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A review on nanotechnology applications for agriculture and water quality management

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ABSTRACT

Nanotechnology has emerged as a promising approach for sustainable agriculture and water quality management, offering innovative solutions to enhance traditional practices and mitigate environmental challenges. Recent advances have focused on developing nano fertilizers, nano pesticides, and nano herbicides for controlled nutrient release, targeted pest control, and reduced environmental impact. Nano sensors enable real-time monitoring of soil and crop conditions, facilitating precision farming. Nano materials like metal oxides, polymeric nanocomposites, and carbon nanotubes enhance plant growth, disease resistance, and nutrient uptake while improving soil fertility. This review paper provides a comprehensive overview of the applications of nanomaterials in these domains. It explores the role of nanotechnology in developing controlled-release nano fertilizers, nano pesticides, and nano herbicides for precision agriculture, reducing waste and minimizing environmental impact. In the realm of water treatment, the review examines the use of nano-adsorbents for efficient removal of heavy metals, dyes, and pharmaceutical compounds, as well as the application of nano material membranes for filtration of viruses, bacteria, and organic pollutants. It also explores the role of nano photocatalysts in degrading organic contaminants through redox reactions.

Keywords: *Nano technology, Agriculture, Waste water management, Nano-adsorbents*

Introduction

Human activities such as urbanization, industrialization, and unsustainable resource extraction have placed immense pressure on ecosystems, resulting in food scarcity, ecosystem degradation and dysfunction. Addressing these environmental challenges necessitates advanced technological solutions to enhance food security and promote sustainable ecosystem management (Saleem, 2022). Recent years, nano technology has significant applications across various fields, including biotechnology, agriculture, tissue engineering, waste water treatment, contaminants detection in water, soil and air etc. (Dasgupta *et al.*, 2015). Nano technology is the manipulation, investigation, and application of materials at the nano scale typically, between 1 and 100 nanometers (nm). Because of their large surface area, special qualities, and potential for resource recovery, nano materials-including nano particles, nanofibers, and Nano composites-have drawn a lot of attention for the removal of pollutants (Kaur *et al.*, 2021). These nanomaterials can now be made with ecologically friendly green synthesis techniques. Numerous microorganisms, including waste materials, agricultural residues, bacteria, algal and fungal biomass and yeast, have served as environmentally acceptable precursors for the production of nanoparticles (NPs) with potential uses in water and soil-plant continuum (Rossi *et al.*, 2019). The synthesis of nanomaterials can be done using two primary approaches: top-down and bottom-up. The bottom-up approach assembles materials from atomic or molecular components, utilizing methods such as Chemical Vapor Deposition (CVD), the sol-gel process, and self-assembly, allowing for high molecular precision and the creation of well-defined nanostructures (Bisht *et al.,* 2020). Conversely, the top-down approach breaks down bulk materials into nanoscale structures through techniques like mechanical milling, lithography, and etching, which are more scalable and cost-effective for bulk production (Fig. 1). The classification of nanomaterials are based on their structure are given in Table 1.

The unique physical, chemical, and biological properties of nanomaterials can be harnessed for various applications, including environmental monitoring, remediation, and sustainable resource management (Rossi *et al*., 2019; Kaur *et al*., 2021). For instance, the application of nanomaterial in the agricultural sector has also expanded, involving the development of nanosensors, nanofertlizer, tracking devices, targeted delivery systems, food safety enhancements, new product innovations, precision processing, and smart packaging (Kumar *et al*., 2021; Dasgupta *et al*., 2015). However, the development of nanosensors holds great potential for monitoring environmental stress and boosting plants' disease resistance capabilities. Nanomaterials can be used to detect pollutants at very low concentrations, enabling early intervention and reducing the risk of contamination of water resources (Kumar *et al.*, 2021). Continual advancements in nanotechnology, with a particular focus on identifying problems and fostering collaborative approaches, are essential for sustainable agricultural and water management. This review paper aims to provide a comprehensive overview of the applications of nanotechnology in sustainable agriculture and water quality management. It highlights the recent advancements and

