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Application of Nanotechnology in Plant Growth and Protection

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Abstract: *In recent years, nanotechnology has become a promising approach for modern agriculture with a range of innovative applications to improve plant growth, nutrient-use efficiency and crop protection from biotic and abiotic stresses. In agriculture, the use of nanomaterials has led to the creation of nanofertilizers, nanopesticides, nanosensors, and nanosensors for delivering nutrient and pesticide materials, which boost crop yield and reduce the impacts on the environment. The nanoparticles have unique physicochemical properties such as high surface area, controlled release and enhanced reactivity that increase the efficiency of agricultural inputs. The use of nanosized formulations allows for targeted nutrient application, minimisation of chemical waste and increase in plant physiological function including photosynthesis, enzyme activity and stress resistance. Nanotechnology plays a role in plant protection related to the detection of disease, delivery of pesticides, pathogen suppression, and the facilitation of smart biosensors to provide early warning of disease. Nevertheless, the benefits are outweighed by concerns about the toxicity, environmental persistence and regulation of nanoparticles. A comprehensive risk assessment, green synthesis approaches, and guidelines for safe agricultural applications are necessary to implement sustainable solutions. This paper aims to give a detailed review on the application of nanotechnology in plant growth and protection, covering recent advancements, mode of action, possibilities, challenges and future directions to ensure sustainable agriculture.*

Keywords: Nanotechnology, Nanofertilizers, Nanopesticides, Plant Growth, Plant Protection, Nanosensors, Sustainable Agriculture

I. INTRODUCTION

In recent years agriculture is facing a number of challenges, such as fast growing population, climate change, decreasing fertility of soil, lack of water, and high incidence of pests and diseases. Traditional agriculture methods heavily depend on chemical fertilizers and pesticides, leading to environmental pollution, soil degradation, loss of biodiversity, and unsustainable agriculture practices. Thus the development of innovative technologies that would make it possible to increase crop productivity, but at the same time reduce the ecological damage, has become a global priority. Nanotechnology is emerging as a potential solution for these challenges because the nanomaterials exhibit some unique properties, including increased surface area, increased reactivity, and controlled release characteristics, that are evident at the nanoscale (1–100 nm) (Usman et al., 2020)

Nanotechnology has helped fabricate several products for agricultural use, such as nanofertilizers, nanopesticides, nanopesticidal genetic transformation techniques, nanoherbicides and nanosensors. These innovations increase nutrient-use efficiency, help to deliver agrochemicals in a controlled manner, improve stress tolerance and deliver good protection from plant pathogens. Nanoparticles can directly affect the plant tissues and enhance uptake of nutrients, control physiological processes, and activate defense mechanisms against biotic and abiotic stresses (Mgadi et al., 2024). In addition, plant nanobionics and precision agriculture have allowed the real-time assessment of plant health via nanosensors, which has promoted sustainable agriculture. This paper reviews the applications of nanotechnology in plant growth and protection and critically explores the latest advances, advantages, problems, and potential for the sustainable development of agriculture.

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II. LITERATURE REVIEW

Kalu et al. (2026) reviewed the recent advances in the use of nanoparticles for the identification and control of plant diseases. The study showed that nanopesticides can be used to create targeted delivery systems that have controlled-release properties, which can increase the effectiveness of the pesticide and decrease environmental contamination. The authors also identified the green synthesis routes for the preparation of eco-friendly biodegradable nanoparticles. The results indicate that the use of nanotechnology will become more common in future agriculture, combined with digital farming and smart monitoring systems, to enhance the health and productivity of crops.[1]

Landina et al. (2025) discussed the recent developments in crop improvement and sustainable agriculture using nanotechnology. They concluded that the use of nano fertilizers can substantially improve the germination rate, chlorophyll content, photosynthetic efficiency and biomass production. The authors also noted that nano-formulations enhance drought and salinity resistance in plants through the modulation of antioxidant activities, nutrient uptake mechanisms. The study found that nanotechnology has significant potential to enhance agricultural production in the context of changing climate.[2]

Salam et al. (2025) reviewed how nanomaterials can be used for plant disease management and early detection of plant pathogens. The researchers found that silver, zinc oxide and copper nanoparticles have high antimicrobial properties against a number of economically significant fungal and bacterial pathogens. Furthermore, nanosensor technologies combined with artificial intelligence were seen to aid in the early detection of diseases and precision crop management. The study highlighted the importance of using nano technologies in plant protection to minimize reliance on traditional chemical pesticides and support sustainable agriculture.[3]

