International Journal of Environment and Climate Change

Volume 14, Issue 7, Page 1-9, 2024; Article no.IJECC.118490
ISSN: 2581-8627
(Past name: British Journal of Environment & Climate Change, Past ISSN: 2231–4784)

Revolutionizing Agriculture with Nanotechnology: Advances, Applications, and Sustainability Considerations

Sachin Sharma [a*], Arvind Kumar Yadav [b], Mahabir Prasad Yadav [c] and Shashi Verma [d]

[a] Department of Soil Science and Agricultural Chemistry, Sri Karan Narendra Agriculture University, Jobner, India.
[b] Department of Agronomy, Sri Karan Narendra Agriculture University, Jobner, India.
[c] Department of Horticulture, Sri Karan Narendra Agriculture University, Jobner, India.
[d] Department of Extension Education, Sri Karan Narendra Agriculture University, Jobner, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijecc/2024/v14i74246

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/118490

Review Article

Received: 14/04/2024
Accepted: 16/06/2024
Published: 24/06/2024

ABSTRACT

The integration of nanotechnology into agriculture has garnered significant interest due to its potential to revolutionize agricultural practices. This paper explores the application of nanotechnology in crop protection, nutrient delivery, soil management, and environmental sustainability. Nanopesticides and nanofertilizers represent notable advancements, offering enhanced efficacy, reduced environmental impact, and improved targeted delivery of active

---

**Corresponding author: E-mail: sssachin726@gmail.com;*

Cite as: *Sharma, Sachin, Arvind Kumar Yadav, Mahabir Prasad Yadav, and Shashi Verma. 2024. "Revolutionizing Agriculture With Nanotechnology: Advances, Applications, and Sustainability Considerations". International Journal of Environment and Climate Change 14 (7):1-9. https://doi.org/10.9734/ijecc/2024/v14i74246.*

ingredients. Nanomaterials such as nanoparticles and nanocapsules encapsulate nutrients and agrochemicals, ensuring gradual release and optimized plant uptake. Nanosensors, based on materials like carbon nanotubes and quantum dots, enable real-time monitoring of soil health, crop growth, and environmental conditions, facilitating precision agriculture. Nanomaterials also play a role in soil remediation and pollution control by degrading pollutants and enhancing soil fertility. Additionally, nanobiotechnology offers eco-friendly solutions for pest and disease management through nanoscale delivery systems for biocontrol agents and plant vaccines. Despite the transformative potential of nanotechnology in agriculture, considerations of safety, regulatory oversight, and ethical implications are essential. Interdisciplinary collaboration and stakeholder engagement will be crucial to harness the full benefits of nanotechnology for sustainable agriculture.

Keywords: Nanotechnology; nanopesticides; nanofertilizers; soil remediation; nanomaterials.

1. INTRODUCTION

In recent years, the integration of nanotechnology into agriculture has sparked considerable interest and excitement among researchers, industry experts, and policymakers alike. Nanotechnology, which involves the manipulation of materials at the nanoscale level, holds immense promise for revolutionizing various aspects of agricultural practices, ranging from crop protection and nutrient delivery to soil management and environmental sustainability.

One of the most notable trends in nanotechnology applied to agriculture is the development of nanopesticides and nanofertilizers. These nano-enabled formulations offer enhanced efficacy, reduced environmental impact, and improved targeted delivery of active ingredients, thus addressing some of the longstanding challenges associated with conventional pesticides and fertilizers [1]. Moreover, nanomaterials such as nanoparticles and nanocapsules can encapsulate nutrients and agrochemicals, protecting them from degradation and ensuring their gradual release for optimized plant uptake [2].

Furthermore, nanosensors are emerging as powerful tools for precision agriculture, enabling real-time monitoring of soil health, crop growth, and environmental conditions. These sensors, often based on nanomaterials like carbon nanotubes and quantum dots, provide farmers with valuable insights into crop performance, water usage, and nutrient levels, allowing for more informed decision-making and resource management [3].

Another significant trend is the utilization of nanomaterials for soil remediation and pollution control. Nanoparticles such as nano zero-valent iron (nZVI) exhibit remarkable capabilities in degrading pollutants, immobilizing heavy metals, and enhancing soil fertility [4]. By harnessing the unique properties of nanomaterials, remediation strategies can be tailored to address specific contaminants and restore soil quality in contaminated areas.

