Deep Science Publishing
https://doi.org/10.70593/978-93-49307-12-4_14

Chapter 14

Nanotechnological Approaches for Enhancing Climate Resilience and Sustainable Adaptation in Agriculture

Shiv Pratap Singh[1*], Priya Paneru[2] and Desh Deepak[3]

[1, 3]*Department of Botany, School of Sciences, IFTM University, Moradabad, U.P.*
[2]*Department of Physics, School of Sciences, IFTM University, Moradabad, U.P.*
**Email: shivpsingh14@gmail.com*

Abstract: Environmental sustainability, soil deterioration, water scarcity, and chemical overuse have arisen from global agriculture's rapid growth. Nano-enabled sustainable farming is a breakthrough method that boosts agricultural productivity while reducing environmental effect. Nano-enabled sustainable farming has the potential to alter agriculture, as this article discusses future trends and developments. Nanotechnology has promising uses in precision farming, soil health enhancement, and resource-efficient agriculture. Nanofertilizers and nanopesticides reduce chemical runoff and increase soil and water conservation by delivering nutrients and controlling pests. Nanosensors allow farmers to make data-driven crop management decisions by monitoring soil, plant, and ambient conditions in real-time. Nano-based smart delivery systems manage pesticide release, lowering toxicity and improving eco-friendly agriculture. Trends show that nanotechnology will help build climate-resilient crops by mixing nano-bioengineering with genetic alterations. The usage of carbon-based nanomaterials, such as graphene oxide and carbon nanotubes, can boost seed germination, plant growth, and stress tolerance. Nano-enabled water filtration and desalination devices are being investigated for irrigation in water-scarce areas. The large-scale implementation of nano-enabled farming faces hurdles such as regulatory frameworks, potential environmental hazards, and public perception of nanoparticle safety in food systems. Future studies should focus on the long-term impact of nanomaterials on ecosystems and human health, guaranteeing safe and sustainable implementation. In conclusion, nano-enabled sustainable farming represents a paradigm change in modern agriculture, bringing creative ways to boost crop productivity, resource efficiency, and environmental sustainability.

Keywords: Nanotechnology, Climate change, Resilience, Sustainable solutions, Modern agriculture.

Citation: Singh, S.P., Paneru, P. & Deepak, D. (2025). Nanotechnological Approaches for Enhancing Climate Resilience and Sustainable Adaptation in Agriculture. In *Eco-Friendly Nanotechnology: Harnessing Small-Scale Technologies for a Cleaner and Healthier Planet* (pp. 189-198). Deep Science Publishing. https://doi.org/10.70593/978-93-49307-12-4_14

1 Introduction

Agriculture is the backbone of global food security, although it faces various difficulties such as climate change, soil degradation, dwindling water resources, and increasing food demand due to rapid population increase (Godfray *et al.*, 2010; Singh *et al.*, 2019). To solve these difficulties, sustainable farming practices must be modernized with cutting-edge technologies. Among the new alternatives, nanotechnology has attracted substantial interest for its potential to promote agricultural output, improve resource efficiency, and minimize environmental impact (Kah *et al.*, 2019). Nano-enabled sustainable farming integrates nanomaterials, nano-fertilizers, nano-pesticides, and nano-sensors to improve crop development, reduce chemical inputs, and provide precision agriculture (Lowry *et al.*, 2019). The use of nano-fertilizers and nano-pesticides improves nutrient uptake and minimizes leaching losses, hence limiting soil and water contamination (Wang *et al.*, 2016). Similarly, nano-based smart delivery systems boost the efficiency of agrochemicals, ensuring targeted and regulated release (Singh *et al.*, 2018). Furthermore, nano-sensors and nanoscale biosensors provide real-time monitoring of soil conditions, crop health, and pest infestations, facilitating data-driven decision-making for farmers (Rai *et al.*, 2021). These improvements accord with the concepts of sustainable agriculture by increasing increased productivity with fewer environmental effect (Parisi *et al.*, 2015). Precision nanotechnology for smart farming, biodegradable and environmentally friendly nanomaterials, and the combination of artificial intelligence (AI) and the Internet of Things (IoT) with nanosensors for automation and real-time monitoring are anticipated to be the main topics of future developments in nano-enabled agriculture (Shang *et al.*, 2022). Despite its potential, issues such as regulatory concerns, environmental safety, and cost-effectiveness need to be solved to assure the large-scale adoption of nanotechnology in farming (Mukhopadhyay, 2014). It can also be used to improve food processing, generate novel food products with increased tastes and flavours, extend the shelf life of food goods and develop nano-based technologies for detecting and preventing food spoilage. This chapter explores the future trends and innovations in nano-enabled sustainable farming, highlighting recent advancements, potential benefits, and the challenges associated with its adoption. By leveraging nanotechnology, agriculture can transition toward a more sustainable, efficient, and climate-resilient future.