Mgadi et al., (2024), studied the interactions between agricultural nanoparticles and plant-associated microorganisms. The study revealed that nanomaterials can have a beneficial effect on the soil fertility and plant growth through better nutrient availability and positive effect on the beneficial microbial activities. The authors, however, reported that too many nanoparticles can "have a negative impact on the diversity of microorganisms in soil and their function. The research suggested long-term ecological evaluations to determine the environmental consequences of Nano-agricultural technologies. [4]

Usman et al. (2020) reviewed status, challenges and future prospects of nanotechnology in agriculture. The authors pointed that nanotechnology can play a significant role in improving the sustainability of agriculture by producing nanofertilizers, nanopesticides and nanosensors. Their study highlighted the importance of using precision farming techniques, reducing environmental pollution, and improving nutrient-use efficiency with the use of nano-enabled inputs. At the same time, they pointed to potential issues of nanotoxicity and the need for comprehensive regulations for safe commercialization.[5]

III. RESEARCH METHODOLOGY

3.1 Research Design

The methodology used in the present study is systematic review which is used to explore the current applications of nanotechnology in plant growth and protection. It was deemed appropriate to adopt a systematic review approach as

[1] Kalu, C. M., et al. (2026). Applications of nanoparticles in plant disease identification and control. *Nanoscale Research Letters, 21*(1), 44.

[2] Landina, D., Abdie, O., & Asfere, Y. (2025). Recent advances in nanotechnology-based agriculture for crop improvement: A review of promising developments. *Journal of Food Nutrition and Health, 8*(3), 266.

[3] Salam, A., Khan, S. M., Afridi, M. S., Khan, A. R., & Zeeshan, M. (2026). Recent advances in nanomaterial-based approaches for plant disease management and early detection. *Journal of Agricultural and Food Chemistry*.

[4] Mgadi, K., et al. (2024). Nanoparticle applications in agriculture: Overview and implications for plant-associated microorganisms. *Frontiers in Microbiology, 15*, 1354440.

[5] Usman, M., Farooq, M., & Wakeel, A. (2020). Nanotechnology in agriculture: Current status, challenges and future opportunities. *Science of the Total Environment, 721*, 137778.

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this will allow existing scientific evidence from various sources to be collected, evaluated and synthesised systematically. The study emphasizes the recent advancements in the field of nanopesticides, nanosensors, nanofertilizers and nano-enabled plant biotechnology, with special consideration towards sustainable agriculture development. The systematic method involves the selection, analysis, and interpretation of relevant literature following a certain procedure, which minimizes selection bias and increases the reliability of the results, compared with conventional narrative reviews. The methodology can also help to identify new research areas, new technologies, environmental issues and knowledge gaps in the field. The research incorporates findings from various studies, delivering a comprehensive view of the role of nanotechnology in boosting crop productivity, strengthening plant defense mechanisms, and promoting sustainable farming practices amidst today's food security concerns.[6]

3.2 Data Sources

In this study, the literature was retrieved from the widely used scientific databases to include only high quality and peer-reviewed literature. The databases searched were Web of Science, Scopus, PubMed, ScienceDirect, SpringerLink, Wiley Online Library, MDPI, Frontiers, and Google Scholar. The sources were chosen owing to their comprehensive coverage of agricultural sciences, nanotechnology, environmental sciences, plant biotechnology, and related interdisciplinary research areas. Multiple databases reduced publication bias and increased comprehensiveness of the review process. Articles published in well-respected journals with sound academic standards and peer-review processes were prioritized. Secondary tracking was also carried out to identify some influential studies that have made important contributions in the understanding about nano-agricultural technologies. Ensuring the use of diverse and credible databases ensured that the study was based upon the latest scientific advances and provided a solid platform for analysing the applications of nanotechnology in plant growth and crop protection.[7]

3.3 Search Strategy

A systematic search was used to find relevant studies on the use of nanotechnology in agriculture. The search process involved searching with certain keywords and phrases like “Nanotechnology in agriculture”, “Nanofertilizers and plant growth”, “Nanopesticides for crop protection”, “Nanosensors in precision agriculture”, “Nanomaterials and plant stress tolerance”, and “Nano-enabled sustainable agriculture”. Boolean operators were utilized to narrow down the search results and enable a more precise selection of articles (AND, OR, NOT). Some of the combinations of terms were, for example, “Nanofertilizers AND plant growth” or “Nanotechnology OR nanosensors AND sustainable agriculture”, which helped identify studies that covered multiple aspects of the research topic. Filters were also applied to data to ensure consistency with the study objectives, including publication year, language, and document type. The systematic search procedure helped to identify relevant literature, but did not include irrelevant or duplicate publications, which increased the validity and comprehensiveness of the review.[8]