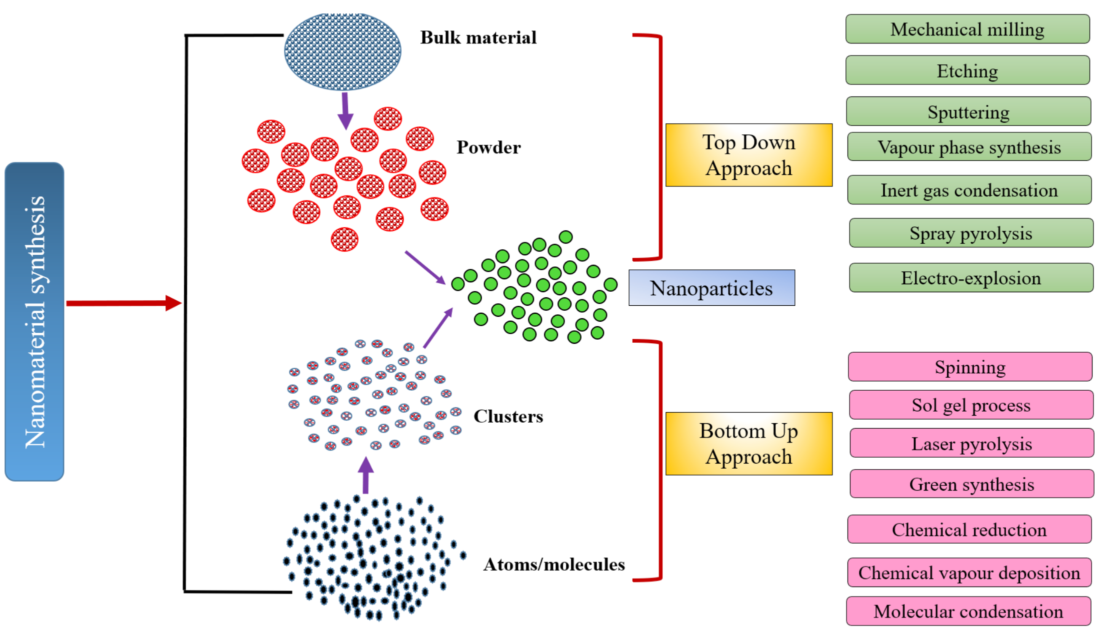

Fig. 1. Synthesis of nanomaterials

Table 1. Classification of nanomaterials based on composition (Kumar *et al*., 2021)

Nanomaterial Type	Examples
Carbon-based Nanomaterials	Graphene, Fullerenes, Carbon Nanotubes, Carbon Nanofibers, and Carbon Black
Metal-based Nanomaterials	Lead (Pb), Silver (Ag), Zinc (Zn), Iron (Fe), Gold (Au), Cadmium (Cd), Cobalt (Co), Copper (Cu), and Aluminum (Al)
Metal Oxide Nanomaterials	Aluminum oxide (Al_2O_3), zinc oxide (ZnO), silicon dioxide (SiO_2), and titanium oxide (TiO_2)
Polymeric Nanomaterials	Dendrimers, Nanofibers, Nanocomposites
Quantum Dots	Semiconductor nanoparticles

potential of nanomaterials, such as nanoparticles, nanocomposites, and nanostructured materials, in various aspects of these domains.