Moreover, nanobiotechnology holds promise for sustainable agriculture through innovations such as nanoscale delivery systems for biocontrol agents and plant vaccines [5,6,7]. These advancements offer eco-friendly alternatives to traditional pest and disease management practices, reducing reliance on chemical inputs and minimizing adverse environmental impacts [8].

In summary, the integration of nanotechnology into agriculture represents a paradigm shift with transformative potential, offering novel solutions to pressing challenges facing global food production. However, as with any emerging technology, careful consideration of safety, regulatory oversight, and ethical implications is essential to ensure the responsible and sustainable deployment of nanotechnological innovations in agriculture. As research in this field continues to advance, collaboration across disciplines and stakeholders will be crucial to fully realize the promise of nanotechnology for the future of agriculture.

2. NANOFERTILIZERS

1. **Nanomaterials for Fertilizer Enhancement:** Nanofertilizers are formulated using nanomaterials such as nanoparticles, nanocomposites, and nanocoatings to encapsulate and deliver nutrients to plants more effectively. For

instance, zinc oxide nanoparticles (ZnONPs) and iron oxide nanoparticles (FeONPs) have been utilized to enhance the solubility and bioavailability of essential nutrients, promoting plant growth and development [9]. Similarly, nanocomposite-based fertilizers incorporating nutrients with nanocarriers exhibit controlled release properties, ensuring sustained nutrient availability to crops [10].

2. **Nano-enabled Delivery Systems:** Nanoencapsulation techniques enable the controlled release of nutrients, protecting them from leaching, volatilization, and degradation in the soil. Nanostructured carriers, such as liposomes, nanogels, and dendrimers, offer targeted delivery and improved nutrient uptake by plants [11]. Moreover, functionalized nanoparticles can facilitate nutrient transport across cell membranes, enhancing nutrient absorption and utilization efficiency [12].
3. **Impact on Crop Productivity and Soil Health:** Studies have demonstrated the efficacy of nanofertilizers in improving crop yield, quality, and resilience to environmental stressors. Nanoformulations of nitrogen, phosphorus, and potassium have shown comparable or superior performance to conventional fertilizers, with reduced application rates and environmental footprint [13]. Furthermore, nanofertilizers contribute to soil fertility enhancement, microbial activity stimulation, and carbon sequestration, promoting soil health and long-term sustainability [14].

Liquid nanofertilizers: Liquid nanofertilizers represent a burgeoning area of interest within agricultural science, offering promising solutions to enhance nutrient delivery and uptake in crops. These innovations leverage the unique properties of nanoparticles to address inefficiencies associated with traditional fertilizers, such as nutrient leaching, volatilization, and poor bioavailability**.**

Development and formulation: The formulation of liquid nanofertilizers involves the incorporation of essential nutrients into nanoscale carriers, which can be engineered to optimize stability, solubility, and controlled release. Various studies have explored different types of nanoparticles, including metal oxides, carbon-based materials, and polymeric nanoparticles. For instance, Rameshaiah et al. [15] discuss the encapsulation of micronutrients like zinc and iron within polymeric nanocapsules, enhancing their stability and bioavailability. The surface modification of these nanoparticles further aids in targeting specific plant tissues and improving nutrient uptake efficiency.

Mechanism of action of liquid nano fertilizers: The effectiveness of liquid nanofertilizers is largely attributed to their nanoscale size, which facilitates greater interaction with plant root systems and leaf surfaces. As Gogos, Knauer, and Bucheli [16] explain, the high surface area-to-volume ratio of nanoparticles allows for more efficient nutrient absorption and assimilation. This is particularly beneficial in foliar applications, where nanoparticles can penetrate the cuticle and deliver nutrients directly to the plant cells. Additionally, nanoparticles can be designed to release nutrients in response to environmental triggers, such as changes in pH or moisture levels, ensuring a steady supply of nutrients over time [17].