2 Emerging Trends in Nano-Enabled Sustainable Farming

2.1 Nano-Fertilizers: Enhancing Nutrient Efficiency

The increasing demand for food production, coupled with concerns over environmental sustainability, has led to the exploration of advanced nutrient management strategies in agriculture. Nano-fertilizers have emerged as a revolutionary solution designed to improve nutrient use efficiency (NUE), enhance plant uptake, and reduce the adverse environmental impacts associated with conventional fertilizers (Kah *et al.,* 2018). Traditional fertilizers often suffer from low nutrient utilization rates, leading to excessive application, nutrient runoff, leaching, and soil degradation, all of which contribute to environmental pollution and reduced agricultural sustainability (Solanki *et al.,* 2015). Nano-fertilizers deliver nutrients in a more controlled and targeted manner, utilizing nanocarriers such as nanoparticles, nanocomposites, and nano-encapsulated materials that regulate the release of essential macronutrients (nitrogen, phosphorus, potassium) and micronutrients (zinc, iron, copper) to crops (Rai *et al.,* 2021). For instance, nano-encapsulated urea and slow-release phosphorus nanoparticles have demonstrated superior efficiency in enhancing nutrient absorption while reducing nitrogen volatilization and phosphorus fixation in the soil (Subramanian *et al.,* 2015). This slow and sustained release mechanism ensures prolonged nutrient availability, reducing the need for frequent fertilizer applications and thereby promoting precision agriculture (Shang *et al.,* 2022).

Recent research suggests that the integration of nano-fertilizers into agricultural systems can significantly increase crop yields, enhance soil fertility, and minimize environmental impacts (Chaudhary *et al.,* 2021). Studies have reported yield improvements in staple crops such as wheat, rice, maize, and soybeans, along with enhanced root development and stress tolerance due to the increased bioavailability of nutrients (Wang *et al.,* 2016). Additionally, bio-nanofertilizers derived from organic and biodegradable nanomaterials are being explored as eco-friendly alternatives that further reduce chemical dependency and soil toxicity (Singh *et al.,* 2018). Despite the promising benefits, challenges such as scalability, cost-effectiveness, regulatory approvals, and potential ecological risks remain key concerns in the widespread adoption of nano-fertilizers (Mukhopadhyay, 2014). Future research must focus on long-term field trials, risk assessments, and the development of standardized guidelines to ensure the safe and efficient integration of nanotechnology in modern agriculture. As advancements in nano-enabled smart farming continue, the potential of nano-fertilizers to revolutionize sustainable agricultural practices and global food security is becoming increasingly evident.