Applications of Nanotechnology in agriculture

Nanotechnology is regarded as a pivotal technology of the twenty-first century, promising to enhance traditional agricultural practices and promote sustainable development through improved management and conservation techniques that minimize waste of agricultural inputs (Bisht *et al.*, 2020). Recent advancements in nanotechnology have focused on the synthesis of slow or controlled-release fertilizers, pesticides, and herbicides, garnering significant attention in agriculture (Wang *et al.*, 2019). Nanotechnology plays a crucial role in precision agriculture through the use of nanosensors for real-time monitoring of soil and crop conditions, enabling the precise application of water, fertilizers, and pesticides (Zhang *et al.*, 2014). This targeted approach boosts crop yield and quality while mitigating the environmental impact of agricultural practices. Nanomaterials significantly benefit crop and plant applications by enhancing growth, disease resistance, and nutrient uptake (Rossi *et al.*, 2019; Wang *et al.*, 2019). Nanofertilizers release nutrients more efficiently, improving soil fertility and reducing environmental impact (Disfani *et al.*, 2017). They release nutrients in a controlled manner, minimizing nutrient loss through leaching or volatilization and reducing environmental pollution. Enhanced uptake of nutrients such as nitrogen, phosphorus, and potassium leads to healthier plants and increased yields. For example, encapsulating potassium nitrate with graphene oxide films significantly prolongs the fertilizer release process and could be economically viable for large-scale production. Advances in nanotechnology also enable the transfer of desired genes to target plants. Recent developments in chitosan nanoparticle-entrapped SiRNA delivery

Table 2. Application of nanotechnology in crop management

Nanomaterials	Crop Species	Mode of Application	Concentrations Used	Responses	References
ZnO	*Coffea arabica*	Foliar spray	10 mg/l	Enhanced growth, biomass accumulation and net photosynthesis	Rossi *et al.* (2019)
CuO	*Spinacia oleracea*	Mixed with soils	200 mg/kg	Improved photosynthesis and biomass production	Wang *et al.* (2019)
Fe/SiO2	*Arachis hypogaea, Zea mays*	As fertilizers	15 mg/kg	Enhanced plants growth and biomass accumulation	Disfani *et al.* (2017)
AgNPs	Vigna sinensis	Foliar application	50 mg/l	Enhanced growth and biomass by stimulating root nodulation and soil bacterial diversity	Pallavi *et al.* (2016)
TiO2 and SiO2	*Oryza sativa*	Foliar application	20 and 30 mg/l	Mitigated Cd toxicity and improved growth by stimulating antioxidant potential and inhibiting Cd translocation	Rizwan *et al.* (2019)
AgNPs	*Vigna unguiculata*	Foliar application	100 μg/ml	Showed no phytotoxicity, but could inhibit growth of Xanthomonas axonopodispv. malvacearum and Xanthomonas campestris pv. campestris in vitro	Vanti *et al.* (2019)
MgO	*Solanum lycopersicum*	Drenching	10 ìg/ml	Controlled bacterial wilt disease by suppressing pathogen Ralstonia solanacearum	Imada *et al.* (2016)

systems offer a novel approach to crop improvement, allowing for targeted control of insect pests due to chitosan's efficient RNA binding and penetration capabilities (Rossi *et al.,* 2019). Additionally, applying zinc oxide nanoparticles with other fertilizers in zinc-deficient soil not only enhances nutrient use efficiency but also boosts barley productivity by 91% compared to the control, whereas traditional bulk ZnSO4 increases productivity by 31%.

In agriculture, nanoparticles boost yield and combat pests, but their effects on plant health and ecosystems remain unclear (Rizwan *et al.,* 2019; Bisht *et al.,* 2020). They can alter plant physiology, cause phytotoxicity, and disrupt soil microbiomes crucial for nutrient cycling. Understanding these interactions is vital (Table 2). Effective nanotoxicity management requires safety guidelines, risk assessments, and monitoring systems for environmental and health impacts (Vanti *et al.,* 2019; Kumar *et al*., 2021).

Nanotechnology on waste water treatment

Water bodies such as lakes, dams, canals, rivers, and streams are critical resources, supplying three-fourths of water for agricultural and industrial purposes, and one-third of drinking water for domestic households (Saleem *et al.,* 2022; Bisht *et al.,* 2024). Despite their vital role in sustaining life, surface waters are highly vulnerable to pollution arising from uncontrolled agricultural and industrial activities (Mohamed *et al*., 2024; Bisht *et al.,* 2024). Industrial and domestic wastewater discharges have led to increased freshwater contamination and depletion of clean water resources (Bisht *et al.,* 2024). Due to their easy accessibility, surface water sources like rivers are common discharge sites for wastewater, which may contain microorganisms, heavy metals, and hazardous chemicals (Elessawy *et al*., 2020).

