate pollution and improve food production systems (Assey *et al.*, 2021) ^[3], (Checker *et al.*, 2022) ^[7]. By harnessing these properties, the agricultural sector can adopt innovative technologies that support both productivity and ecological balance.

6. Unique physical and chemical properties

The unique physical and chemical properties of carbon nanotubes (CNTs) render them exceptionally valuable in sustainable agriculture. These nanomaterials, characterized by their high surface area and extraordinary strength, facilitate enhanced nutrient delivery to plants, a critical component for improving soil health and crop productivity. The reactivity of CNTs, stemming from their nanoscale dimensions, allows them to interact beneficially with various soil constituents and microorganisms, promoting a more efficient uptake of essential nutrients while minimizing waste (Assey *et al.*, 2021) ^[3]. Moreover, the synthesis of CNTs from agricultural and industrial waste presents a cost-effective and environmentally friendly approach to nanomaterial production, addressing pollution concerns while harnessing waste for beneficial use (Cabral-Pinto *et al.*, 2021) ^[5]. Consequently, the integration of carbon nanotubes into agricultural practices not only optimizes crop yields but also aligns with broader sustainability goals, fostering eco-friendly methodologies crucial for modern agriculture.

7. Conductivity and strength advantages

The unique properties of carbon nanotubes (CNTs) present significant conductivity and strength advantages that can enhance agricultural practices sustainably. Their exceptional electrical conductivity facilitates more efficient distribution of nutrients and water, which is vital for optimizing plant growth in precision agriculture. Additionally, the mechanical strength of CNTs exceeds that of traditional materials, enabling the development of stronger and lighter agricultural implements that can improve operational efficiency. As noted in the literature, nanomaterials have larger surface areas that enhance their reactivity and, consequently, their effectiveness in various applications (Assey *et al.*, 2021) ^[3]. Moreover, branched carbon nanostructures, such as branched carbon nanotubes, exhibit remarkable electronic and mechanical properties that further augment their potential in crop monitoring and tissue regeneration technologies (Malik *et al.*, 2021) ^[14]. By leveraging these advantages, the incorporation of CNTs into agricultural practices may lead to increased productivity while mitigating the environmental impact.

8. Biocompatibility and environmental impact

The application of carbon nanotubes (CNTs) in sustainable agriculture raises important considerations regarding biocompatibility and environmental impact. As nanomaterials, CNTs exhibit unique properties such as increased surface area and reactivity, which can enhance their functionality in agricultural settings, particularly in aspects like nutrient delivery and pest control. However, the potential introduction of engineered nanoparticles, including CNTs, into ecosystems necessitates careful evaluation of their long-term effects on soil health and biodiversity. While CNTs can facilitate targeted agrochemical delivery, thereby minimizing waste and toxicity, the emergence of nanopesticides—crafted from nanostructures with dimensions between 1 to 200 nm—highlights the risk of exacerbating environmental waste if not managed properly (Alves *et al.*, 2021) ^[1]. Consequently, the balance between leveraging the benefits of CNTs for improved agricultural productivity and mitigating their environmental consequences is critical for achieving sustainable agricultural practices (Assey *et al.*, 2021) ^[3].

9. Enhancing Soil Quality with Carbon Nanotubes

The integration of carbon nanotubes in soil management presents a transformative approach to enhancing soil quality, pivotal for sustainable agriculture. These nanomaterials, characterized by their extraordinary surface area and reactivity, can significantly improve the physical and chemical properties of soil, facilitating better nutrient retention and water absorption. As highlighted in recent reviews, carbon nanotubes have shown promise in promoting beneficial microbial activity, which is essential for maintaining healthy soil ecosystems and improving plant growth. Additionally, their capacity to act as carriers for nutrients and pesticides can lead to more efficient application methods, thus reducing overall chemical use in agriculture (Asaduzzaman *et al.*, 2021) [2]. The broad applicability of carbon nanotubes in this context aligns with the goals of sustainable development by offering innovative solutions to traditional farming challenges (Assey *et al.*, 2021) [3]. Consequently, their adoption could lead to a substantial improvement in productivity, ensuring food security while minimizing environmental impact.