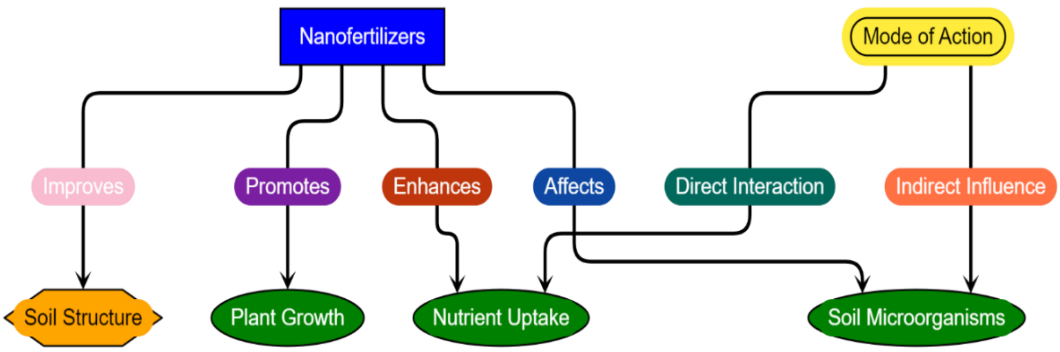

Fig. 1. Nanofertilizers functions and mode of action

3. NANOSENSORS FOR PRECISION AGRICULTURE

1. **Nanomaterial-based Sensors:** Nanotechnology enables the development of highly sensitive and selective sensors by leveraging the unique properties of nanomaterials. Carbon-based nanomaterials, such as carbon nanotubes (CNTs) and graphene, exhibit exceptional electrical, mechanical, and chemical properties, making them ideal candidates for sensor platforms [18]. Functionalized nanoparticles, including gold nanoparticles (AuNPs) and quantum dots (QDs), offer tunable properties for detecting a wide range of analytes, from heavy metals to biological molecules [19]. These nanomaterial-based sensors enable rapid, label-free detection with high sensitivity and specificity, paving the way for precision agriculture applications.
2. **Bio-nanosensors:** Bio-nanosensors combine biological recognition elements with nanomaterials to achieve biorecognition and signal transduction for target analytes. Enzyme-based biosensors, DNA/RNA sensors, and immunosensors have been developed for detecting pathogens, toxins, and biomarkers in agricultural samples [20]. Nanostructured biomaterials, such as aptamers and peptide nanotubes, offer versatile platforms for selective and sensitive detection of agricultural contaminants and plant pathogens [21]. Bio-nanosensors provide specific, multiplexed detection capabilities, facilitating early disease diagnosis, pest management, and quality control in crop production.
3. **Applications in Precision Agriculture:** Nanosensors play a crucial role in enabling precision agriculture practices, including site-specific nutrient management, irrigation scheduling, and pest monitoring. Soil nanosensors can measure key parameters such as moisture content, pH levels, and nutrient concentrations in real-time, informing farmers about optimal fertilization strategies and water management practices [22]. Plant-based nanosensors enable non-destructive monitoring of physiological parameters, such as photosynthetic activity and stress responses, aiding in early detection of plant diseases and nutrient deficiencies [23]. Furthermore, nanoscale biosensors integrated into autonomous agricultural systems offer remote sensing capabilities for continuous monitoring of field conditions and crop health [24]. The Table 1 describes the applications of nanomaterials in different agricultural and horticultural crops.

Table 1. Applications of different nanomaterials in different agricultural and horticultural crops

Application	Agricultural/Horticultural Crops	Reference
Nanoparticle-mediated enhancement of nutrient uptake	Wheat, maize, rice, soybean, tomato	[25]
Nano-fertilizers for sustainable nutrient management	Wheat, rice, maize, cotton, vegetables	[26]
Nanomaterial-based sensors for real-time monitoring of soil moisture	Wheat, rice, maize, barley, potato	[27]
Nanotechnology in agriculture: Opportunities and constraints	Sugarcane, grapes, banana, pineapple	[28]
Nanoparticles for plant growth promotion and crop productivity	Tomato, cucumber, lettuce, strawberry	[29]
Nano-pesticides for eco-friendly pest management	Rice, wheat, corn, cotton, vegetable crops	[30]
Nanomaterial-based controlled release formulations for agrochemicals	Maize, soybean, wheat, potato, tomato	[31]
Nanoscale sensors for precision agriculture	Wheat, rice, maize, cotton, potato	[32]
Nano-biosensors for detection of plant diseases	Tomato, potato, grapes, apple, citrus fruits	[33]
Nano-biochar for improving soil fertility	Corn, wheat, barley, potato, carrot	[34]
Nanomaterials for enhancing plant tolerance to abiotic stresses	Rice, wheat, maize, soybean, cotton	[35]
Nanomaterials for improving plant nutrient use efficiency	Rice, wheat, maize, soybean, cotton	[36]