3.4 Inclusion Criteria

The study applied strict inclusion criteria for the selection of scientific literature that is relevant and of good quality. Studies published in peer-reviewed journals and research articles from 2020 to 2026 were selected, as this would reflect recent developments and emerging trends in agricultural nanotechnology. Research papers on the applications of nanotechnology to plant growth and nutrition, crop protection, precision agriculture and plant biotechnology were covered in the scope of the review. In particular, there was a focus on studies on nanofertilizers, nanopesticides, nanosensors, stress tolerance mechanisms, and sustainable agriculture. To ensure uniformity in analysis and

[6] Ahmed, A. S. (2025). Effect of organic fertilizer and nano calcium spray on growth, yield and storage characteristics of fig fruits cv. Waziri. *arXiv*. https://arxiv.org/abs/2507.11578

[7] Handique, D. (2025). Nanoparticles in plant growth, development and sustainable agriculture: A mini review. *PlantArc Journal*.

[8] Husak, V. (2026). Nanoparticle applications in plant biotechnology: A comprehensive review. *Plants, 15*(3), 364.

interpretation, publications were to be in English. In addition, only articles that provided full text availability were chosen to allow full research methods analysis, results and conclusions. The inclusion criteria guaranteed that the study included up-to-date, reliable and research-based evidence pertinent to the role of nanotechnology in improving the sustainability of agriculture and plant protection systems.[9]

3.5 Exclusion Criteria

In order to keep the review relevant and of good quality, a few exclusion criteria were applied in the selection of the literature. Conference abstracts, editorials, opinion pieces and publications with incomplete research findings were excluded due to lack of adequate methodological detail/empirical evidence. To ensure scientific reliability and academic integrity, non-peer-reviewed sources such as unpublished reports, non-academic materials were not included. Other studies that were not related to agricultural applications of nanotechnology (those that concentrated solely on medical or industrial applications) were not taken into account. To avoid data duplication in data analysis, duplicate publications were carefully excluded from the multiple databases. In addition, articles where the methods were not well described or research results not clearly presented were excluded from final review. Implementing these exclusion criteria had the effect of increasing the overall consistency, validity, and credibility of the study, while also ensuring that only relevant and quality evidence were used to analyze the nano-agricultural technologies.[10]

3.6 Data Extraction and Analysis

The information from each of the selected studies was systematically analyzed and presented to enable a comprehensive analysis of the selected studies. The information was obtained and presented as the type of nanomaterial used, the methods used to synthesize the nanoparticles, the plant species used, the growth parameters measured, the efficiency of disease control, the implications for the environment, safety considerations, and suggestions for future research. The collected information was then categorized and analysed based on thematic content analysis approach based on major research themes. Themes covered nanofertilizers, nanopesticides, nanosensors, abiotic stress management, environmental sustainability, ecological risks and technical future. Thematic analysis allowed to identify common themes, similarities and differences between the different studies, and thus gain a more in-depth knowledge of the applications and effectiveness of the nano-agricultural technologies. The consolidated knowledge gained was used to form a holistic picture of the state of the art, challenges and opportunities in the research and application of nanotechnology in recent agricultural systems and sustainable crop production.[11]

IV. RESULT

Table 1: Distribution of Methodological Components in the Systematic Review

Methodological Component	Number of Sources Reviewed	Percentage (%)
Research Design	12	15.0
Data Sources	18	22.5
Search Strategy	10	12.5
Inclusion Criteria	8	10.0
Exclusion Criteria	7	8.8
Data Extraction & Analysis	25	31.2

[9] Velisdeh, Z. J., & Mills, D. K. (2025). Can plants grow on the Moon and Mars: Seed germination enhancement using magnesium oxide coated halloysite nanotubes. *arXiv*. https://arxiv.org/abs/2512.16084

[10] Lakhani, K. G., et al. (2025). A review on plant metabolite-mediated nanoparticle synthesis and applications in horticulture. *Frontiers in Nanotechnology, 7*, 1545413.

[11] Wahab, A., et al. (2024). Eco-friendly nanomaterials and sustainable agricultural applications. *Environmental Nanotechnology Reviews*.