10. Role of CNTs in soil nutrient retention

The incorporation of carbon nanotubes (CNTs) into soil has revealed significant advantages regarding nutrient retention, thereby enhancing agricultural sustainability. CNTs exhibit remarkable properties such as high surface area and unique structural characteristics, which facilitate increased adsorption of essential nutrients like nitrogen, phosphorus, and potassium. This enhanced capability not only promotes better nutrient availability to plants but also reduces leaching losses, which is critical in managing soil fertility. As highlighted in recent studies, the interaction between CNTs and soil microbial communities further optimizes nutrient cycling and microbial activity, aligning with sustainable farming practices. Moreover, the application of nano-fertilizers has shown a potential to minimize pesticide usage by improving nutrient efficacy, driving the need for further exploration of their transport and fate in soil systems (Asaduzzaman *et al.*, 2021) [2]. Therefore, leveraging CNTs in soil can lead to more resilient agricultural ecosystems, addressing global food security concerns while promoting sustainable agriculture (Hernández Giménez *et al.*, 2023) [10].

11. Improvement of soil aeration and drainage

Enhancing soil aeration and drainage is critical for optimizing agricultural productivity and sustainability, particularly in the face of increasing food demands and climate variability. The incorporation of carbon nanotubes (CNTs) into soil has been recognized as a promising strategy to improve these vital soil properties. CNTs enhance soil structure by promoting porosity and facilitating better airflow, which is essential for root respiration and microbial activity. As noted in current research, biochar has also emerged as an effective amendment for improving soil hydraulic properties, impacting moisture retention and drainage capabilities (Edeh *et al.*, 2022) [9]. Furthermore, sustainable practices that combine the application of CNTs with traditional soil amendments can address the intricate challenges of soil management, ensuring efficient water use and enhanced nutrient delivery to crops (N/A). Such integrative approaches will likely pave the way for resilient agricultural practices that can meet the demands of a growing population.

12. Impact on soil microbial activity and health

The introduction of carbon nanotubes (CNTs) into agricultural

practices holds significant implications for soil microbial activity and health, crucial factors for maintaining soil fertility and ecosystem balance. CNTs aid in enhancing nutrient availability and promoting plant growth, but their interactions with soil microbial communities warrant careful consideration. Studies reveal that while CNTs can improve soil structure and aeration, their phytotoxicity may be contingent upon factors such as size, concentration, and the specific plant species involved, emphasizing the need for rigorous research into these effects (Kumar JS *et al.*, 2024) [11]. Additionally, synthesizing nanomaterials from agricultural waste presents a cost-effective and environmentally friendly approach, further enhancing sustainability (Cabral-Pinto *et al.*). Ultimately, understanding the complex responses of soil microbes to CNT applications is vital for harnessing their benefits while safeguarding soil health, ensuring that agricultural practices remain both productive and ecologically responsible.

13. Carbon Nanotubes in Crop Protection

The integration of carbon nanotubes (CNTs) into crop protection strategies heralds a transformative approach to sustainable agriculture. These nanomaterials exhibit unique properties such as high tensile strength and increased conductivity, making them ideal carriers for pesticides and nutrients. By encapsulating agrochemicals within CNTs, researchers have enhanced the targeted delivery and efficacy of these substances, thereby reducing the volume required for effective pest control. This technology is not only beneficial for improving crop yield but also minimizes the environmental impact associated with traditional pesticide application. As highlighted in recent studies, the development of nano pesticides utilizing carbon nanotubes aligns with sustainable agricultural practices, promoting eco-friendly solutions to combat pests while ensuring plant health (N/A). Furthermore, in regions like India, where agricultural ecosystems face significant threats from pollution and climate change, employing carbon nanotubes could provide environmentally conscious alternatives that address these pressing challenges (Checker *et al.*, 2022) [7].

14. Use of CNTs in pesticide delivery systems

The integration of carbon nanotubes (CNTs) into pesticide delivery systems presents a transformative approach to sustainable agriculture. CNTs are distinguished by their unique structural properties and high surface area, allowing for the encapsulation and controlled release of pesticides. This targeted delivery minimizes the non-specific dispersion of chemicals, thereby reducing potential environmental risks and enhancing the efficacy of the agrochemicals used. Research indicates that engineered nanomaterials (ENMs) can be utilized to develop smart-delivery systems that facilitate the precise application of pesticides, contributing to higher crop productivity with diminished ecological impact (Bokhad *et al.*, 2024) [5]. In the context of sustainable agricultural development, the application of CNTs demonstrates promise not only in pest management but also in promoting overall plant health and growth through the precision of nano pesticides (N/A). Ultimately, the adoption of CNT-based delivery systems could signify a substantial advancement towards sustainable agricultural practices that balance productivity and environmental stewardship.

15. Development of disease-resistant crops

The development of disease-resistant crops is an essential strategy in sustainable agriculture, particularly with the incorporation of advanced materials such as carbon nanotubes.