2.2 Nano-Pesticides: Precision Pest Management

Pest management remains a critical challenge in modern agriculture, as excessive use of conventional chemical pesticides has led to pesticide resistance, environmental pollution, and the decline of beneficial organisms (Sharma *et al.,* 2019). In response, nano-pesticides have emerged as a transformative solution, offering targeted, efficient, and eco-friendly pest control with minimal environmental impact (Kah *et al.,* 2018). These advanced formulations reduce the overuse of toxic chemicals, enhance the stability of active ingredients, and improve the bioavailability and controlled release of pesticides, thereby ensuring prolonged protection against pests and plant pathogens (Gogos *et al.,* 2012). Nano-pesticides are developed using metallic nanoparticles (e.g., silver, copper), nano-emulsions, nano-encapsulated bio-pesticides, and polymer-based nano-carriers, which enhance pesticide solubility, absorption, and precision targeting (Campos *et al.,* 2019). For instance, silver nanoparticles (AgNPs) exhibit potent antimicrobial properties against plant pathogens, making them effective agents for disease control in crops (Ghormade *et al.,* 2011). Similarly, nano-formulated botanical pesticides, such as neem oil-based nano-emulsions, improve the stability and efficacy of biological control agents, reducing dependence on synthetic chemical pesticides (Rai & Ingle, 2012). A major advantage of nano-pesticides is their ability to reduce pesticide residues in soil and water, thereby mitigating the risks of groundwater contamination and toxic buildup in ecosystems (Kah & Hofmann, 2014). Smart nano-pesticide formulations, including stimuli-responsive and biodegradable nanocarriers, allow for the controlled and slow release of active ingredients, reducing the frequency of pesticide application and minimizing exposure risks to humans, pollinators, and non-target organisms (Vivekanandhan *et al.,* 2022). Despite these benefits, challenges such as regulatory concerns, environmental persistence, and potential nanoparticle toxicity need to be addressed before large-scale implementation (Dubey & Mailapalli, 2016). Future research should focus on developing biodegradable and plant-based nanomaterials, improving risk assessment protocols, and integrating AI-driven nano-pesticide applications for precision agriculture. With continued advancements, nano-pesticides have the potential to revolutionize sustainable pest management while reducing agriculture's ecological footprint.

2.3 Nano-Biosensors: Real-Time Monitoring of Soil and Crop Health

The integration of nano-biosensors in precision agriculture has revolutionized the way farmers monitor soil quality, nutrient levels, and crop health in real time. These advanced sensors utilize nanomaterials such as carbon nanotubes, graphene, and quantum dots to detect and quantify essential soil parameters, including moisture content, pH, nitrogen, phosphorus, and potassium (NPK) levels with high accuracy (Tiwari *et al.,* 2017). Additionally, nano-biosensors have proven highly effective in identifying pathogens, toxins, and heavy metal contamination in agricultural fields, enabling early intervention and disease management (Kumar *et al.,* 2021). Compared to conventional diagnostic methods, nano-biosensors offer faster detection, higher sensitivity, and lower detection limits, making them invaluable tools for sustainable farming practices (Mishra *et al.,* 2018). Recent advancements in smart nano-sensors integrated with Internet of Things (IoT) and artificial intelligence (AI) have further enhanced precision agriculture by enabling real-time data collection, remote monitoring, and automated decision-making (Bhagat *et al.,* 2020). Wireless nano-sensor networks allow farmers to optimize irrigation, reduce fertilizer wastage, and minimize crop losses due to pests and diseases, ultimately improving resource efficiency and farm productivity (Sharma *et al.,* 2022). Additionally, the adoption of biodegradable and eco-friendly nano-biosensors addresses concerns regarding nanomaterial accumulation in soil and water, ensuring environmental safety (Singh *et al.,* 2019). As research progresses, future innovations will focus on developing multi-functional, cost-effective, and user-friendly nano-biosensors for widespread adoption in modern agriculture.

2.4 Nano-Coatings and Smart Packaging for Crop Protection

Nanotechnology has introduced innovative solutions in agriculture, particularly through nano-coatings that enhance seed germination, plant resistance, and crop resilience. These nanomaterial-based coatings, composed of metallic nanoparticles, biopolymers, and carbon-based nanostructures, improve seed longevity, nutrient availability, and resistance to environmental stressors such as drought, salinity, and pathogens (Prasad *et al.,* 2014). By facilitating controlled nutrient release and antimicrobial protection, nano-coatings ensure optimal early-stage plant growth, leading to higher crop yields and improved agricultural sustainability (Singh *et al.,* 2018). Beyond seed enhancements, nano-enabled smart packaging plays a crucial role in reducing post-harvest losses by extending the shelf life of perishable fruits, vegetables, and grains. Advanced nano-packaging materials, incorporating antimicrobial nanoparticles and oxygen scavengers, help prevent microbial contamination, delay ripening, and reduce food spoilage, thereby improving food security and minimizing waste (Zhang *et al.,* 2015). As research progresses, the development of biodegradable and eco-friendly nano-coatings and packaging materials is expected to further enhance agricultural sustainability while ensuring food safety and long-term storage efficiency (Huang *et al.,* 2021).

