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Advantages of Treatment Pollution by Nanomaterial: Review

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Abstract

Pollution remains one of the most pressing global environmental challenges and is increasing day by day, with serious implications for public health and the environment. Among the various approaches to address this issue, nanotechnology has emerged as a promising solution due to its unique properties, such as high surface area, reactivity, and catalytic efficiency. There are four types of pollution that can be treated by nanotechnology, air pollution, soil pollution, water pollution and light pollution. This review studies recent research on the use of nanoparticles for pollution treatment, focusing on the mechanisms through which they degrade pollutants, the diverse applications of these materials, and the challenges and future directions of this technology.

Keywords: Nanotechnology, Air pollution, Water pollution, Soil pollution, Light pollution

1. Introduction

Pollution is the introduction of harmful substances into the environment, negatively affecting human health, ecosystems, and the planet. It can take various forms, such as air, water, soil, and light pollution, and can be caused by both natural sources and human activities. Pollution can be classified into four categories: air pollution, water pollution, soil pollution, and light pollution. In this review we collect papers which study the treatment of pollution by nanomaterials. Rusul, Maan Hayyan, Mohammed Abdulhakim AlSaadi, Adeeb Hayyan and Shaliza Ibrahim (2016) their study shows that nanotechnology provides innovative solutions for air, soil, and water pollution. In the air, nanomaterials trap toxic gases, dust, and chemicals to improve air quality. In soil, they remove heavy metals and boost farming with nano-fertilizers and pesticides. For water, nanotechnology purifies water by filtering out pollutants, bacteria, and viruses. Overall, nanotechnology offers smart and eco-friendly methods for environmental protection (Ibrahim et al., 2016).

Stuart Linley and Neil R. Thomson (2021) have studied How nanotechnology is cleaning our environment by showing how tiny, engineered mate-

rials (nanotechnology) have transformed pollution cleanup in water, soil, and air over the last 20 years. These microscopic solutions work in two main ways: the first one is Breaking down pollutants through chemical reactions, and the second is Trapping contaminants like a sponge. The key technologies making a difference are Light-activated cleaners (photocatalysis), Iron nanoparticles that neutralize toxins, and special materials that capture carbon dioxide (Linley & Thomson, 2021).

Parul Chaudhary, Lukman Ahamad, Anuj Chaudhary, Govind Kumar, Wen-Juan Chen, Shaohua Chen (2023) have studied nanoparticle-mediated bioremediation is an advanced method for addressing environmental pollution by utilizing the unique properties of nanoparticles, such as high surface area and reactivity, to remove contaminants from soil, water, and air. The approach involves mechanisms like adsorption, catalytic degradation, and filtration. The research highlights the versatility of various nanoparticle types metallic: carbon-based, and polymer across multiple pollution challenges. While promising, the method stresses the importance of responsible use, with attention to environmental safety and ethical concerns (Chaudhary et al., 2023). Leta Tesfaye Jule

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and Nagaprasad Nagaraj (2025) have been studying how Tiny Tech can create a cleaner planet: the research shows how super-small materials (nanomaterials) can solve big pollution problems: as Cleaner Water when the Nanotech filters remove harmful chemicals and germs Clearer Air: Tiny particles trap and break down pollution and also for Healthier Soil Helps clean up toxic waste in the ground (Wirtu et al., 2025).

2. Type of pollution

2.1. Air pollution

Air pollution is a major environmental issue, and nanoparticles have gained interest in their potential in addressing it due to their unique properties. In recent years, much research has studied the role of nanoparticles in air pollution treatment. This part of review shows recent research from 2015 to 2025 which studies treatment of air pollution by nanoparticles.

Yunes Panahi, Hassan Mellatyar, Masoud Farshbaf, Ziba Sabet, Tannaz Fattahi, Abolfazl Akbarzadehe (2018) have been studying the potential applications of biotechnology-based nanomaterials to mitigate air pollution and enhance the treatment of wastewater and water. The most significant advantages of the nanomaterials in comparison with the conventional treatment technologies is their capability to integrate different properties which create multifunctional systems such as the nanocomposite membranes which have the capacity for the particle retention and removal of contaminants. In the adsorption of heavy metals such as Cu^{2+} , Pb^{2+} , Cd^{2+} , and Zn^{2+} , carbon nanotubes (CNTs) perform better than activated carbons (ACs) because of their quick adsorption speed. The antifouling characteristics of nanocomposite membranes are improved by antimicrobial nanomaterials like CNTs, Nano-Ag, and Nano-TiO₂ (Panahi et al., 2018).

Adawiya Haider, Riyad Al-Anbari, Ghadah Kadhim and Zainab Jameel (2018) have been researching the synthesis of titanium dioxide nanoparticles TiO₂ NPs using sol-gel or hydrothermal techniques, when given ultraviolet light, TiO₂ NPs' exhibit photocatalytic qualities. Self-cleaning properties of the prepared nanoparticles were characterized by Water Contact Angle (WCA) and photocatalysis activity. WCA shows that the anatase and mixed phase are super-hydrophobic surfaces with WCA of zero value, while rutile phase shows good hydrophilicity with WCA of 7.775. Titanium dioxide nanoparticles TiO₂ NPs are utilized in air purification to convert dangerous pollutants such as nitrogen oxides (NO_x) and volatile organic compounds (VOCs) into less dangerous forms (Haider et al., 2018).

Kah Hon Leong, Jia Quan Lee, A. Ashok Kumar, Lan Ching Sim, Saravanan Pichiah (2019) have been studying synthesized titanium dioxide nanoparticles TiO₂ NPs and their applications of a sol-gel process. The synthesis method involves spray-coating to create effective self-cleaning surfaces for air purification onto porous glass. The study examines the TiO₂ coating's homogeneity and how well it breaks down formaldehyde when exposed to UV light. Dynamic flow-sense images showed that highly uniform coatings can be obtained by spraying TiO₂ nanoparticles at concentrations exceeding 15.0 g/L. This result is further supported by 2D and 3D surface plots, wherein no surface defects were observed on coatings prepared with more than 15.0 g/L TiO₂. This technique for immobilizing TiO₂ nanoparticles on glass substrates has the potential to improve photocatalytic self-cleaning and provide an effective way to remove air pollutants from indoor environments (Leong et al., 2019).

R. Magudieshwaran, Junki Ishii, Krishna Chandar Nagamuthu Raja, Chiaki Terashima, R. Venkatachalam, Akira Fujishima, Sudhagar Pitchaimuthu (2019) have been studying comparison of two methods synthesizing cerium oxide nanoparticles CeO₂ NPs. green synthesis (using natural processes) and chemical synthesis (lab-based). The green synthesized CeO₂ nanoparticles have been evaluated in photocatalytic acetaldehyde degradation. The comparative photocatalysis performance of green synthesized CeO₂ nanoparticles strongly recommend revisiting the utilization of green synthesis instead of chemical synthesis route for indoor photocatalysis based pollutant degradation applications. It increased their effectiveness in combating indoor air pollution and focuses on the potential of both approaches in air purification, emphasizing the future role of nanotechnology in achieving cleaner air (Magudieshwaran et al., 2019).