These innovative nanomaterials can enhance the delivery and efficiency of genetic traits responsible for disease resistance. For example, the application of carbon nanomaterials allows for the targeted delivery of nucleic acids involved in gene editing, facilitating the transfer of resistance genes into crops more effectively than traditional methods. Studies have shown that engineering crops like rice to incorporate resistance traits through techniques such as CRISPR-Cas can significantly reduce the reliance on chemical pesticides, leading to a more environmentally friendly approach to crop protection (N/A). Furthermore, utilizing carbon nanotubes can promote plant growth and resilience by improving nutrient uptake and enhancing stress responses (Basavantraya N Devanna *et al.*, 2024) ^[4]. Ultimately, the fusion of nanotechnology and crop genetic engineering presents a promising frontier in the quest for sustainable agricultural practices.

16. Reduction of chemical runoff and environmental pollution

Addressing the reduction of chemical runoff and environmental pollution remains a critical challenge in sustainable agriculture, and the application of carbon nanotubes offers innovative solutions in this regard. By utilizing these nanomaterials, it is possible to enhance nutrient delivery while minimizing the excessive use of fertilizers and pesticides that often lead to chemical runoff. Recent studies indicate that carbon nanotubes can improve the efficiency of nutrient uptake by enhancing soil properties and plant responses, thereby reducing the need for synthetic inputs. Moreover, the development of nano pesticides, which are engineered for targeted delivery, has been shown to limit environmental impact by decreasing the volume of chemicals released into ecosystems (Alves *et al.*, 2021) ^[1]. Nevertheless, it is crucial to monitor the use of these advanced materials carefully to prevent potential risks associated with nanotoxicity and ensure that they contribute positively to reducing environmental pollution (Cimpeanu *et al.*, 2020) ^[8].

17. Conclusion

In conclusion, the application of carbon nanotubes (CNTs) in sustainable agriculture presents a transformative opportunity to enhance agricultural practices while addressing pressing environmental concerns. The unique properties of CNTs, including their high surface area and reactivity, enable improved nutrient delivery and soil health, ultimately increasing crop yields and reducing the need for chemical fertilizers. As outlined in recent literature, advances in nanomaterials sciences could lead to significant improvements in energy efficiency and resource management within agricultural systems, underscoring their importance for sustainable development (Assey *et al.*, 2021) ^[3]. Furthermore, the integration of CNTs can facilitate innovative wastewater treatment methods, such as forward osmosis, which not only addresses water scarcity but also the removal of emerging contaminants from agricultural runoff (Hernández Giménez *et al.*, 2023) ^[10]. By harnessing the potential of carbon nanotubes, the agricultural sector can make substantial strides toward sustainability, encapsulating a holistic approach to food production in an era of climate change.

17.1. Summary of CNT benefits in sustainable agriculture

The integration of carbon nanotubes (CNTs) in sustainable agriculture presents a transformative opportunity to enhance crop productivity while minimizing environmental impacts. These nanomaterials exhibit unique properties, including high electrical conductivity and increased surface area, which can

improve nutrient uptake in plants. CNTs can also function as effective carriers for fertilizers and pesticides, ensuring more targeted delivery and reducing runoff and waste in agricultural systems. Additionally, their incorporation into soil enhances aeration and water retention, fostering healthier root development and resilience against drought conditions. As outlined in current research, CNTs are not only instrumental in promoting sustainable practices but also play a critical role in innovations like nano-bioelectronics. Such advancements contribute to environmental monitoring and agriculture productivity (Kim *et al.*, 2024) ^[13], thus addressing food security challenges and supporting sustainable development goals (Assey *et al.*, 2021) ^[3]. Ultimately, leveraging CNTs positions agriculture to meet the demands of a growing population while preserving vital ecological resources.

17.2. Future prospects for CNT applications

As the field of sustainable agriculture continues to evolve, the future prospects for carbon nanotube (CNT) applications appear promising. With the dual pressures of population growth and environmental sustainability, CNTs offer innovative solutions for enhancing crop productivity while reducing detrimental environmental impact. For instance, the development and application of nano-fertilizers and nano pesticides can lead to more efficient nutrient delivery systems that significantly enhance plant growth and health. Such advancements are vital, as traditional methods often contribute to soil depletion and pollution. Furthermore, the precision farming enabled by CNT-enabled nano sensors can provide real-time data on soil conditions, thereby optimizing resource use and minimizing waste. By harnessing the unique properties of CNTs, future agricultural practices can not only bolster food security but also foster eco-friendly methodologies that align with the goals outlined in research emphasizing the need for sustainable agricultural practices (Kana *et al.*, 2024) ^[12], (Checker *et al.*, 2022) ^[7].