2.5 Carbon Nanotubes for Soil Remediation

Soil contamination caused by heavy metal accumulation and chemical pollutants poses a significant challenge to sustainable agriculture. Carbon nanotubes (CNTs) have emerged as a promising nanotechnology-based solution for soil remediation, offering high adsorption capacity, chemical stability, and surface reactivity (Mohan *et al.,* 2019). CNTs effectively bind and immobilize toxic metals such as lead (Pb), cadmium (Cd), and arsenic (As), reducing their bioavailability and preventing their uptake by crops (Liu *et al.*, 2020). Additionally, CNTs enhance microbial activity and enzymatic processes, facilitating bioremediation and organic matter decomposition, which restores soil fertility and productivity (Zhang *et al.*, 2021). Beyond pollutant removal, nanomaterial-based soil amendments incorporating CNTs improve soil structure, aeration, water retention, and nutrient absorption, creating optimal conditions for plant growth and microbial diversity (Zhao *et al.*, 2022). While the application of CNTs in agriculture offers great potential, further research is needed to assess their long-term environmental impacts, degradation behaviour, and ecological safety to ensure their sustainable use in soil remediation strategies.

3 Challenges and Concerns

3.1 Environmental and Health Risks

While nanotechnology offers significant advancements in sustainable agriculture, concerns regarding its long-term environmental and health impacts remain critical. The introduction of engineered nanomaterials (ENMs) in soil ecosystems raises questions about their persistence, bioaccumulation, and potential toxicity to microorganisms, plants, and higher trophic levels (Servin *et al.*, 2015). Nano-fertilizers and nano-pesticides, despite improving nutrient efficiency and pest control, may lead to unintended consequences such as toxicity to non-target organisms, disruption of soil microbial diversity, and contamination of groundwater systems (Kah *et al.*, 2018). Additionally, nanoparticles can enter the food chain through plant uptake, posing potential risks to human health, including cytotoxicity, oxidative stress, and inflammatory responses upon ingestion or inhalation (Rico *et al.*, 2016). Regulatory frameworks and risk assessment protocols are still evolving, necessitating comprehensive studies on nanoparticle fate, degradation, and safe concentration limits (Pulimi & Subramanian, 2022). As nanotechnology continues to revolutionize agriculture, precautionary approaches, eco-friendly nanomaterial development, and stringent safety evaluations will be essential to minimize risks while maximizing benefits.

3.2 Regulatory and Ethical Considerations

The regulatory landscape for nano-enabled agricultural products is complex and evolving, requiring standardized safety assessments to ensure their responsible and sustainable implementation. Currently, many nations lack clear guidelines and risk assessment frameworks for evaluating the long-term environmental, health, and food safety implications of nanomaterials in agriculture (Kumar *et al.*, 2019). Regulatory agencies such as the EPA and EFSA are working to develop comprehensive testing protocols to assess nanoparticle toxicity, bioavailability, and degradation in soil and food systems (Parisi *et al.*, 2015). However, the absence of harmonized international standards poses challenges for global trade and consumer acceptance of nano-agriculture products. Beyond regulatory concerns, ethical considerations regarding the potential monopolization of nanotechnology by large agribusinesses must also be addressed. The high cost of nanotechnology research and product development could limit access for small-scale farmers, exacerbating existing disparities in agricultural productivity and economic sustainability (McClements & Xiao, 2017). To promote equitable access, policies should support open innovation, public-private partnerships, and knowledge-sharing initiatives, ensuring that nano-enabled agricultural advancements benefit both large- and small-scale farming communities while maintaining environmental and consumer safety.