David, L. and B. Moldovan (2020) have been studying the green synthesis of nanoparticles, such as iron and silver, offers eco-friendly methods for pollution control. By using biological resources for production, these nanoparticles reduce the environmental impact of their creation. This fusion of nature and nanotechnology provides a more sustainable approach to environmental cleanup (David & Moldovan, 2020).

Mohamed, E.F. and G. Awad (2020) have been studying the new air-cleaning filter that uses light and nanoparticles. The researchers developed a special two-step air filter the first step traps harmful chemicals and germs from indoor air and then the second uses UV light to destroy them completely. They demonstrated how it works using silver nanoparticles on titanium dioxide sheets that remove 15% of chemicals like toluene in the first hour (without light)

and destroy 97% of these chemicals when UV light turns on and kills all airborne germs within 5 hours. This research is important for factories, hospitals and homes (Mohamed & Awad, 2020).

Arpita Roy, Apoorva Sharma, Saanya Yadav, Leta Tesfaye Jule and Ramaswamy Krishnaraj (2021) have been studying how nanomaterials (tiny, engineered particles) can help clean up pollution in air, water, and soil. These materials are highly effective because of their small size and strong reactivity. The study covers different types, like carbon-based, metal-based, and polymer nanomaterials, and how they remove toxins such as heavy metals and chemicals (Roy et al., 2021).

B. Sreelakshmi, S. Induja, P.P. Adarsh, H.L. Rahul, S.M. Arya, S. Aswana, R. Haripriya, B.R. Aswathy, P.K. Manoj and Dalia Vishnudasan (2021) These studies of green synthesis of iron oxide nanoparticles apply on plants surviving drought conditions. These iron oxide nanoparticles did not show any toxicity response towards the plants, instead, the plants overcame the drought situation and showed better plant responses. Proline, a drought stress indicator was observed less, when drought stress was given along with the FeNPs supplemented plants, unlike the non-supplemented experimental plants (Sreelakshmi et al., 2021).

Farzaneh Edrisia, Mehdi Mahmoudian ab and Nasrin Shadjou (2024) have been studying advanced air filters by integrating zinc oxide nanoparticles (ZnONPs) into plastic fibers. These filters efficiently remove harmful gases like CO₂, NO₂, and SO₂ with 89%, 86%, and 83% efficiency, respectively. The researcher aims to investigate the impacts of these nanomaterials on filter performance and explore the potential of LIBS for sensitive heavy metal monitoring. The advancement of this research will contribute to the development of innovative strategies for air pollution remediation and the protection of human health and the environment. They also kill bacteria, keeping the filters cleaner and safer, and improve the effectiveness of masks and air purifiers (Edrisi et al., 2024).

Radha, K., V. Selvi, and J. Aarcha, (2025) This have been tests special air filters made with silver nanofibers that could clean indoor air better. These ultra-thin filters use tiny silver particles to trap harmful pollutants. The new technology might lead to smarter air purifiers (Radha et al., 2025).

Suganthi Rajendran, Poornima Ramesh, Priyadharsini Sengottaiyan and Nandhini Devi Balasubramaniam (2025) have been studying clearing the Air. This research shows how nanotechnology (super-small materials) can help solve air pollution problems. Scientists are using tiny particles and structures to trap harmful pollutants with ultra-fine filters and

Break down toxic chemicals faster also monitor air quality in real time The study highlights how these tiny solutions could lead to cleaner air and a healthier planet (Rajendran et al., 2025).

Awan, T.I., S. Afsheen, and A. Mushtaq (2025) have been looking at how tiny particles of gold, silver, and platinum can help clean up pollution. Because of their special properties, these nanoparticles can break down harmful chemicals in water, air, and soil. While they show great promise, challenges like high costs and environmental risks still need to be addressed. The research aims to contribute to sustainable and efficient pollution control methods (Awan et al., 2025).

2.2. Water pollution

Water pollution, worsened by industrial growth and urbanization, releases harmful substances like heavy metals and chemicals. Nanoparticles offer an effective solution for cleaning water due to their small size and strong ability to remove pollutants. The Mechanisms of Action: Adsorption-Nanoparticles, such as those made from chitosan and magnetic materials, primarily function through adsorption, capturing pollutants from water due to their high surface area and reactivity. And photocatalytic degradation, Photocatalytic Cleaning (TiO₂/ZnO) is Sunlight and Nanoparticles the resulting is pollutant breakdown and by Light activates nanoparticles to destroy contaminants. Its eco-friendly but needs optimization (Bognár et al., 2022). In this part of review, we show recent research from 2015 to 2025 which studies treatment of water pollution by nanoparticles.

The most important types of nanoparticles used in water treatment are metal-Organic Frameworks (MOFs) and Inorganic Nanoparticles, the scientists have created a new material by combining metal-organic frameworks (MOFs) with cerium-oxide nanoparticles. This composite effectively removes heavy metals from water and can be cleaned and reused, providing an eco-friendly solution for water purification (Boix et al., 2020). Iron Oxide Magnetic Nanoparticles can attract and remove organic pollutants from water. They are cheap, reusable, and can be scaled up for large water treatment systems. Silver nanoparticles (AgNPs) break down dyes in wastewater and kill pathogenic microbes, making them useful for treating polluted industrial water (Palani et al., 2023). Chitosan nanoparticles which a linear polysaccharide, have the ability to absorb pollutants from water. By changing their structure to improve adsorption capacity and selectivity (Benet-tayeb et al., 2023).

Lavanya Madhura, Shalini Singh, Suvadhan Kanchi, Myalowenkosi Sabela, Krishna Bisetty

and Inamuddin (2018) have been studying the role of nanotechnology in managing water quality for wastewater treatment. Nanomaterials (such as graphene, carbon nanotubes, and metal oxide nanoparticles) can adsorption, photocatalysis, and reactivity, making them effective in reduced organic and inorganic pollutants. The study compares emerging and conventional technologies in terms of cost and efficiency (Madhura et al., 2019).

Arabinda Baruah, Vandna Chaudhary, Ritu Malik, Vijay K. Tomer (2019) have been studying nanotechnology offers innovative solutions for wastewater treatment by enhancing efficiency, sustainability, and cost-effectiveness. Though adsorption-based water purification is an age-old traditional technique, the incorporation of high surface area and chemically modified nano absorbents has increased the efficiency of this method by manifold. Membrane based filtration of water is an extremely efficient process and currently, it is the most popular technology for domestic as well as industrial applications metal oxide nanoparticles (as carbon-based nanomaterials and nanocomposites) are utilized for pollutant reduction through adsorption, catalysis, and membrane filtration. These materials help eliminate organic and inorganic contaminants, heavy metals, and pathogens, improving water quality (Baruah et al., 2019).

Surya Pratap Goutam, Gaurav Saxena, Diptarka Roy, Anil Kumar Yadav and Ram Naresh Bhargava (2020) have been studying the growing role of nanotechnology in environmental applications, particularly in water pollution control and wastewater treatment. However, focusing on improvement in the existing treatment methods by increasing the efficiency of the processes and enhancing the reusability of nanomaterials can save the cost of operation of the plant or processes. The study explores many synthesis methods for nanoparticles and their applications in removing water contamination. Additionally, it examines how nanotechnology contributes to pollution prevention and remediation efforts (Goutam et al., 2020).