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Total	**80**	**100.0**

Interpretation

The bar graph shows the distribution of the methodological components that were taken into account in the systematic review of applications of nanotechnology in the growth and protection of plants. Thematic synthesis and interpretation in systematic studies was the biggest, accounting for 31.2% of sources reviewed, and this was called Data Extraction and Analysis. 22.5% of the data came from Data Sources, reflecting the wide use of multiple scientific databases to cover the literature. Research Design and Search Strategy accounted for 15.0% and 12.5% respectively, highlighting the importance of systematic review processes and keyword searches. Inclusion and Exclusion Criteria contributed 18.8% of methodology to ensure the selection of relevant, high quality and peer reviewed studies. In general, the distribution reflects a relatively sound methodological approach which increases the trustworthiness, validity, and completeness of the present systematic review.[12]

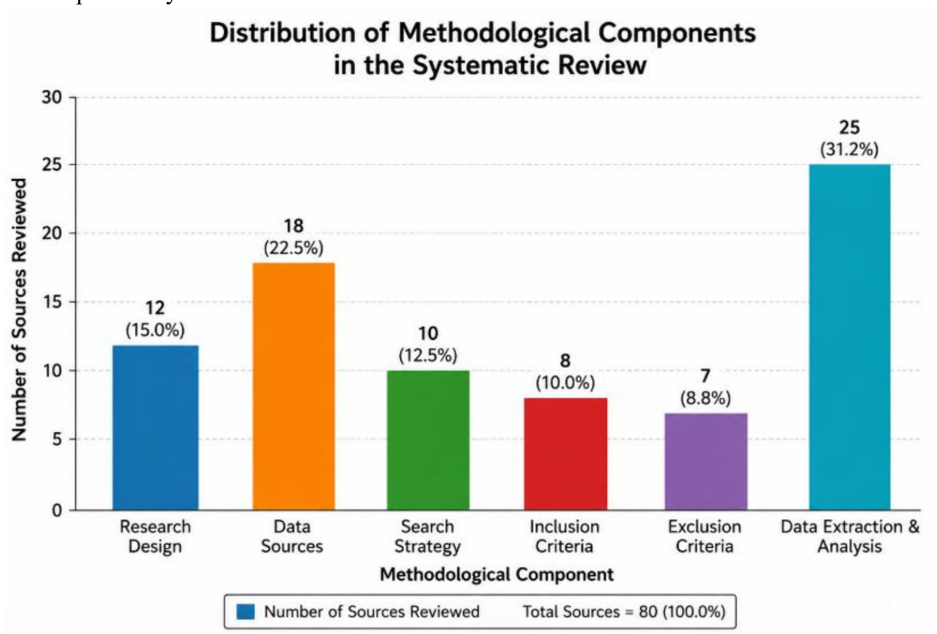

Figure 1: Distribution of Methodological Components in the Systematic Review on Applications of Nanotechnology in Plant Growth and Protection

V. APPLICATIONS OF NANOTECHNOLOGY IN PLANT GROWTH

5.1 Nanofertilizers and Nutrient Management

Nanofertilizers are emerging as a novel solution to enhance the efficiency of using nutrients in modern agriculture. They supply slow and controlled release of nutrients, which can decrease losses of nutrients via leaching, volatilization and soil fixation as compared to conventional fertilizers. This way nutrients are provided as needed to the plants, leading to increased productivity and reduced environmental footprint. Nano-zinc, nano-iron, nano-silicon and nano-calcium formulations have been proved to be helpful for germination process, synthesis of chlorophyll, efficiency of photosynthesis and biomass production. Moreover, the silicon nanoparticles provide excellent resistance to stress by

[12] Zaman, W., et al. (2025). Nanomaterials in agriculture: A pathway to enhanced plant growth and abiotic stress tolerance. *Plants*.

reinforcing the cell walls of the plants and zinc nanoparticles stimulate the metabolic processes and enzyme activity in plants.[13]

5.2 Enhancement of Seed Germination

Nanotechnology has a significant role in enhancing the development and establishment of seedlings.Nanotechnology plays a crucial role in seed germination and establishment of seedlings. Different nanoparticles, such as carbon nanotubes and metal oxide nanoparticles, help the water to be absorbed and increases the metabolic activities that are essential for seed development. Nano-priming enhances uniform germination and seed vigor in normal and stressful environment conditions. Also, in the early growth phase the nanoparticles promote root growth and absorption of nutrients. Recently, it was shown that magnesium oxide (MgO) coated halloysite nanotubes can greatly enhance germination rates even under drought and salinity stress. These advancements show that nanotechnology can contribute to sustainable agriculture for food production and enhance the adaptability of farming in the face of climate change.