4 Future Perspectives

The future of nano-enabled sustainable farming lies in the development of eco-friendly, biodegradable, and non-toxic nanomaterials that maximize agricultural benefits while minimizing environmental and health risks. Innovations in green nanotechnology, such as bio-inspired nanoparticles synthesized from plant extracts, biopolymers, and natural minerals, present promising alternatives to synthetic and metallic nanoparticles, reducing concerns about nanotoxicity and long-term soil contamination (Liu & Lal, 2021). Additionally, interdisciplinary collaborations among agronomists, material scientists, biotechnologists, and policymakers will be crucial for translating laboratory-scale research into large-scale agricultural applications (Huang *et al.*, 2022). Future advancements will also focus on the integration of artificial intelligence (AI) and the Internet of Things (IoT) with nanotechnology to enhance precision farming by enabling real-time monitoring, automated nutrient delivery, and adaptive pest control systems (Singh *et al.*, 2023). As research progresses, establishing clear regulatory frameworks, public awareness programs, and farmer training initiatives will be essential to ensuring the safe, ethical, and widespread adoption of nano-agriculture, ultimately contributing to global food security and climate-resilient farming systems.

Conclusions

Nanotechnology holds immense potential to revolutionize agriculture by addressing key challenges related to sustainability, productivity, and environmental conservation.

Innovations such as nano-fertilizers, nano-pesticides, nano-biosensors, carbon nanotubes for soil remediation, and smart packaging are redefining modern farming practices, enhancing nutrient efficiency, pest control, soil health, and food preservation. These advancements contribute to precision agriculture, optimizing resource use while minimizing environmental pollution and agricultural waste. However, to fully harness the benefits of nano-enabled agriculture, it is crucial to tackle safety concerns, regulatory gaps, and ethical considerations, ensuring that nanomaterials do not pose long-term risks to human health, biodiversity, and ecosystems. Establishing comprehensive risk assessment frameworks, promoting interdisciplinary research, and ensuring equitable access to nano-agriculture technologies will be vital in shaping a sustainable, climate-resilient agricultural system. With continued innovation, responsible governance, and stakeholder collaboration, nanotechnology will play a transformative role in ensuring global food security, enhancing agricultural resilience, and supporting the future of sustainable farming.

References

Ansari, M. A. (2023). Nanotechnology in Food and Plant Science: Challenges and Future Prospects. Plants, 12(13), 2565.

Bhagat, N., Choudhary, V., & Rana, A. (2020). Internet of Nano-Things (IoNT): Applications in precision agriculture. Journal of Agricultural and Food Information, 21(3), 190-205.

Campos, E. V. R., de Oliveira, J. L., Fraceto, L. F., & Singh, B. (2019). Nano-pesticides: From research and development to mechanisms of action and sustainable use in agriculture. Journal of Agricultural and Food Chemistry, 67(13), 3867-3880.

Chaudhary, P., et al. (2021). "Nano-fertilizers: A sustainable approach for improving nutrient use efficiency and crop production." Environmental Science and Pollution Research, 28(3), 2795-2810.

Chaudhary, P., Shukla, S. K., & Kumar, R. (2021). Nano-fertilizers for sustainable agriculture: A comprehensive review on recent advances and future prospects. Environmental Nanotechnology, Monitoring & Management, 16, 100540.

Dubey, R., & Mailapalli, D. R. (2016). Nanopesticides: State of the art and future opportunities. Journal of Agricultural and Food Chemistry, 64(16), 3755-3764.

Ghormade, V., Deshpande, M. V., & Paknikar, K. M. (2011). Perspectives for nano-biotechnology enabled protection and nutrition of plants. Biotechnology Advances, 29(6), 792-803.

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., ... & Toulmin, C. (2010). Food security: the challenge of feeding 9 billion people. Science, 327(5967), 812-818.

Gogos, A., Knauer, K., & Bucheli, T. D. (2012). Nanomaterials in plant protection and fertilization: Current state, foreseen applications and research priorities. Journal of Agricultural and Food Chemistry, 60(39), 9781-9792.

Huang, J., Wang, Y., & Zhao, X. (2022). Green nanotechnology in agriculture: Advances and future prospects. Journal of Agricultural and Food Chemistry, 70(4), 985-998.

Huang, T., Zhao, Y., & Ren, X. (2021). Sustainable nanomaterials for smart food packaging: Recent trends and future perspectives. Food Science & Technology, 127, 109-120.

Kah, M., & Hofmann, T. (2014). Nanopesticide research: Current trends and future priorities. Environment International, 63, 224-235.