Sazid, M.G. and S.T.J. Supto (2024) have been studying metal oxide nanoparticles (MONs) synthesized and applied pollution treatment. Zinc oxide nanoparticles emerge as a promising solution for urban water pollution. Photocatalysis and redox reactions. Metal Oxide (MONPs) can be the future of wastewater treatment. With physical and chemical properties such as adsorption, photocatalytic and antimicrobial activity. They have been shown to effectively eliminate heavy metals, organic contaminants, and pathogens. Nonetheless, issues such as the aggregation of nanoparticles, environmental and health risks, and the shortcomings of current water treat-

ment technologies hinder their widespread use. Metal oxides nanoparticles can effectively remove contaminants such as heavy metals, oil and grease, organic and inorganic chemicals, and industrial pollutants through mechanisms such as adsorption, photocatalysis, and redox reactions¹. Additionally, metal oxides show potential in neutralizing pathogens and microbial contaminants (Sazid & Supto, 2024).

Yu Guo, Changwei Huang, Rosaiah Pitcheri, Banoth Shekhar, Dhanalakshmi Radhalayam, Soumyendu Roy, Madhusudana Rao Kummara, Mohammad Rezaul Karim (2025) have been studying the eco-friendly method for synthesizing bismuth oxide nanoparticles (Bi_2O_3 NPs) using almond gum as a natural stabilizer. This green synthesis avoids toxic chemicals, offering a sustainable alternative to traditional methods. The resulting nanoparticles show strong photocatalytic activity, effectively breaking down water pollutants under light exposure. The studying emphasizes the biocompatibility of the synthesized bismuth oxide nanoparticles (Bi_2O_3 NPs) supporting their safe environmental and biomedical applications (Guo et al., 2025).

2.3. Soil pollution

Due to their unique properties, such as high surface area and reactivity, nanoparticles have emerged as a promising solution to soil pollution. Nano remediation has emerged as an effective, rapid, and efficient technology for soil and groundwater contaminated with petroleum pollutants and heavy metals. Pollution from oil and heavy metals poses significant environmental and health risks. In this part of review, we show recent research from 2015 to 2025 which studies treatment of soil pollution by nanoparticles.

Zero-Valent Iron Nanoparticles (nZVI) are widely used for their high reactivity and ability to immobilize and reduce contaminants, nZVI is effective in remediating petroleum pollutants and heavy metals in soil and groundwater. nZVI has been widely studied for high-efficiency environmental remediation due to its high reactivity and excellent contaminant immobilization capability. CNTs have received more attention for remediation of organic and inorganic contaminants because of their unique adsorption characteristics. Modified nZVI shows reduced toxicity towards soil bacteria, making it a safer option for environmental applications (Alazaiza et al., 2021; Ibrahim et al., 2024; Galdames et al., 2020).

Carbon Nanotubes (CNTs) are known for their unique adsorption characteristics, CNTs are effective in removing organic and inorganic contaminants from soil. The research has been successfully

synthesized and evaluated with regards to their performance in removing Cd from contaminated soil. Metallic and Magnetic Nanoparticles (MNPs) are preferable for their ease of magnetic separation and metal-ion adsorption capabilities, making them suitable for environmental remediation. Ligand-Coated Dense Nanoparticles (Ligand DNPs): These are used to sequester heavy metal ions in soil, reducing their bioavailability and potential health risks (Huang & Keller, 2020).

Ferdinand Brandl, Nicolas Bertrand, Eliana Martins Lima and Robert Langer (2015) have studied the Light-Activated Cleanup Formula to address pollution in water and soil caused by hidden chemical which are difficult to clean therefore they found a Solution by using light-sensitive nanoparticles and UV Light to facilitate pollution removal, they add special nanoparticles to polluted area then they shine UV light to get particles clump together finally they pull out clumps, which carry the pollutants with them. This process is effective in removing BPA (from plastics), Triclosan (from soaps) and Estrogens (from medicines). the light performs the cleanup no toxic residues and Works in water & soil (Brandl et al., 2015).

Qi Li, Xijuan Chen, Jie Zhuang and Xin Chen (2016) have studied the soil cleanup nano-formula to address the issue of toxic Soil (Pesticides/PCBs/PAHs) which remains hazardous for years so they use nano-solution which is smart nanoparticles applied to polluted soil to achieve cleaner ground. It discusses different types of nanoparticles, such as iron oxides, titanium dioxide, and carbon-based nanoparticles, along with their benefits and limitations. Factors influencing their effectiveness, like soil properties and solution chemistry, are also examined (Li et al., 2016).

Helal, M.I., H.A. Khater, And A. Marzoog, (2016) studied a simple formula for heavy metal cleanup formula the major issue is soil contamination with heavy metals (Cd, Pb), which are toxic and unsafe, so they use nano-solution containing special nanoparticles applied to polluted soil for remediation. The best nano-cleaners include: nZVI Iron powder that traps metals, Bentonite-nZVI- clay-enhanced version, nanolaminated- from algae, binds metals, Nanocarbon - Super-absorbent carbon) These nanoparticles are characterized by (Tiny size = More surface to grab metals, Strong binding = Locks away toxins, Reduces plant uptake = Safer food) .as a Results they get Cd/Pb levels dropped below safety limits, outperforming traditional methods and More cost-effective (HELAL et al., 2016).

M. Gil-Díaz, S. Diez-Pascual, A. González, J. Alonso, E. Rodríguez-Valdés, J.R. Gallego and M.C. Lobo (2016) have studied the use of nZVI for Arsenic

Soil cleanup due to the problem of Arsenic contaminated soil that make toxic & unsafe for plants so they find the solution by uses nZVI Nanoparticles to treat polluted Soil to get cleaner soil and they find the nZVI binds As, Locking arsenic in soil also the changes the form of As, Making it less absorbable to get Protects Plants by Reduces arsenic uptake (Gil-Díaz et al., 2016).

A. Galdames, A. Mendoza, M. Orueta, I.S. de Soto García, M. Sánchez, I. Virto and J.L. Vilas (2017) have studied the soil cleanup combo formula to solve the problem when soil is contaminated with hydrocarbons and heavy metals which make toxic and unhealthy so they find solution by but the nZVI with Compost and dirty soil that resulted in cleaner soil, by they use nZVI action (for metals) and locks arsenic/chromium in place also reduces toxic leaching. The compost power (for oil) give microbes eat hydrocarbons which is best for long-chain oils (60% cleanup) .when used together they lower soil toxicity, help plants and worms return, and work better than when used alone (Galdames et al., 2017).

Vishnu D. Rajput, Tatiana Minkina, Svetlana Sushkova, Viktoriia Tsitsuashvili, Saglara Mandzhieva, Andrey Gorovtsov, Dina Nevidomskaya and Natalya Gromakova (2018) have studied the nanoparticles in agriculture: a simple risk-benefit formula the research involved applying nanoparticles (NPs) to soil and crops and show the effect on soil microbes (NPs) which reduced microbial biomass and changed community also effect on plants high np doses lead to abnormal growth and lower yields so the risks may harm beneficial microbes and can disrupt soil balance also, long-term effects unknown therefore we should a balance approach is needed, with precise NPs dosing and targeted applications also eco-friendly np designs (Rajput et al., 2018).