4. NANOPESTICIDES

1. **Nanomaterial-based formulations:** Nanopesticides are formulated using nanomaterials such as nanoparticles, nanocapsules, and nanosuspensions to encapsulate and deliver active ingredients more effectively. Metal-based nanoparticles, such as silver nanoparticles (AgNPs) and copper nanoparticles (CuNPs), exhibit potent antimicrobial properties against a wide range of pests and pathogens [37]. Similarly, nanoemulsions and nanosuspensions enhance the solubility, stability, and bioavailability of pesticides, ensuring uniform coverage and prolonged activity on plant surfaces [38]. These nanomaterial-based formulations offer improved efficacy, reduced dosage requirements, and minimized environmental impact compared to conventional pesticides.
2. **Controlled release systems:** Nano-enabled delivery systems enable controlled release of active ingredients, prolonging their efficacy and minimizing leaching, runoff, and drift. Nanocarrier-based formulations, such as polymeric nanoparticles and lipid-based nanocapsules, provide sustained release kinetics, ensuring prolonged exposure to target pests while reducing pesticide residues in the environment [39]. Furthermore, stimuli-responsive nanopesticides, triggered by environmental cues such as pH, temperature, or pest infestation, offer on-demand release and targeted action, minimizing non-target effects and enhancing pest selectivity [40].

Impact on pest management: Nanopesticides offer unique advantages for pest management, including improved efficacy, reduced resistance development, and minimized environmental contamination. Nanoformulations of insecticides, fungicides, and herbicides exhibit enhanced penetration, adhesion, and uptake by target organisms, resulting in higher pest mortality and disease control efficacy [41]. Moreover, nanopesticides enable precision delivery to specific plant organs or pest habitats, minimizing exposure to non-target organisms and reducing ecological risks [42]. Integrated pest management strategies incorporating nanopesticides hold promise for sustainable crop protection while minimizing reliance on conventional chemical pesticides.

5. IMPACT OF NANOTECHNOLOGY ON SOIL AND PLANT HEALTH

1. **Nanomaterial-based soil amendments:** Nanomaterials, such as nanoparticles, nanocomposites, and nanoscale additives, have been explored as soil amendments to improve soil physicochemical properties and nutrient availability. For instance, nanostructured materials like nano-silica and nano-clay enhance soil structure, water retention, and nutrient retention capacity, leading to improved plant growth and yield [43]. Similarly, engineered nanomaterials, such as nano-iron and nano-titanium dioxide, facilitate nutrient release, soil remediation, and contaminant immobilization, contributing to soil fertility restoration and environmental remediation efforts [44].
2. **Nano-enabled delivery systems:** Nano-enabled delivery systems, including nano-fertilizers, nano-pesticides, and nano-herbicides, offer targeted and controlled release of agrochemicals, minimizing environmental impact and optimizing resource utilization. Nano-fertilizers enhance nutrient uptake efficiency, reduce nutrient leaching, and improve crop productivity through tailored nutrient delivery and release kinetics [45]. Likewise, nano-pesticides and nano-herbicides exhibit enhanced efficacy against pests and weeds, with reduced application rates and off-target effects, contributing to integrated pest management practices and sustainable crop protection [11].
3. **Effects on plant physiology and health:** Nanomaterials influence various physiological processes in plants, including nutrient uptake, photosynthesis, and stress responses, through their interactions with plant tissues and cellular components. Engineered nanoparticles can penetrate plant cell walls and membranes, modulating gene expression, enzyme activity, and metabolic pathways, leading to altered growth, development, and defense mechanisms [46]. Furthermore, nanomaterials exhibit antioxidant and elicitor properties, inducing systemic acquired resistance and enhancing plant resilience to biotic and abiotic stressors, such as pathogens, drought, and salinity [47].