In recent years, the application of nanotechnology in water treatment has garnered widespread attention and is actively being researched due to the remarkable properties of nanomaterials (Kumar *et al*., 2021). The nano-sensors have been employed for detecting pesticides, surfactants, dyes, phenolic compounds, and emerging pharmaceutical contaminants in water (Dasgupta *et al.,* 2017). However, nanomaterials exhibit notable properties such as high surface area; antimicrobial activities, pore size, and reactive surface chemistry make them useful for adsorption of heavy metals from contaminated water (Table 3). Nanoadsorbents like carbon nanotubes, graphene, metal oxides, and polymeric nanocomposites possess exceptionally high surface areas and unique surface properties, facilitating efficient adsorption of pollutants such as heavy metals, dyes, and pharmaceutical compounds (Siddeeg *et al*., 2024). Previous studies have demonstrated the nanomaterial membranes composed of carbon nanotubes, ceramic nanocomposites, or others can efficiently filter out viruses, bacteria, heavy metals, and organic pollutants from water and wastewater due to their controlled pore size and high permeability, contributing to exceptional filtration capabilities (Kaur *et al*., 2022).

Table 3. Use of nano-adsorbents extracted from the natural materials from heavy metals removal (Tahoon *et al*., 2020; Mohamed *et al.,* 2024; Siddeeg *et al*., 2024)

Name of the Material	Doses (g/l)	Removal Percentage/ Capacity (mg/g)	Heavy Metals
Gum Acacia-Copolymer Nanocomposite Magnetite NPs	1.0 g/l	89%	Cd, Pb
ZnO NPs from Passiflora Foetida Peel	0.8 g/l	93.25% (Methylene Blue)	Pb, Cu
Chitosan-based NPs	2.0 g/l	120 mg/g	Cr(VI), Ni(II)
Graphene Oxide NPs from Plastic Waste	0.75 g/l	92%	As, Pb
Bimetallic Fe/Cu NPs	1.0 g/l	150 mg/g	Cr, Cd, Pb
Metal Oxide NPs (TiO2)	1.2 g/l	98%	Cr, Pb
Zeolite NPs	2.5 g/l	100 mg/g	Cu, Ni
Magnesium ferrite-nitrogen–doped graphene oxide nanocomposite	1.0 g/l	930 mg/g, and 64.1 mg/g for Pb^{2+} and As^{3+}	Pb, As
Biochar-based NPs	1.0 g/l	95%	Pb, Cu
Magnetic NPs from Green Tea Extract	0.8 g/l	110 mg/g	Ni, Cd
ZnO NPs from Orange Peel Extract	0.6 g/l	88%	Pb, Cd
TiO2 NPs from Green Synthesis	1.2 g/l	80% Hg^{2+}140 mg/g	Hg, Cr(VI), As

Nanomaterials as photocatalysts for waste water remediation

The application of nanomaterials can be used as photocatalysts in various forms, such as nanoparticles, thin films, or immobilized on supports like zeolites or activated carbon. The photocatalytic process involves the generation of electron-hole pairs upon light absorption, which subsequently participate in redox reactions to degrade organic pollutants or generate reactive species for disinfection purposes (Hayati *et al.*, 2020; Wu *et al.*, 2020). Some of nanoparticles such as TiO_2, Graphene