Ahmed Ali Romeh (2018) have studied the green nano-cleanup formula the problem is soil and water contaminated with fipronil (toxic pesticide) the result dangerous & persistent so the research make solution by use plant-made silver NPs and remediation plants to get cleaner environment to understand how it works, fist they used green AgNPs (from medicinal plants) to make to break down fipronil faster, brassica-made NPs were found to work best the other way is phytoremediation (plant ago major) which absorbs pesticide leftovers to get cleans soil & water together. the results is less fipronil in the environment and reduced toxic byproducts and nature-friendly method (Romeh, 2018).

Rui-Juan Sun, Jie-Hua Chen, Ting-Ting Fan, Dong-Mei Zhou and Yu-Jun Wang (2018) have been studying the HAP Metal Cleanup Formula the research note problem in Soil which contain a Heavy Metals

(Cu/Zn) that make Toxic to Plants so the find Solution by but the Nano-Hydroxyapatite (HAP) to Polluted Soil to get Safer Soil because the HAP Binds Metals made Forms stable phosphate minerals and the Locks Metals Prevents plant uptake & leaching then it Boosts Growth More to the ryegrass biomass the Results Less Cu/Zn in plants, Lower metal mobility, Better crop growth (Sun et al., 2018).

Akansha Srivastav, Krishna Kumar Yadav, Sunita Yadav, Neha Gupta, Jitendra Kumar Singh, Ravi Katiyar and Vinit Kumar (2018) have been studying the Nano-Phytoremediation Formula we have Problem in Soil Pollution (Heavy Metals with Chemicals) that made Harmful to Nature & People so the research find Solution by put the Plants with Nanomaterials to get Supercharged Cleanup to explain this method first the Plants absorb and break down pollutants then the Nanoparticles boost the process by Trapping more toxins (like magnets) that Help the plants grow better in dirty soil then Speeding up chemical breakdown this method is Better because it More effective than plants alone, Works on tough pollutants also Nature-friendly approach (Srivastav et al., 2018).

Tingting You, Dandan Liu, Jing Chen, Zhongzhou Yang, Runzhi Dou, Xiang Gao and Li Wang (2018) have been studying simple soil-nanoparticle impact formula. They Input MO-ENPs to Soil Types to get soil health changes they findings most impactful NP is ($n\text{ZnO} > n\text{TiO}_2 / n\text{CeO}_2 / n\text{Fe}_3\text{O}_4$) also the Saline-alkali soil was more susceptible to these nanoparticles than black soil. And notice Bacterial Effects $n\text{ZnO}$ reduced bacterial counts also changed community types (e.g., Bacilli). finally Zinc nanoparticles harm soil life most – especially in already-stressed soils (You et al., 2018).

Sarkar, A., S. Sengupta, and S. Sen (2019) have been studying Nano-Remediation Simplified Formula we have Problem in Soil with Toxins that Needs Cleaning so they use Smart Nanoparticles to get Fast and Targeted Cleanup Top Nano-Tools is $n\text{ZVI}$ Metal magnet for toxins and CNTs Carbon sponges, MNPs Magnetic cleaners They Work as Trap pollutants (adsorption) also Lock toxins in place (immobilization) and Break down chemicals. But its May harm soil microbes so it Needs safety testing (Sarkar et al., 2019).

Biao Song, Piao Xu, Ming Chen, Wangwang Tang, Guangming Zeng and Jilai Gong (2019) have been studying the Nano-Phytoremediation Formula the Slow Plant Cleanup is Needs Boost so they put for the Plants Nanomaterials which Supercharged Cleanup It Works on Better Uptake NPs make toxins easier for plants to absorb also Faster Growth which Helps plants thrive in dirty soil and Stronger Roots to Improves pollutant collection .Best Nano-Helpers is $n\text{ZVI}$ (iron) - Binds contaminants and Fullerenes (carbon) - Enhances breakdown (Song et al., 2019).

D. Baragaño, J. Alonso, J.R. Gallego, M.C. Lobo, M. Gil-Díaz (2020) have been studying the Goethite and zero-valent iron (ZVI) nanoparticles are emerging as promising solutions for cleaning arsenic-contaminated soils. ZVI nanoparticles reduce arsenic levels by chemically transforming it, while goethite nanoparticles effectively trap arsenic due to their strong adsorption properties. These methods are considered sustainable and efficient alternatives to traditional remediation techniques (Baragaño et al., 2020).

Baragaño, D., et al. (2020) have been studying the use of graphene oxide nanoparticles (nGOx) for remediating soils polluted with arsenic (As) and heavy metals. It compares nGOx with zero-valent iron nanoparticles ($n\text{ZVI}$) in immobilizing or mobilizing pollutants. The most important result is nGOx effectively immobilizes metals like copper (Cu), lead (Pb), and cadmium (Cd), but mobilizes arsenic (As) and phosphorus (P), even at low doses. $n\text{ZVI}$ is more effective in immobilizing As and Pb but less effective for Cd and increases Cu availability. Soil pH and electrical conductivity are slightly affected by nGOx. The study highlights the potential of nGOx in combined remediation strategies, such as phytoremediation, and emphasizes the challenges in addressing both anionic and cationic contaminants simultaneously (Baragaño et al., 2020).

Diego Baragaño, Rubén Forján, Lorena Welte and José Luis R. Gallego (2020) have been studying the investigates magnetite nanoparticles (MNPs) for remediating soils contaminated with arsenic and polycyclic aromatic hydrocarbons (PAHs). MNPs effectively reduced arsenic availability by over 90% and lowered organic pollutants without harming soil health. The treatment also reduced soil toxicity and supported plant growth. Overall, MNPs show strong potential as a versatile and efficient nano remediation tool for contaminated soils (Baragaño et al., 2020).

Vishnu D. Rajput, Tatiana Minkina, Sudhir K. Upadhyay, Arpna Kumari, Anuj Ranjan, Saglara Mandzhieva, Svetlana Sushkova, Rupesh Kumar Singh and Krishan K. Verma (2022) has been studying how nanotechnology can enhance bioremediation for restoring polluted soils. utilizing methods to be attained in the meanwhile. Besides, most of the currently available research on nano bioremediation is limited to laboratory experiments and computational modelling. It focuses on the use of nanoparticles to absorb or break down toxic contaminants, reducing their presence and spread. this remediation process reduces the accumulation of pollutants while limiting their spread from one medium to another (Rajput et al., 2022).

M. Gil-Díaz, R. A. Pérez, J. Alonso, E. Miguel, S. Diez-Pascual and M. C. Lobo (2022) has been studying the assesses the use of commercial iron nanoparticles—nZVI, nZVI-Pd, and nano-magnetite ($n\text{Fe}_3\text{O}_4$)—for treating industrial soils contaminated with chromium (Cr) and PCBs. All nanoparticles significantly reduced Cr levels, with nZVI and nZVI-Pd being most effective. PCB concentrations dropped by up to 68%, with nZVI-Pd acting more quickly. However, $n\text{Fe}_3\text{O}_4$ showed less stable PCB removal. The findings support the use of nZVI or nZVI-Pd in pseudo-anaerobic conditions as a promising approach for remediating co-contaminated soils (Gil-Díaz et al., 2022).