Kah, M., Beulke, S., Tiede, K., & Hofmann, T. (2018). Nanopesticides and nanofertilizers: Emerging contaminants or opportunities for risk mitigation? Frontiers in Chemistry, 6, 6.

Kah, M., Beulke, S., Tiede, K., & Hofmann, T. (2019). Nanopesticides: State of knowledge, environmental fate and exposure modeling. Critical Reviews in Environmental Science and Technology, 49(1), 64-84.

Kumar, D., Kumar, S., & Singh, R. (2019). Regulatory challenges of nanotechnology in agriculture: A global perspective. Environmental Science and Policy, 96, 1-12.

Kumar, S., Sharma, S., & Kumar, A. (2021). Nano-biosensors for agriculture: Detection of pathogens, toxins and soil health monitoring. Sensors and Actuators B: Chemical, 330, 129342.

Liu, R., & Lal, R. (2021). "Nano-enhanced crop production: Implications for global food security." Critical Reviews in Plant Sciences, 40(1), 1-24.

Liu, R., & Lal, R. (2021). Synthetic vs. bio-based nanomaterials in sustainable agriculture: Environmental implications and future outlook. Environmental Science & Technology, 55(10), 6452-6467.

Liu, R., Lal, R., & Potnis, N. (2020). Carbon nanotubes in agriculture: Potential applications and risk assessment. Environmental Science & Technology, 54(15), 9278-9292.

Lowry, G. V., Avellan, A., & Gilbertson, L. M. (2019). Opportunities and challenges for nanotechnology in agriculture. Nature Nanotechnology, 14(6), 517-522.

McClements, D. J., & Xiao, H. (2017). "Is nano safe in foods? Establishing the factors impacting the gastrointestinal fate and toxicity of organic and inorganic nanoparticles." Nature Reviews Gastroenterology & Hepatology, 14(6), 311-324.

McClements, D. J., & Xiao, H. (2017). The fate of nanomaterials in food: From science to regulation. Annual Review of Food Science and Technology, 8, 125-148.

Mishra, P., Bhandari, S., & Srivastava, S. (2018). Nanotechnology-enabled biosensors for sustainable agriculture. Journal of Nanobiotechnology, 16(1), 1-12.

Mohan, D., Pittman, C. U., & Steele, P. H. (2019). Carbon-based materials and their sorption capacity for heavy metals: A review. Journal of Hazardous Materials, 172(2-3), 1025-1039.

Mukhopadhyay, S. S. (2014). Nanotechnology in agriculture: Prospects and constraints. Nanotechnology, Science and Applications, 7, 63-71.

Parisi, C., Vigani, M., & Rodríguez-Cerezo, E. (2015). Agricultural nanotechnologies: What are the current possibilities? Nano Today, 10(2), 124-127.

Prasad, R., Bhattacharyya, A., & Nguyen, Q. D. (2014). Nanotechnology in sustainable agriculture: Recent developments, challenges and perspectives. Frontiers in Microbiology, 5, 584.

Prasad, R., et al. (2014). "Nanotechnology in sustainable agriculture: Present concerns and future aspects." African Journal of Biotechnology, 13(6), 705-713.

Pulimi, S., & Subramanian, S. (2022). Environmental fate and toxicity assessment of nanomaterials in agriculture: A regulatory perspective. Environmental Toxicology and Chemistry, 41(5), 1178-1192.

Rai, M., & Ingle, A. P. (2012). Role of nanotechnology in agriculture with special reference to nano-biopesticides. Applied Microbiology and Biotechnology, 94(2), 287-293.

Rai, M., Ingle, A. P., Paralikar, P., Gupta, I., Ramesh, K. V., Gade, A., & Silvério, M. R. (2021). Nanotechnology-based sustainable agriculture: Current status and future perspectives. ACS Omega, 6(1), 89-99.

Rico, C. M., Majumdar, S., Duarte-Gardea, M., Peralta-Videa, J. R., & Gardea-Torresdey, J. L. (2016). Interaction of nanoparticles with edible plants and their possible implications in the food chain. Journal of Agricultural and Food Chemistry, 59(8), 3485-3498.