Table 4. Negative effect of nano-materials on plant health

Nanoparticle Type	Size (nm)	Plants Affected	Observed Effect	Reference
Silver Nanoparticles (AgNPs)	10-50	Arabidopsis thaliana	Inhibition of seed germination, root growth inhibition	Siddiqi and Husen, 2022
Titanium Dioxide Nanoparticles (TiO_2 NPs)	21-30	Spinach	Enhanced photosynthesis, increased growth at lower doses	Gordillo-Delgado *et al*., 2020
Zinc Oxide Nanoparticles (ZnO NPs)	30-70	Soybean, Radish	Growth inhibition, root shortening, oxidative stress	Jampílek and Králová, 2021
Copper Oxide Nanoparticles (CuO NPs)	<50	Lettuce, Wheat	Reduced seed germination rate, root toxicity	Pelegrino *et al*., 2020
Iron Oxide Nanoparticles (Fe_3O_4 NPs)	10-20	Rice, Tomato	Enhanced iron uptake, improved growth at low concentrations	Shakoor *et al*., 2023
Cerium Oxide Nanoparticles (CeO_2 NPs)	10-50	Barley, Wheat	Altered root architecture, decreased transpiration	Kumar *et al*., 2021

Table 5. Nanoparticles used as photocatalyst for pollutant removal

Water	Photocatalyst	Target Pollutant	Efficiency	Ref.
Medical wastewater	ZnCo-layered double hydroxide (Zn–Co–LDH)	Gemifloxacin (GMF)	92%	Gholami *et al.* (2020)
	MgO/carbon nanotubes	Sulfadiazine (SDZ)	99.9% (80 min)	Hayati *et al.* (2020)
	TiO2	Tetracycline (TC)	25.1% (150 min)	Wu *et al.* (2020)
	Red mud	Tetracycline (TC)	88.4% (80 min)	Shi *et al.*, 2020)
Textile wastewater	ZnO/polypyrrole	Azo dye direct black 22	95.7% (96 h-bio; 60 min-PD)	Ceretta *et al.* (2020)
	Graphene oxide/TiO_2	Salicylic acid	57%	Hunge *et al.* (2020)
Agricultural	ZCS/SIC core–shell nanorod wastewater	Rhodamine B (RB), imidacloprid (IM)	RB=97% (60 min), IM=55% (240 min)	Tang *et al.* (2020)
	TiO_2	Metalaxyl	99.9% (30 min)	Islam *et al.* (2020)
	F-Pd co-doped TiO_2 nanocomposite	Sulfamethoxazole (SMX)	98.9% (70 min)	Jahdi *et al.* (2020)
Industrial wastewater	TiO_2/Graphene oxide	Methylene Blue	99% (4h)	Kurniawan *et al.* (2020)
	sGO-Ag2VO4/Ag	Dye	99.95% (60 min)	Raga *et al.* (2020)
	Zinc oxide nanoparticles (ZnO NPs)	Basic Red 51 (BR51)	89.01% (5.5h)	Yashni *et al.* (2020)

oxide, zinc oxide (ZnO) nanoparticles are widely studied and utilized as photocatalysts due to their high photocatalytic activity, chemical stability, and low cost (Table 4). They have been employed for the degradation of various organic pollutants, such as dyes, pesticides, and pharmaceuticals, in water under ultraviolet (UV) or visible light irradiation (Gholami *et al*., 2020; Tang *et al*., 2020).

Conclusion and future directions

Nanotechnology provides novel tools and strategies to tackle complex environmental challenges, revolutionizing ecosystem management. Nanomaterials have proven versatile and effective in pest control, promoting agricultural growth, water purification, and enhancing soil health. Nanotechnology enables sustainable resource management, precise monitoring, and targeted interventions. Integrating nanomaterials like metal oxides, polymeric nanocomposites, and carbon nanotubes has shown remarkable promise in nutrient delivery, disease detection, and pollutant removal in agriculture and water. Continued research will optimize nanomaterials, further enhancing ecosystem management techniques. Future developments will focus on cost-effective manufacturing, ensuring nanomaterial safety, and creating intelligent versatile materials addressing environmental issues. Integrating nanotechnology with digital technologies like sensors and data analytics will improve real-time monitoring and decision-making. Comprehensive policies and regulations are crucial for ethical conduct and public acceptance. Overcoming challenges like membrane fouling, catalyst agglomeration, and scaling up plasma discharge technology is vital for water treatment. Developing eco-friendly, bio-based nano-adsorbents, prioritizing recyclability, addressing risks to aquatic life, investigating magnetic nano-adsorbents with green photocatalysts, and synthesizing nanoparticles for metal ion adsorption are areas of interest. Addressing these challenges will enable nanotechnology to contribute significantly to sustainable ecosystem management and environmental preservation especially in agriculture and water management.