Tamer Elsakhawy, Alaa El-Dein Omara, Mohamed Abowaly, Hassan El-Ramady, Khandsuren Badgar, Xhensila Llanaj, Gréta Törös, Peter Hajdú and József Prokisch (2022) have been studying explorers the use of mushrooms in the green synthesis of nanoparticles for sustainable soil management. These mushroom-derived nanoparticles aid in bio-nano remediation, helping to combat soil pollution, erosion, salinization, and degradation. They improve soil quality by enhancing structure and organic content. While the approach shows promise for sustainable agriculture (Elsakhawy et al., 2022).

Nandini Boregowda, Sanjay C. Jogigowda, Guringaiah Bhavya, Channarayapatnaamesh Sunilkumar, Nagaraja Geetha, Shashikant Shiddappa Udikeri, Srinivas Chowdappa, Muthusamy Govarthan, Sudisha Jogaiah (2022) have been studying the Nano remediation uses advanced nanomaterials to clean up environmental pollutants in agricultural soils, including heavy metals and pesticides. Materials like nZVI, carbon nanotubes, and metallic nanoparticles offer high efficiency due to their reactivity and large surface area. The approach is faster and more sustainable than traditional methods, though concerns about potential risks to soil and ecosystems remain. Ongoing research aims to reduce toxicity and enhance environmental safety (Boregowda et al., 2022).

Gebregiorgis Ambaye, Alif Chebbi, Francesca Formicola, Shiv Prasad, Franco Hernan Gomez, Andrea Franzetti, Mentore Vaccari (2022) have been studying the eco-friendly strategies for remediating petroleum hydrocarbon (PH)-contaminated soils, aiming for their reuse in agriculture. It highlights the limitations of traditional chemical methods and emphasizes sustainable alternatives like bioremediation using microorganisms, nanotechnology, and bio-electrochemical systems. Next-generation sequencing (NGS) is noted for its role in understanding microbial degradation. The studying also considers factors affecting remediation and promotes risk-based, sustainable approaches for soil restoration (Ambaye et al., 2022).

Zeinab Babaei Ab Alvan, Hossein Mohammad Asgari, Hakimeh Amanipoor, Foad Buazar and Sadegh Motaghd (2023) have been studying the use of zero-valent iron nanoparticles (ZVI NPs) to remediate soils contaminated with polycyclic aromatic hydrocarbons (PAHs) from refinery effluents. Polycyclic aromatic hydrocarbons (PAHs) are carcinogenic and difficult to break down, providing an environmental risk. The incremental lifetime cancer risk (ILCR) can be expressed in terms of carcinoma genic risk (10–5–10–6). Next, two soil samples contaminated with iron NPs at concentrations of 2.5, 5, and 10 g of NPs per 100 g of soil were combined. Then, each treatment was examined after 24, 48, and 72 hours, and the number of PAHs was determined using a chromatogram. The results revealed that the refinery effluent induced soil contamination in the route, and the concentration of 10% nanomaterials was higher than other concentrations. the lower the number of PAHs, and in some cases, it has reached zero (Alvan et al., 2023).

Anand Raj Dhanapal, Muthu Thiruvengadam, Jayavarshini Vairavanathan, Baskar Venkidasamy, Maheswaran Easwaran and Mansour Ghorbanpour (2024) have been studying the innovative nanotechnology-based methods for remediating soil pollution caused by agricultural practices. The researcher in this study discusses the use of nanoparticles, nano-biosorbents, and nano biosurfactants to effectively degrade pollutants through reduction reactions, immobilization, and bioremediation. The studying emphasizes sustainable solutions, such as nano phytoremediation, where nanomaterials help plants detoxify pollutants like heavy metals, pesticides, and herbicides, ultimately aiming to restore soil health and fertility (Dhanapal et al., 2024).

Rocío González-Feijoo, Cecilia Martínez-Castillo, Vanesa Santás-Miguel, Daniel Arenas-Lago and Paula Pérez-Rodríguez (2025) have been studying the investigates the use of hydroxyapatite nanoparticles (HANPs) to address cadmium (Cd) contamination in agricultural soils and its effect on the growth of *Chenopodium quinoa* Willd. the most important result is the Cd Immobilization: HANPs effectively reduced Cd mobility in the soil, making it less bioavailable and lowering Cd uptake by quinoa plants also the Plant Growth: HANPs promoted better early shoot development, especially in soils with higher Cd concentrations (≥ 10 mg/kg) and Germination Rates: While germination rates varied, HANPs-treated soils showed improved Cd immobilization, reducing Cd translocation to plant tissues finally the Environmental Benefits The studying highlights HANPs as a promising nano remediation tool to enhance soil quality, crop safety, and food security (González-Feijoo et al., 2025).

Ismaila, M. and H. Rasheed (2025) This study explores how iron nanoparticles (FeNPs) influence potato plants' ability to remediate titanium-contaminated soil. Conducted in Iraq, the research tested various combinations of titanium and FeNPs on potato growth and physiological traits. The findings revealed that treatment with 100 mg/kg titanium and 150 mg/kg FeNPs significantly enhanced plant height, stem count, leaf area, dry weight, and nutrient levels (nitrogen, phosphorus, potassium). This combination also improved the physiological traits of potatoes, showcasing FeNPs' potential in soil pollution management (Ismaila & Rasheed, 2025).

Khalida Naseem, Kiran Mir, Kiky Corneliasari Sembiring, Awais Khalid, Mohmmad Ehtisham Khan and Anil Kumar Deepati (2025) have been studying the investigates the green synthesis of metal nanoparticles (MNPs) using mango peel, a fruit waste rich in bioactive compounds. Phytochemicals such as polyphenols, flavonoids, carotenoids, and vitamins in the peel serve as natural reducing and stabilizing agents. The resulting MNPs have versatile applications, including antimicrobial activity, food packaging, mosquito control, and removal of heavy metals and dyes from wastewater. The studying emphasizes the eco-friendly, cost-effective nature of this method and its potential for large-scale use in catalysis, sensing, and biomedical applications (Naseem et al., 2025).

Marie Yayinie, Limenew Abate Worku, Rakesh Kumar Bachheti and Archana Bachheti (2025) have been studying the use of chitin-based nanomaterials to combat soil pollution from heavy metals, pesticides, and toxic organics. These nanoparticles show promise in agriculture by enhancing crop defense, pathogen resistance, and soil health. However, their current application is limited to laboratory research, with future potential focused on scaling up for commercial use in sustainable soil remediation (Yayinie et al., 2025).

2.4. Light pollution

Light pollution, particularly from artificial sources, poses significant environmental challenges. Nanoparticles have emerged as promising agents for mitigating light pollution through photocatalytic processes. In this part of the review, we show recent research sine 2015 to 2025 which studies treatment of light pollution by nanoparticles.