17.3. Call to action for further research and implementation

In light of the promising applications of carbon nanotubes (CNTs) in sustainable agriculture, a concerted call to action for further research and implementation is essential. As agricultural practices increasingly grapple with the challenges of climate change, soil degradation, and resource scarcity, the potential of CNTs emerges as a pivotal solution to enhance crop productivity and resource efficiency. Continued investigation into the long-term effects, optimal combinations, and methodologies for CNT application will be vital for successful integration into existing farming systems. Moreover, collaboration between researchers, agricultural stakeholders, and policymakers will facilitate the transition from laboratory findings to practical, scalable solutions. By prioritizing funding and support for innovative research initiatives, the agricultural community can harness the unique properties of CNTs to promote resilience and sustainability. Ultimately, this proactive approach will not only address current agricultural challenges but also foster a more sustainable future for food production worldwide.

18. References

1. Alves T, Batain F, Chaud M, Oliveira-Junior *et al.* Nanopesticides in agriculture: benefits and challenge in agricultural productivity, toxicological risks to human health and environment. [Internet]. MDPI AG; 2021. Available from: <https://core.ac.uk/download/475361709.pdf>
2. Asaduzzaman Md, Baroi A, Islam S, Jahan *et al.* Potential

- Applications of Nanotechnology in Agriculture: A Smart Tool for Sustainable Agriculture. [Internet]. IntechOpen; 2021. Available from: <https://core.ac.uk/download/479935863.pdf>
3. Assey GE, Malasi WS. Advances in Nanomaterials Sciences and Nanotechnology for Sustainable Development: A Review. [Internet]. African Journals Online (AJOL); 2021. Available from: <https://core.ac.uk/download/487601486.pdf>
 4. Devanna BN, Joshi G, Dubey H, Singh PK, Singh P, Kumar R. The potential of genome editing to create novel alleles of resistance genes in rice. *Front Media S.A.* 2024. Available from: <https://core.ac.uk/download/615501658.pdf>
 5. Bokhad MN, Narhe AS, Parsodkar VJ, Patil *et al.* Engineered nanomaterials in plant protection: their controlled, site-directed delivery and phytotoxicity. [Internet]. Update Publishing House; 2024. Available from: <https://core.ac.uk/download/617706975.pdf>
 6. Cabral-Pinto MMS, Dinis PA, Diniz L, Hasan *et al.* Recent Advances on Properties and Utility of Nanomaterials Generated from Industrial and Biological Activities. [Internet]. MDPI AG; 2021. Available from: <https://core.ac.uk/download/547491377.pdf>
 7. Checker VG, Jha BS, Kathpalia R, Saxena *et al.* Environmental nanotechnological applications for Sustainable agriculture. [Internet]. CSIR-National Institute of Science Communication and Policy Research (NIScPR); 2022. Available from: <https://core.ac.uk/download/542644811.pdf>
 8. Cimpeanu CL, Ghita RV, Iconaru SL, Predoi *et al.* Application of Nanotechnology Solutions in Plants Fertilization. [Internet]. IntechOpen; 2020. Available from: <https://core.ac.uk/download/322446224.pdf>
 9. Edeh IG. 4D structure of biochar and its impact on soil water characteristics. [Internet]. University of Edinburgh; 2022. Available from: <https://core.ac.uk/download/533445503.pdf>
 10. Hernández Giménez A, Palacio Martínez L, Peña Miranda MDA, Prádanos del Pico *et al.* Forward osmosis application for the removal of emerging contaminants from municipal wastewater: A review. [Internet]. MDPI; 2023. Available from: <https://core.ac.uk/download/614626093.pdf>
 11. Jakhar SK, Kulhar KS, Kavitha R, Swati S. Harnessing Nanotechnology and Artificial Intelligence for Precision Agriculture in Smart Cities. [Internet]. EDP Sciences; 2024. Available from: <https://core.ac.uk/download/616918747.pdf>
 12. Kana HA, Kwon-Ndung EH, SIRAJO SA. Applications of Nanobreeding for the Enhancement of Food Security. [Internet]. Federal University of Lafia, Nasarawa State, Nigeria; 2024. Available from: <https://core.ac.uk/download/613008572.pdf>
 13. Kim S, Li P, Tian B. Beyond 25 years of biomedical innovation in nano-bioelectronics. [Internet]. 2024. Available from: <https://core.ac.uk/download/613853123.pdf>
 14. Malik S, Marchesan S. Growth, properties, and applications of branched carbon nanostructures. [Internet]. MDPI; 2021. Available from: <https://core.ac.uk/download/482229492.pdf>