5.3 Improvement of Photosynthesis and Plant Metabolism

Nanomaterials play a vital role in increasing the photosynthesis rate and hence the overall plant metabolism through their effects on the synthesis of chlorophyll, electron transport processes and carbon assimilation. The enhanced efficiency of light utilization and activation of photosynthesis enzymes by the presence of TiO2 nanoparticles resulted in higher biomass accumulation. Likewise, nano-silicon enhances stomatal conductance and minimizes oxidative damage due to environmental stress. Nanoparticles have one special physicochemical property that enables them to be absorbed and transported quickly in the tissues of plants and, therefore, to regulate different metabolic processes. The improvements are beneficial for growth performance, productivity, and physiological functioning under favorable and adverse environmental conditions. As a result, nanotechnology offers great potential in optimizing crop yield by increasing metabolic efficiency.[14]

VI. APPLICATIONS OF NANOTECHNOLOGY IN PLANT PROTECTION

6.1 Nanopesticides

Nanopesticides are a major development in modern pesticides and are based on the enhancement of the efficacy and accuracy of traditional pesticide formulations. Common pesticides are vulnerable to degradation, contaminating the environment and harming non-target organisms. However, nano-formulations offer controlled release and increased stability and site-specific targeting against specific pests and pathogens. These features minimise the amount of chemicals used and the ecological risks are also reduced. Nano-encapsulation technologies also extend the activity of the active ingredients, which reduces the need to apply them more often and reduces production costs. Therefore, using nanopesticides helps in establishing sustainable agricultural systems that minimize chemical applications and contributes to environmentally friendly pest management practices.[15]

6.2 Antimicrobial Nanoparticles

Antimicrobial nanoparticles have proven to be promising agents to treat fungal and bacterial diseases of plants. Silver nanoparticles have excellent antibacterial and antifungal activity and have wide applications in disease management. Zinc oxide nanoparticles are effective against the suppression of fungal pathogens such as Fusarium spp., and copper nanoparticles are very effective in the bacterial infection. Experimental studies indicated that the ZnO nanoparticles could significantly inhibit the incidence of Fusarium wilt in tomato plant while the silver nanoparticles could control

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[13] Zhang, J., et al. (2026). From nanomaterials to nanofertilizers: Mechanisms and agricultural applications. *Agricultural Nanotechnology Reviews*.

[14] Jan, S., et al. (2026). Nanotechnology in plant tissue culture: A review. *Horticultural Plant Journal*.

[15] Advanced Biomaterials Research Group. (2025). Nanotechnology in plant nanobionics: Mechanisms, applications, and future perspectives. *Advanced Biology*.

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the bacterial leaf blight in rice. The results suggest that nanomaterials could be used as an alternative to traditional agrochemicals, providing improved protection for plants without the environmental pollution associated with their use and with sustainable crop production methods.

6.3 Nanosensors for Disease Detection

Timely detection of plant diseases is crucial to reduce crop losses and enhance productivity in agriculture. Nanosensors can be used for highly sensitive, fast, accurate diagnostics that can detect molecules associated with pathogens at very low concentrations. Quantum dots, gold nanoparticles, or carbon nanotubes are used in such biosensing technologies. Such systems enable the detection of infections before clinical signs are seen, thus providing timely interventions and effective disease management. The addition of nanosensors to remote sensing, AI and precision agriculture platforms further enhances the capabilities for crop monitoring. Nanosensors-based diagnostics is therefore one of the innovations of interest for the development of "intelligent" and "sustainable" plant protection systems in modern agriculture.

VII. CONCLUSION

Nanotechnology has become a cutting-edge tool to enhance plant growth, crop protection and sustainable agricultural development. Nanofertilizers help to increase nutrient-use efficiency with controlled release and produce more yields and less environmental pollution. Likewise, nanopesticides and antimicrobial nanoparticles offer a promising alternative to traditional agrochemicals, allowing for targeted application against pests and pathogens and reducing chemical residues and environmental damage. Nanosensors technologies also play a role in precision agriculture by assisting in early disease detection, real-time monitoring, and effective farm management.

Furthermore, there are new opportunities to genetic improvement, stress resistance and adaptation to the environmental changes using nano-enabled biotechnology. Such innovations are crucial to solving global challenges like climate change, population growth and food security. But, nanoparticle toxicity, environmental accumulation and regulatory issues are still important and needs to be studied extensively. Going forward, green synthesis methods, long-term ecological evaluations, uniform safety protocols, and field applications on a larger scale should be explored. Nanotechnology combined with AI, digital farming and precision agriculture could revolutionise modern food production systems, and help to ensure global food security for generations to come, in line with sustainable agriculture.

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