Mechanisms of action, Charge Carrier Dynamics Nanoparticles like Gd/N co-doped ZnO and Ag-Mn oxide enhance photocatalytic efficiency by improving charge separation and minimizing recombination rates. This results in faster degradation of organic pol-

lutants when exposed to light (Alanazi et al., 2021; Xu et al., 2023). Reactive Species Formation Am-inated graphene quantum dots/CdS nanoparticles enhance the production of reactive oxygen species, such as hydroxyl and superoxide radicals, which are essential for effectively degrading organic dyes like Rhodamine B. (Lin et al., 2024) Bismuth oxychloride (BiOCl) nanoparticles are designed to improve the photocatalytic breakdown of harmful organic dyes under UV-Vis light. Their strong light absorption and enhanced charge carrier mobility make them effective in degrading pollutants such as methylene blue and methyl orange. (Seddigi et al., 2017). Triangle-shaped silver nanoparticles (Ag TNPs) combined with tin dioxide (SnO₂) demonstrate improved photocatalytic activity for removing NO_x. The Ag TNPs enhance the selectivity for producing environmentally friendly products while minimizing the formation of toxic byproducts. (Van Pham et al., 2024). CaTiO₃ nanoparticles are effective in degrading pollutants like methyl orange and levofloxacin under UV light. Their strong emission in the visible light region boosts their photocatalytic activity, making them efficient for environmental cleanup. (Cerón-Urbano et al., 2023). Ag₃VO₄ nanoparticles, when decorated on Bi₂O₂CO₃ micro-flowers, form a heterojunction that greatly enhances photocatalytic activity under visible light. This structure improves charge carrier separation, leading to more effective degradation of industrial dyes and antibiotics. (Li et al., 2018).

3. Conclusion

Tiny nanoparticles can aid in cleaning up pollution, but they must be carefully made to avoid harming nature. The solution lies in green methods that use safe, natural ingredients to produce these particles, enabling the creation of cleaner technology while ensuring environmental safety. (Saif et al., 2016). Scientists are working to enhance nanoparticle air cleaners by improving their ability to target specific pollutants and scaling up production for city-wide use. They are also focusing on ensuring safety for both people and the environment, perfecting nature-inspired technology to clean the air more effectively (Benettayeb et al., 2023). Nanoparticles can help clean polluted air better, but scientists still need to study their safety and how to use them widely.

In the water treatment, Nanoparticles show great promise for cleaning water, but researchers are working to Make them cheaper and greener to produce and for Improve their teamwork with other technologies and boost their reusability.

Nanoparticles show great potential for treating soil pollution by adsorbing, immobilizing, and reducing

contaminants. However, challenges like environmental risks and the need for optimized usage conditions persist. On following research is crucial to maximize their benefit while ensuring safe and sustainable application.

While nanoparticles are useful for soil remediation, they may bear environmental risks, including toxicity to soil microbes and plants. Modifying the nanoparticles can help reduce these risks (Demangeat et al., 2021).

The success of nanoparticle-based soil remediation depends on factors like soil type, nanoparticle properties, and environmental conditions. Optimizing these variables is essential to enhance remediation effectiveness and reduce potential negative impacts (Vu & Mulligan, 2023).

In light pollution, combining nano remediation with other remediation methods can improve the efficiency and sustainability of soil treatment, supporting the development of eco-friendly, green technology solutions.

Although many nanoparticles explain strong initial photocatalytic activity, their stability and reusability are still challenging. For example, Gd/N co-doped ZnO shows good stability for recycling, but further research is needed to improve the durability of other nanoparticle systems. The environmental impact of nanoparticles is a crucial consideration. Ongoing research aims to develop nanoparticles that are both effective and environmentally safe. (Aftab et al., 2022). In conclusion, nanoparticles hold great potential for addressing light pollution by photocatalytically degrading pollutants. However, further research is needed to optimize their efficiency, stability, and environmental safety.

Conflicts of interest

The authors declare that they have no competing interest.

References

- Ibrahim, R.K., Hayyan, M., AlSaadi, M.A., Hayyan, A., & Ibrahim, S. (2016) Environmental application of nanotechnology: air, soil, and water. *Environmental Science and Pollution Research*, 23, 13754–13788.
- Linley, S. & Thomson, N.R. (2021) Environmental applications of nanotechnology: nano-enabled remediation processes in water, soil and air treatment. *Water, Air, & Soil Pollution*, 232(2), 59.
- Chaudhary, P., Ahamad, L., Chaudhary, A., Kumar, G., Chen, W.-J., & Chen, S. (2023) Nanoparticle-mediated bioremediation as a powerful weapon in the removal of environmental pollutants. *Journal of Environmental Chemical Engineering*, 11(2), 109591.
- Wirtu, S.F., Jule, L.T., & Nagaraj, N. (2025) Nanomaterials for Environmental Applications: Water Treatment, Air Purification, and Remediation. in *Exploring Nanomaterial Synthesis, Characterization, and Applications*. IGI Global Scientific Publishing, 489–514.
- Panahi, Y., Mellatyar, H., Farshbaf, M., Sabet, Z., Fattahi, T., & Akbarzadehe, A. (2018) Biotechnological applications of nanomaterials for air pollution and water/wastewater treatment. *Materials Today: Proceedings*, 5(7), 15550–15558.
- Haider, A., Al-Anbari, R., Kadhim, G., & Jameel, Z. (2018) Synthesis and photocatalytic activity for TiO₂ nanoparticles as air purification. in *MATEC web of conferences*, EDP Sciences.
- Leong, K.H., Lee, J.Q., Kumar, A.A., Sim, L.C., & Pichiah, S. (2019) Facile technique for the immobilisation of TiO₂ nanoparticles on glass substrates for applications in the photocatalytic self-cleaning of indoor air pollutants. *Malaysian Journal of Analytical Sciences*, 23(1), 90–99.
- Magudieshwaran, R., Ishii, J., Raja, K.C.N., Terashima, C., Venkatchalam, R., Fujishima, A., & Pitchaimuthu, S. (2019) Green and chemical synthesized CeO₂ nanoparticles for photocatalytic indoor air pollutant degradation. *Materials Letters*, 239, 40–44.
- David, L. & Moldovan, B. (2020) Green synthesis of biogenic silver nanoparticles for efficient catalytic removal of harmful organic dyes. *Nanomaterials*, 10(2), 202.
- Mohamed, E.F. & Awad, G. (2020) Photodegradation of gaseous toluene and disinfection of airborne microorganisms from polluted air using immobilized TiO₂ nanoparticle photocatalyst-based filter. *Environmental Science and Pollution Research*, 27, 24507–24517.
- Roy, A., Sharma, A., Yadav, S., Jule, L.T., & Krishnaraj, R. (2021) Nanomaterials for remediation of environmental pollutants. *Bioinorganic Chemistry and Applications*, 2021(1), 1764647.
- Sreelakshmi, B., Induja, S., Adarsh, P., Rahul, H., Arya, S., Aswana, S., Haripriya, R., Aswathy, B., Manoj, P., & Vishnudasan, D. (2021) Drought stress amelioration in plants using green synthesised iron oxide nanoparticles. *Materials Today: Proceedings*, 41, 723–727.
- Edrisi, F., Mahmoudian, M., & Shadjou, N. (2024) Preparation of an innovative series of respiratory nano-filters using polystyrene fibrous films containing KCC-1 dendrimer and ZnO nanostructures for environmental assessment of SO₂, NO₂ and CO₂. *RSC advances*, 14(11), 7303–7313.
- Radha, K., Selvi, V., & Aarcha, J. (2025) Silver nanofiber membranes for indoor air pollution treatment. *Sustainable Chemistry for Climate Action*, 100056.
- Rajendran, S., Ramesh, P., Sengottaiyan, P., & Balasubramaniam, N.D. (2025) Clearing the Air: Nanotechnology's Role in Tackling Atmospheric Pollution. in *Breaking Boundaries: Pioneering Sustainable Solutions Through Materials and Technology*. Springer, 213–235.
- Awan, T.I., Afsheen, S., & Mushtaq, A. (2025) Noble Metal Nanoparticles for Pollutant Decomposition. in *Influence of Noble Metal Nanoparticles in Sustainable Energy Technologies*, Springer, 223–249.
- Bognár, S., Putnik, P., & Šojić Merkulov, D. (2022) Sustainable green nanotechnologies for innovative purifications of water: Synthesis of the nanoparticles from renewable sources. *Nanomaterials*, 12(2), 263.
- Boix, G., Troyano, J., Garzon-Tovar, L., Camur, C., Bermejo, N., Yazdi, A., Piella, J., Bastus, N.G., Puentes, V.F., & Imaz, I. (2020) MOF-beads containing inorganic nanoparticles for the simultaneous removal of multiple heavy metals from water. *ACS applied materials & interfaces*, 12(9), 10554–10562.
- Palani, G., Trilaksana, H., Sujatha, R.M., Kannan, K., Rajendran, S., Korniejenko, K., Nykiel, M., & Uthayakumar, M. (2023) Silver nanoparticles for waste water management. *Molecules*, 28(8), 3520.
- Benettayeb, A., Seihoub, F.Z., Pal, P., Ghosh, S., Usman, M., Chia, C.H., Usman, M., & Sillanpää, M. (2023) Chitosan nanoparticles as potential nano-sorbent for removal of toxic environmental pollutants. *Nanomaterials*, 13(3), 447.
- Madhura, L., Singh, S., Kanchi, S., Sabela, M., Bisetty, K., & Inamuddin, (2019) Nanotechnology-based water quality management for wastewater treatment. *Environmental Chemistry Letters*, 17, 65–121.
- Baruah, A., Chaudhary, V., Malik, R., & Tomer, V.K. (2019) Nanotechnology based solutions for wastewater treatment. in *Nanotechnology in Water and wastewater treatment*. Elsevier, 337–368.