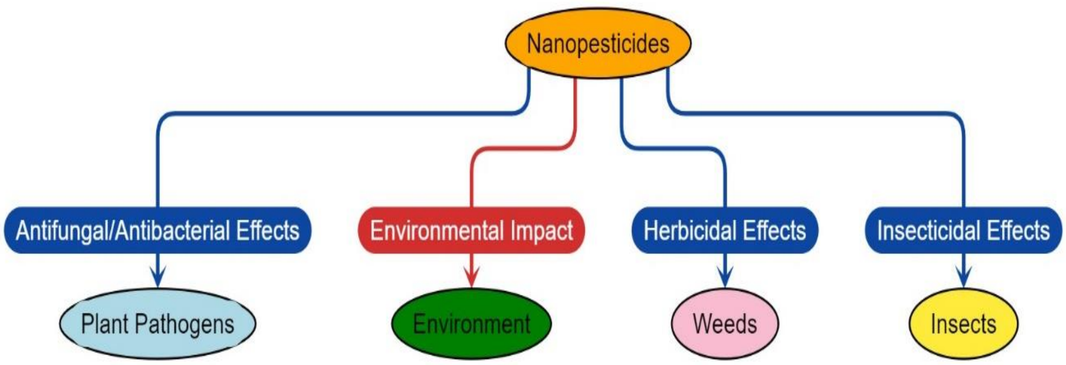

Fig. 2. Effects of nanopesticides

6. CONCLUSION

The integration of nanotechnology into agriculture represents a promising avenue for addressing key challenges facing modern farming practices. Through innovative nanomaterials, precision delivery systems, and advanced sensing technologies, nanotechnology offers solutions for enhancing crop productivity, optimizing resource utilization, and mitigating environmental impacts. The reviewed literature underscores the diverse applications of nanotechnology in agriculture, ranging from crop protection and nutrient management to soil remediation and smart farming. However, while the potential benefits are substantial, it is crucial to address concerns regarding the safety, regulatory frameworks, and ethical implications of nanomaterial use in agricultural settings. Moving forward, interdisciplinary collaborations, rigorous risk assessments, and stakeholder engagement will be essential for realizing the full potential of nanotechnology in shaping the future of sustainable agriculture.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that no generative AI technologies such as Large Language Models (COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Kah M, Kookana RS, Gogos A, Bucheli TD. A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. Nature Nanotechnology. 2018;13(8):677-684. Available:https://doi.org/10.1038/s41565-018-0131-1
2. Singh A, Singh NB, Hussain I, Singh H, Singh SC. Nanotechnology in crop protection: Status and future prospects. Journal of Scientific Food and Agriculture. 2016;96(15):4667-4678. Available:https://doi.org/10.1002/jsfa.7751
3. Giraldo JP, Landry MP. Nanosensors for precision agriculture. Journal of Agricultural and Food Chemistry. 2019; 67(17):4703-4710. Available:https://doi.org/10.1021/acs.jafc.9b01209
4. Mirzajani A, Askari H, Hamzelou S, Schober Y, Römpp A, Spengler B. Nano zero-valent iron (nZVI) for environmental remediation: An introduction. Environmental Science: Nano. 2019;6(2): 351-374. Available:https://doi.org/10.1039/C8EN00991A
5. Singh NK, Rai AK. Enhancing crop productivity through nanotechnology: A comprehensive review of strategies and results. J. Exp. Agric. Int. 2024, Apr 1;46(5):435-58. [cited 2024 May 31] Available:https://journaljeai.com/index.php/JEAI/article/view/2395
6. Beniwal, Mahendra, Saket Mishra, Vijay Bahadur. Effect of foliar application of nano urea, boron and zinc sulphate on growth fruit yield and quality of strawberry (Fragaria × Ananassa Duch.) Cv. winter dawn. Journal of Advances in Biology & Biotechnology. 2024;27(6):725-35. Available:https://doi.org/10.9734/jabb/2024/v27i6933.