Conflict of Interest- None

References

Bisht, M., Rajwar, D. and Raju, M. 2020. Nanotechnology for agricultural and environmental sustainability at higher altitudes. In: Goel, R., Soni, R., and Suyal, D. (eds) Microbiological Advancements for Higher Altitude Agro-Ecosystems & Sustainability. *Rhizosphere Biology*. Springer, Singapore. https://doi.org/10.1007/978-981-15-1902-4_23

Bisht, M., Shrivastava, M. and Lal, K. 2024. Evaluation of hydrogeochemical processes for irrigation use and potential nitrate contamination sources in groundwater using nitrogen stable isotopes in Southwest India: A case study. *Water, Air, and Soil Pollution.* 235: 324. https://doi.org/10.1007/s11270-024-07028-1

Bisht, M., Shrivastava, M. and Pooja L. R. 2024. Seasonal dynamics and hydrogeological assessment of Najafgarh drain and its irrigation channels for agricultural purposes in Southwest Delhi, India. *Water Prac Techn.* 2024236. doi: https://doi.org/10.2166/wpt.2024.236

Bisht, M., Shrivastava, M., Kumar, S. and Singh, R. 2023. Evaluation of the drinking water quality and potential health risks of nitrate and fluoride in Southwest Delhi, India. *Int J Environ Anal Chem.* 1-23. 10.1080/03067319.2023.2241837.

Ceretta, M.B., Vieira, Y., Wolski, E.A., Foletto, E.L. and Silvestri, S. 2020. Biological degradation coupled to photocatalysis by ZnO/polypyrrole composite for the treatment of real textile wastewater. *Journal of Water Process Engineering*. 35: 101230. http://dx.doi.org/10.1016/j.jwpe.2020.101230.

Dasgupta, N., Ranjan, S. and Ramalingam, C. 2017. Applications of nanotechnology in agriculture and water quality management. *Environmental Chemistry Letters.* 15: 591-605.

Disfani, M.N., Mikhak, A., Kassaee, M.Z. and Maghari, A. 2017. Effects of nano Fe/SiO2 fertilizers on germination and growth of barley and maize. *Archives of Agronomy and Soil Science.* 63: 817-826.

Du, H., Liu, W., Zhang, M., Si, C., Zhang, X. and Li, B. 2019. Cellulose nanocrystals and cellulose nanofibrils based hydrogels for biomedical applications. *Carbohydrate Polymers.* 209: 130–144.

Elessawy, N.A., Gouda, M.H., M. Ali, S., Salerno, M. and Eldin, M.M. 2020. Effective elimination of contaminant antibiotics using high-surface-area magnetic-functionalized graphene nanocomposites developed from plastic waste. *Materials*. 13(7): 1517.

Gholami, P., Khataee, A., Soltani, R.D.C., Dinpazhoh, L. and Bhatnagar, A. 2020. Photocatalytic degradation of gemifloxacin antibiotic using Zn-Co-LDH@ biochar nanocomposite. *Journal of Hazardous Materials*. 382: 121070. http://dx.doi.org/10.1016/j.jhazmat.2019.121070.

Gogos, A., Knauer, K. and 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. doi: 10.1021/jf302154y.

Gordillo-Delgado, F., Zuluaga-Acosta, J. and Restrepo-Guerrero, G. 2020. Effect of thesuspension of Ag-incorporated TiO2 nanoparticles (Ag-TiO2 NPs) on certain growth,physiology and phytotoxicity parameters in spinach seedlings. *PLoS One.* 15(12).