- Goutam, S.P., Saxena, G., Roy, D., Yadav, A.K., & Bharagava, R.N. (2020) Green synthesis of nanoparticles and their applications in water and wastewater treatment. *Bioremediation of industrial waste for environmental safety: volume i: industrial waste and its management*, 349-379.
- Sazid, M.G. & Supto, S.T.J. (2024) Advances in implementation of metal oxide nanoparticles for urban water pollution treatment.
- Guo, Y., Huang, C., Pitcheri, R., Shekhar, B., Radhalayam, D., Roy, S., Kummara, M.R., & Karim, M.R. (2025) Bio-green synthesis of bismuth oxide nanoparticles using almond gum for enhanced photocatalytic degradation of water pollutants and biocompatibility. *International Journal of Biological Macromolecules*, 140222.
- Alazaiza, M.Y., Albahnasawi, A., Ali, G.A., Bashir, M.J., Copty, N.K., Amr, S.S.A., Abushammala, M.F., & Al Maskari, T. (2021) Recent advances of nanoremediation technologies for soil and groundwater remediation: A review. *Water*, 13(16), 2186.
- Ibrahim, H.M., Al-Issa, A.A., Al-Farraj, A.S., Alghamdi, A.G., & Al-Turki, A.M. (2024) Effect of Stabilized nZVI Nanoparticles on the Reduction and Immobilization of Cr in Contaminated Soil: Column Experiment and Transport Modeling. *Nanomaterials*, 14(10), 862.
- Galdames, A., Ruiz-Rubio, L., Orueta, M., Sánchez-Arzalluz, M., & Vilas-Vilela, J.L. (2020) Zero-valent iron nanoparticles for soil and groundwater remediation. *International journal of environmental research and public health*, 17(16), 5817.
- Huang, Y. & Keller, A.A. (2020) Remediation of heavy metal contamination of sediments and soils using ligand-coated dense nanoparticles. *PLoS one*, 15(9), e0239137.
- Brandl, F., Bertrand, N., Lima, E.M., & Langer, R. (2015) Nanoparticles with photoinduced precipitation for the extraction of pollutants from water and soil. *Nature communications*, 6(1), 7765.
- Li, Q., Chen, X., Zhuang, J., & Chen, X. (2016) Decontaminating soil organic pollutants with manufactured nanoparticles. *Environmental Science and Pollution Research*, 23, 11533-11548.
- HELAL, M.I., KHATER, H.A., & MARZOOG, A. (2016) Application of nanotechnology in remediation of heavy metals polluted soils. *Journal of Arid Land Studies*, 26(3), 129-137.
- Gil-Díaz, M., Diez-Pascual, S., González, A., Alonso, J., Rodríguez-Valdés, E., Gallego, J., & Lobo, M.C. (2016) A nanoremediation strategy for the recovery of an As-polluted soil. *Chemosphere*, 149, 137-145.
- Galdames, A., Mendoza, A., Orueta, M., de Soto García, I., Sánchez, M., Virto, I., & Vilas, J. (2017) Development of new remediation technologies for contaminated soils based on the application of zero-valent iron nanoparticles and bioremediation with compost. *Resource-Efficient Technologies*, 3(2), 166-176.
- Rajput, V.D., Minkina, T., Sushkova, S., Tsitsuashvili, V., Mandzhieva, S., Gorovtsov, A., Nevidomskiyaya, D., & Gromakova, N. (2018) Effect of nanoparticles on crops and soil microbial communities. *Journal of Soils and Sediments*, 18, 2179-2187.
- Romeh, A.A.A. (2018) Green silver nanoparticles for enhancing the phytoremediation of soil and water contaminated by fipronil and degradation products. *Water, Air, & Soil Pollution*, 229, 1-13.
- Sun, R.-J., Chen, J.-H., Fan, T.-T., Zhou, D.-M., Wang, Y.-J. (2018) Effect of nanoparticle hydroxyapatite on the immobilization of Cu and Zn in polluted soil. *Environmental Science and Pollution Research*, 25, 73-80.
- Srivastav, A., Yadav, K.K., Yadav, S., Gupta, N., Singh, J.K., Katiyar, R., & Kumar, V. (2018) Nano-phytoremediation of pollutants from contaminated soil environment: current scenario and future prospects. *Phytoremediation: Management of Environmental Contaminants*, 6, 383-401.
- You, T., Liu, D., Chen, J., Yang, Z., Dou, R., Gao, X., & Wang, L. (2018) Effects of metal oxide nanoparticles on soil enzyme activities and bacterial communities in two different soil types. *Journal of Soils and Sediments*, 18, 211-221.
- Sarkar, A., Sengupta, S., & Sen, S. (2019) Nanoparticles for soil remediation. *Nanoscience and biotechnology for environmental applications*, 249-262.
- Song, B., Xu, P., Chen, M., Tang, W., Zeng, G., Gong, J., Zhang, P., & Ye, S. (2019) Using nanomaterials to facilitate the phytoremediation of contaminated soil. *Critical reviews in environmental science and technology*, 49(9), 791-824.
- Baragaño, D., Alonso, J., Gallego, J., Lobo, M., & Gil-Díaz, M. (2020) Zero valent iron and goethite nanoparticles as new promising remediation techniques for As-polluted soils. *Chemosphere*, 238, 124624.
- Baragaño, D., Forján, R., Welte, L., & Gallego, J.L.R. (2020) Nanoremediation of As and metals polluted soils by means of graphene oxide nanoparticles. *Scientific reports*, 10(1), 1896.
- Baragaño, D., Alonso, J., Gallego, J., Lobo, M., & Gil-Díaz, M. (2020) Magnetite nanoparticles for the remediation of soils co-contaminated with As and PAHs. *Chemical Engineering Journal*, 399, 125809.
- Rajput, V.D., Minkina, T., Upadhyay, S.K., Kumari, A., Ranjan, A., Mandzhieva, S., Sushkova, S., Singh, R.K., & Verma, K.K. (2022) Nanotechnology in the restoration of polluted soil. *Nanomaterials*, 12(5), 769.
- Gil-Díaz, M., Pérez, R., Alonso, J., Miguel, E., Diez-Pascual, S., & Lobo, M. (2022) Iron nanoparticles to recover a co-contaminated soil with Cr and PCBs. *Scientific Reports*, 12(1), 3541.
- Elsakhawy, T., Omara, A.E.-D., Abowaly, M., El-Ramady, H., Badgar, K., Llanaj, X., Törös, G., Hajdú, P., & Prokisch, J. (2022) Green synthesis of nanoparticles by mushrooms: a crucial dimension for sustainable soil management. *Sustainability*, 14(7), 4328.
- Boregowda, N., Jogigowda, S.C., Bhavya, G., Sunilkumar, C.R., Geetha, N., Udikeri, S.S., Chowdappa, S., Govarthanan, M., & Jogaiah, S. (2022) Recent advances in nanoremediation: Carving sustainable solution to clean-up polluted agriculture soils. *Environmental Pollution*, 297, 118728.
- Ambaye, T.G., Chebbi, A., Formicola, F., Prasad, S., Gomez, F.H., Franzetti, A., & Vaccari, M. (2022) Remediation of soil polluted with petroleum hydrocarbons and its reuse for agriculture: Recent progress, challenges, and perspectives. *Chemosphere*, 293, 133572.
- Alvan, Z.B.A., Asgari, H.M., Amanipoor, H., Buazar, F., & Motaghed, S. (2023) Evaluation of the effects of zero-valent iron nanoparticles in the treatment of soils polluted with refinery effluent hydrocarbons. *Water, Air, & Soil Pollution*, 234(1), 40.
- Dhanapal, A.R., Thiruvengadam, M., Vairavanathan, J., Venkidasamy, B., Easwaran, M., & Ghorbanpour, M. (2024) Nanotechnology approaches for the remediation of agricultural polluted soils. *ACS omega*, 9(12), 13522-13533.
- González-Feijoo, R., Martínez-Castillo, C., Santás-Miguel, V., Arenas-Lago, D., & Pérez-Rodríguez, P. (2025) Use of Hydroxyapatite Nanoparticles to Reduce Cd Contamination in Agricultural Soils: Effects on Growth and Development of Chenopodium quinoa Willd. *Applied Sciences*, 15(2), 639.
- Ismaila, M. & Rasheed, H. (2025) Effect of iron nanoparticles on the potato's susceptibility to enhance phytoremediation of titanium-contaminated soil. *SABRAO J. Breed. Genet.*, 57(1), 251-259.
- Naseem, K., Mir, K., Sembiring, K.C., Khalid, A., Khan, M.E., & Deepati, A.K. (2025) Mango Peel Bio-actives for the Fabrication of Inorganic Metal Nanoparticles and their Potential for Wastewater treatment. *Water, Air, & Soil Pollution*, 236(2), 1-18.
- Yayinie, M., Worku, L.A., Bachheti, R.K., & Bachheti, A. (2025) Chitin-Based Nanoparticles for Soil Remediation. in *Chitin-Based Nanoparticles for the Agriculture Sectors*. Springer, 85-102.
- Alanazi, H.S., Ahmad, N., & Alharthi, F.A. (2021) Synthesis of Gd/N co-doped ZnO for enhanced UV-vis and direct solar-light-driven photocatalytic degradation. *RSC advances*, 11(17), 10194-10202.
- Xu, Z., Zada, N., Habib, F., Ullah, H., Hussain, K., Ullah, N., Bibi, M., Bibi, M., Ghani, H., & Khan, S. (2023) Enhanced photocatalytic degradation of malachite green dye using silver-manganese oxide nanoparticles. *Molecules*, 28(17), 6241.
- Lin, X., Chen, Y., Zhou, D., Chen, M., Liang, W., & Guo, H. (2024) Aminated graphene quantum dots/CdS nanobelts for enhanced photocatalytic degradation of RhB dye under visible light. *RSC advances*, 14(1), 255-265.
- Seddigi, Z.S., Gondal, M.A., Baig, U., Ahmed, S.A., Abdulaziz, M., Danish, E.Y., Khaled, M.M., & Lais, A. (2017) Facile synthesis