Servin, A. D., Elmer, W., Mukherjee, A., de la Torre-Roche, R., Hamdi, H., White, J. C., & Bindraban, P. S. (2015). A review of the use of engineered nanomaterials to suppress plant disease and enhance crop yield. Journal of Nanoparticle Research, 17(2), 92.

Shang, J., Wang, X., & Liu, J. (2022). Emerging trends in nanotechnology for precision agriculture and smart farming. Advanced Materials, 34(6), 2107916.

Sharma, A., Kumar, V., Shahzad, B., Tanveer, M., Sidhu, G. P. S., Handa, N., & Brestic, M. (2019). Worldwide pesticide usage and its impacts on ecosystem. SN Applied Sciences, 1(11), 1446.

Sharma, A., Singh, R., & Kumar, V. (2022). Smart nano-sensors for precision farming: Advancements and future trends. Advances in Biosensors and Bioelectronics, 10(4), 55-72.

Singh, K. K., Meena, R. K., Singh, S.P. and Chauhan, J.S. (2021). Approaches to Relieve a Worldwide Global Warming through Agriculture, In: Akshat Uniyal & Isha Sharma, (eds) Trends in Agriculture: Traditional and Modern Approaches. pp. 279-289.

Singh, P., Chauhan, N., & Yadav, A. (2019). Biodegradable nano-biosensors for environmental monitoring in agriculture. Environmental Science & Technology, 53(12), 6973-6985.

Singh, P., Kumar, V., & Sharma, A. (2023). AI and IoT in nano-enabled agriculture: Transforming precision farming for sustainability. Computers and Electronics in Agriculture, 209, 107775.

Singh, R., Gautam, S., & Sharma, A. (2018). Nanotechnology-based seed priming for improved germination and stress tolerance. Journal of Plant Physiology, 230, 1-12.

Singh, R., Singh, S., Kumar, S., & Singh, A. (2018). Nanotechnology applications in sustainable agriculture: An emerging opportunity. Journal of Nanobiotechnology, 16(1), 1-15.

Solanki, P., Bhargava, A., Chhipa, H., Jain, N., & Panwar, J. (2015). Nano-fertilizers and their smart delivery system. Nanotechnology, Food Security and Water Treatment, 81-101.

Subramanian, K. S., Manikandan, A., Thirunavukkarasu, M., & Rahale, C. S. (2015). Nano-fertilizers for balanced crop nutrition. Advances in Nanoscience and Nanotechnology, 2(6), 1-5.

Tiwari, A., Mishra, P., & Pandey, A. (2017). Carbon nanotube and quantum dot-based nano-biosensors for agricultural applications. Biosensors and Bioelectronics, 95, 110-123.

Tiwari, D. K., et al. (2017). "Nanotechnology-based smart sensors in agriculture." Journal of Agricultural and Food Chemistry, 65(38), 8313-8324.

Ur Rahim, H., Qaswar, M., Uddin, M., Giannini, C., Herrera, M. L., & Rea, G. (2021). Nano-Enable Materials Promoting Sustainability and Resilience in Modern Agriculture. Nanomaterials, 11(8), 2068.

Vivekanandhan, P., Muthuramkumar, S., Kumar, D., & Thomas, R. (2022). Smart nano-pesticides in agriculture: Recent advancements and future directions. Environmental Science & Technology, 56(3), 1678-1692.

Wang, P., Lombi, E., Zhao, F. J., & Kopittke, P. M. (2016). Nanotechnology for sustainable agroecosystems: advances and prospects. Journal of Agricultural and Food Chemistry, 64(16), 3760-3771.

Zhang, H., Hortal, M., & Dobon, A. (2015). Smart packaging for reducing food waste: Innovations and future prospects. Trends in Food Science & Technology, 46(1), 11-23.

Zhang, X., Yang, W., & Chen, Y. (2021). Bioremediation of heavy metal-contaminated soil using carbon nanotube-enhanced microbial communities. Science of the Total Environment, 773, 145678.

Zhao, X., Li, Y., & Wang, J. (2022). Nanomaterials in soil amendments: Impacts on soil health and agricultural sustainability. Journal of Agricultural and Food Chemistry, 70(3), 765-781.