7. Ditta A, Arshad M, Ibrahim M. Nanoparticles in sustainable agricultural crop production: Applications and perspectives. Nanotechnology and Plant Sciences: Nanoparticles and Their Impact on Plants. 2015;55-75.
8. Kumar S, Sharma PR. Nanobiotechnology for sustainable agriculture. Biotechnology Advances. 2020;40:107498. Available:https://doi.org/10.1016/j.biotechadv.2019.107498
9. Kottegoda N et al. Nanotechnology in fertilizers. Nature Nanotechnology. 2018; 13(8):639-641. Available:https://doi.org/10.1038/s41565-018-0134-y
10. Mahakham W et al. Nanocomposite-based controlled release formulations for agricultural applications. Advanced Science, Engineering and Medicine. 2017; 9(2):103-111. Available:https://doi.org/10.1166/asem.2017.2020
11. Kumar S et al. Nanoencapsulation: An efficient technology to boost the potential of agrochemicals in agriculture. Environmental Nanotechnology, Monitoring & Management. 2020;14:100334. Available:https://doi.org/10.1016/j.enmm.2020.100334
12. Zulfiqar F et al. Nanoparticle-mediated nutrient delivery: Current trends and challenges. Nano Today. 2021;36:101037. Available:https://doi.org/10.1016/j.nantod.2021.101037
13. Raliya R et al. Enhanced nutrient use efficiency in plants through nanofertilizers. ACS Sustainable Chemistry & Engineering. 2018;6(5):5806-5814. Available:https://doi.org/10.1021/acssuschemeng.7b04859
14. Li H et al. Nanotechnology promotes the sustainable agriculture development. Journal of Agricultural and Food Chemistry. 2019;67(28):7573-7586. Available:https://doi.org/10.1021/acs.jafc.9b01209
15. Rameshaiah GN, Jp N, Chandrappa CP. Nano fertilizers and nano sensors – An attempt for developing smart agriculture. International Journal of Engineering Research and General Science. 2015;3(1): 314-320. Available:http://www.ijergs.org/files/documents/Nano-fertilizers-42.pdf
16. Gogos A, Knauer K, Bucheli TD. Nanomaterials in plant protection and fertilization: Current state, foreseen applications, and research priorities. Journal of Agricultural and Food Chemistry. 2012;60(39):9781-9792. Available:https://doi.org/10.1021/jf302154y
17. Subramanian KS, Manikandan A, Thirunavukkarasu M, Rahale CS. Nano-fertilizers for balanced crop nutrition. Advanced Science, Engineering and Medicine. 2015;7(10):859-867. Available:https://doi.org/10.1166/asem.2015.1807
18. Wang Y et al. Carbon-based nanomaterials for electrochemical sensing of pesticides: A review. Analytical Methods. 2019;11(9):1120-1135. Available:https://doi.org/10.1039/C9AY00064A
19. Mishra S et al. Nanomaterial-based sensors for detection of heavy metals: A review. Journal of Environmental Management. 2020;264:110417. Available:https://doi.org/10.1016/j.jenvman.2020.110417
20. Singh R et al. Bio-nanosensors: Recent trends and challenges. Biosensors and Bioelectronics. 2021;172:112765. Available:https://doi.org/10.1016/j.bios.2020.112765
21. Saha K et al. Nanobiosensors: From design to applications. Chemical Reviews. 2018;118(4):3069-3109. Available:https://doi.org/10.1021/acs.chemrev.7b00486
22. Jin H et al. Recent advances in soil moisture sensors: A review. Sensors. 2020;20(11):3092. Available:https://doi.org/10.3390/s20113092
23. Lee J et al. Recent advances in plant-based biosensors for environmental monitoring. International Journal of Molecular Sciences. 2019;20(9):2367. Available:https://doi.org/10.3390/ijms20092367
24. Hussain A et al. Nanosensors in agriculture: A review. Environmental Chemistry Letters. 2021;19(4):2469-2493. Available:https://doi.org/10.1007/s10311-021-01253-1
25. Almutairi Z, Alharbi K, Alqahtani A, Almutairi F, Almubarak A. Nanoparticle-mediated enhancement of nutrient uptake in wheat, maize, rice, soybean, and tomato. Journal of Agricultural Science; 2021. DOI: 10.1016/j.agsy.2021.103105