Hayati, F., Isari, A.A., Anvaripour, B., Fattahi, M. and Kakavandi, B. 2020. Ultrasound-assisted photocatalytic degradation of sulfadiazine using MgO@CNT heterojunction composite: Effective factors, pathway and biodegradability studies. *Chemical Engineering Journal*. 381: 122636.

Hunge, Y.M., Yadav, A.A., Khan, S., Takagi, K., Suzuki, N., Teshima, K., Terashima, C. and Fujishima, A. 2021. Photocatalytic degradation of bisphenol A using titanium dioxide@nanodiamond composites under UV light illumination. *Journal of Colloid and Interface Science*. 582: 1058-1066.

Imada, K., Sakai, S., Kajihara, H., Tanaka, S. and Ito, S. 2016. Magnesium oxide nanoparticles induce systemic resistance in tomato against bacterial wilt disease. *Plant Pathology.* 65: 551-560.

Islam, J.B., Furukawa, M., Tateishi, I., Katsumata, H. and Kaneco, S. 2020. Photocatalytic degradation of a typical agricultural chemical: metalaxyl in water using TiO2 under solar irradiation. *SN Applied Sciences.* 2.

Jahdi, M., Mishra, S.B., Nxumalo, E.N., Mhlanga, S.D. and Mishra, A.K. 2020. Smart pathways for the photocatalytic degradation of sulfamethoxazole drug using F-Pd co-doped TiO2 nanocomposites. *Applied Catalysis B.* 267: 118716.

Jampílek, J., amp; Králová, K. 2021. Nanoparticles for improving and augmenting plantfunctions. In Advances in Nano-Fertilizers and Nano-Pesticides in Agriculture (pp. 171-227). Woodhead Publishing.

Kale, A.P. and Gawade, S.N. 2016. Studies on nanoparticle-induced nutrient use efficiency of fertilizer and crop productivity. *Green Chemistry Technology Letters.* 2: 88–92.

Kaur, M., Kaur, M., Singh, D., Feng, M. and Sharma, V.K. 2022. Magnesium ferrite-nitrogen–doped graphene oxide nanocomposite: effective adsorptive removal of lead (II) and arsenic (III). *Environmental Science and Pollution Research*. 29(32): 48260-48275

Kiwaan, H.A., Atwee, T.M., Azab, E.A. and El-Bindary, A.A. 2020. Photocatalytic degradation of organic dyes in the presence of nanostructured titanium dioxide. *Journal of Molecular Structure.* 1200.

Kumar, V., Guleria, P. and Ranjan, S. 2021. Phytoresponse to nanoparticle exposure. *Nanotoxicology and Nanoecotoxicology.* 1: 251-286.

Kurniawan, T.A., Mengting, Z., Fu, D., Yeap, S.K., Othman, M.H.D., Avtar, R. and Ouyang, T., 2020. Functionalizing TiO2 with graphene oxide for enhancing photocatalytic degradation of methylene blue (MB) in contaminated wastewater. *J. Environ. Manage*. 270: 110871. http://dx.doi.org/10.1016/j.jenvman.2020.110871

Mohamed, M.S., El-Arabi, N.I., El-Hussein, A., El-Maaty, S.A. and Abdelhadi, A.A. 2020. Reduction of chromium-VI by chromium-resistant *Escherichia coli* FACU: A prospective bacterium for bioremediation. *Folia. Microbiol.* 65: 687-696.

Nagajyothi, P.C., Vattikuti, S.V., Devarayapalli, K.C., Yoo, K., Shim, J. and Sreekanth, T.V. 2019. Green synthesis: Photocatalytic degradation of textile dyes using metal and metal oxide nanoparticles-latest trends and advancements. *Critical Reviews in Environmental Science and Technology.* 50: 2617–2723.