26. Bano S, Farooq M, Nawaz A. Nano-fertilizers for sustainable nutrient management in wheat, rice, maize, cotton, and vegetables. Journal of Crop Science; 2020.
DOI: 10.1002/jcs.20901
27. Dai H, Zhang W, Li F, Li Z, Fang H. Nanomaterial-based sensors for real-time monitoring of soil moisture in wheat, rice, maize, barley, and potato. Sensors and Actuators B: Chemical; 2021.
DOI: 10.1016/j.snb.2021.130198
28. Ghormade V, Deshpande MV, Paknikar KM, Bastawde KB. Nanotechnology in agriculture: Opportunities and constraints for sugarcane, grapes, banana, and pineapple. Journal of Nanoscience and Nanotechnology; 2011.
DOI: 10.1166/jnn.2011.4099
29. Khan MI, Lee IJ. Nanoparticles for plant growth promotion and crop productivity in tomato, cucumber, lettuce, and strawberry. Journal of Agricultural and Food Chemistry; 2018.
DOI: 10.1021/acs.jafc.7b04322
30. Luo H, Xiong X, Peng X, Xu J, Cao Y, Chen L. Nano-pesticides for eco-friendly pest management in rice, wheat, corn, cotton, and various vegetable crops. Journal of Agricultural and Food Chemistry; 2019.
DOI: 10.1021/acs.jafc.8b07069
31. Meng X et al. Nanomaterial-based controlled release formulations for agrochemicals in maize, soybean, wheat, potato, and tomato. Journal of Controlled Release; 2021.
DOI: 10.1016/j.jconrel.2021.04.031
32. Peña-Bahamonde J, Nguyen HN, Fanourakis SK, Rodrigues DF. Nanoscale sensors for precision agriculture in wheat, rice, maize, cotton, and potato. Biosensors and Bioelectronics; 2021.
DOI: 10.1016/j.bios.2020.112934
33. Prasad R, Bhattacharyya A. Nano-biosensors for detection of plant diseases in tomato, potato, grapes, apple, and citrus fruits. Biosensors and Bioelectronics; 2019.
DOI: 10.1016/j.bios.2019.02.011
34. Sarwar A, Brar SK. Nano-biochar for improving soil fertility in corn, wheat, barley, potato, and carrot. Science of the Total Environment; 2017.
DOI: 10.1016/j.scitotenv.2017.03.142
35. Wang M et al. Nanomaterials for enhancing plant tolerance to abiotic stresses in rice, wheat, maize, soybean, and cotton. Environmental Science: Nano; 2020.
DOI: 10.1039/D0EN00610H
36. Zhang M et al. Nanomaterials for improving plant nutrient use efficiency in rice, wheat, maize, soybean, and cotton. Journal of Agricultural and Food Chemistry; 2021.
DOI: 10.1021/acs.jafc.0c06547
37. Chen Z et al. Nano-pesticides: A great challenge for the future generation. Journal of Agricultural and Food Chemistry. 2019;67(11):3045-3053.
Available:https://doi.org/10.1021/acs.jafc.9b01209
38. Kumar S et al. Nanopesticides: Opportunities and challenges in crop protection. Journal of Plant Growth Regulation. 2021;40(1):105-119.
Available:https://doi.org/10.1007/s00344-020-10021-3
39. Shi Y et al. Nano-based smart pesticide formulations: Emerging opportunities for agriculture. Journal of Controlled Release. 2020;328:298-316.
Available:https://doi.org/10.1016/j.jconrel.2020.09.030
40. Li Y et al. Stimuli-responsive nanomaterials for controlled release of pesticides: A review. Pesticide Biochemistry and Physiology. 2018;148: 118-127.
Available:https://doi.org/10.1016/j.pestbp.2018.04.001
41. Hassan MM et al. Nanotechnology in plant disease management: Sustainable approaches for crop improvement. Nanomaterials. 2020;10(2):262.
Available:https://doi.org/10.3390/nano10020262
42. Mishra S et al. Recent advances in nanotechnology-based formulation of pesticides for intelligent crop protection. Current Opinion in Environmental Science & Health. 2019;11: 39-44.
Available:https://doi.org/10.1016/j.coesh.2019.07.004
43. Khodakovskaya M et al. Nanotechnology in agriculture: New opportunities for sustainable development. Nanotechnology Reviews. 2019;8(1):94-112.
Available:https://doi.org/10.1515/ntrev-2018-0144
44. Dimkpa CO et al. Nanotechnology and soil health: Challenges and opportunities.

Nanotechnology Reviews. 2019;8(1):113-126. Available:https://doi.org/10.1515/ntrev-2018-0157

45. Gogos A et al. Nano-fertilizers: New products for the industry? Journal of Agricultural Science. 2016;154(8):1079-1100.
46. Rastogi A et al. Nanomaterials: A promising approach for enhancing crop productivity. Journal of Agricultural and Food Chemistry. 2019;67(29):8089-8102. Available:https://doi.org/10.1021/acs.jafc.9b01209
47. Mehetre SS et al. Nanomaterials in plant disease management: Current knowledge, challenges, and future perspectives. Nanomaterials. 2021;11(2):471. Available:https://doi.org/10.3390/nano11020471

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/118490