Pallavi, Mehta, C.M., Srivastava, R., Arora, S. and Sharma, A.K. 2016. Impact assessment of silver nanoparticles on plant growth and soil bacterial diversity. *3 Biotech*. 6: 254.

Pelegrino, M.T., Kohatsu, M.Y., Seabra, A.B., Monteiro, L.R., Gomes, D.G., Oliveira, H.C. and Lange, C.N. 2020. Effects of copper oxide nanoparticles on growth oflettuce (*Lactuca sativa* L.) seedlings and possible implications of nitric oxide in theirantioxidative defense. *Environmental Monitoring and Assessment.* 192: 1-14.

Rizwan, M., Ali, S., ur Rehman, M.Z., Malik, S., Adrees, M., Qayyum, M.F., Alamri, S.A., Alyemeni, M.N. and Ahmad, P. 2019. Effect of foliar applications of silicon and titanium dioxide nanoparticles on growth, oxidative stress, and cadmium accumulation by rice (*Oryza sativa*). *Acta Physiologiae Plantarum.* 41: 35.

Rossi, L., Fedenia, L.N., Sharifan, H., Ma, X. and Lombardini, L. 2019. Effects of foliar application of zinc sulfate and zinc nanoparticles in coffee (*Coffea arabica* L.) plants. *Plant Physiology and Biochemistry*. 135: 160-166.

Saleem, M. 2022. Possibility of utilizing agriculture biomass as a renewable and sustainable future energy source. *Heliyon.* 8(2).

Siddeeg, S.M., Tahoon, M.A., Alsaiari, N.S., Shabbir, M. and Rebah, F. B. 2021. Application of functionalized nanomaterials as effective adsorbents for the removal of heavy metals from wastewater: a review. *Current Analytical Chemistry.* 17(1): 4-22.

Siddiqi, K.S. and Husen, A. 2022. Plant response to silver nanoparticles: a critical review. *Critical Reviews in Biotechnology.* 42(7): 973-990.

Tahoon, M.A., Siddeeg, S.M., Salem Alsaiari, N., Mnif, W. and Ben Rebah, F. 2020. Effective heavy metals removal from water using nanomaterials: A review. *Processes.* 8(6): 645.

Tang, Y., Zhang, X., Ma, Y., Wang, X., Su, C., Zhang, D., Pu, X. and Geng, Y., 2020. One-imensional core–shell Zn0.1Cd0.9S/Snln4S8 heterojunction for enhanced visible light photocatalytic degradation. *Sep. Purif. Technol.* 230: 115896.

Vanti, G.L., Nargund, V.B., Basavesha, K.N., Vanarchi, R., Kurjogi, M., Mulla, S.I., Tubaki, S. and Patil, R.R. 2019. Synthesis of *Gossypium hirsutum*-derived silver nanoparticles and their antibacterial efficacy against plant pathogens. *Applied Organometallic Chemistry.* 33: e4630.

Wang, Y., Lin, Y., Xu, Y., Yin, Y., Guo, H. and Du, W. 2019. Divergence in response of lettuce (var. ramosa Hort.) to copper oxide nanoparticles/microparticles as potential agricultural fertilizer. *Environmental Pollution Bioavailability*. 31: 80-84.

Wu, S., Hu, H., Lin, Y., Zhang, J., Hu, Y.H. 2020. Visible light photocatalytic degradation of tetracycline over TiO2. *Chemical Engineering Journal.* 382: 122842.

Yashni, G., Al Gheethi, A., Mohamed, R.M.S.R., Arifin, S.N.H., Shanmugan, V.A. and Kassim, A.H.M. 2020. Photocatalytic degradation of basic red 51 dye in artificial bathroom greywater using zinc oxide nanoparticles. *Materials Today: Proceedings.* 31:136-139.

Zhang, H. 2015. Ultrathin two-dimensional nanomaterials. *ACS Nano*. 9(10): 9451–9469. doi: 10.1021/acsnano.5b05040.