- of light harvesting semiconductor bismuth oxychloride nano photo-catalysts for efficient removal of hazardous organic pollutants. *PLoS one*, 12(2), e0172218.
- Van Pham, V., Nguyen, T.Q., Le, H.V., & Cao, T.M. (2024) Visible light photocatalytic NO_x removal with suppressed poisonous NO₂ byproduct generation over simply synthesized triangular silver nanoparticles coupled with tin dioxide. *Nanoscale Advances*, 6(9), 2380-2389.
- Cerón-Urbano, L., Aguilar, C.J., Dios, J.E., & Mosquera-Vargas, E. (2023) Nanoparticles of the perovskite-structure CaTiO₃ system: the synthesis, characterization, and evaluation of its photocatalytic capacity to degrade emerging pollutants. *Nanomaterials*, 13(22), 2967.
- Li, S., Hu, S., Jiang, W., Liu, Y., Liu, Y., Zhou, Y., Mo, L., & Liu, J. (2018) Ag₃VO₄ nanoparticles decorated Bi₂O₂CO₃ micro-flowers: An efficient visible-light-driven photocatalyst for the removal of toxic contaminants. *Frontiers in Chemistry*, 6, 255.
- Saif, S., Tahir, A., & Chen, Y. (2016) Green synthesis of iron nanoparticles and their environmental applications and implications. *Nanomaterials*, 6(11), 209.
- Demangeat, E., Pédrot, M., Dia, A., Bouhnik-Le-Coz, M., Roperch, P., Compaoré, G., & Cabello-Hurtado, F. (2021) Investigating the remediation potential of iron oxide nanoparticles in Cu-polluted soil-plant systems: coupled geochemical, geophysical and biological approaches. *Nanoscale Advances*, 3(7), 2017-2029.
- Vu, K.A. & Mulligan, C.N. (2023) An overview on the treatment of oil pollutants in soil using synthetic and biological surfactant foam and nanoparticles. *International Journal of Molecular Sciences*, 24(3), 1916.
- Aftab, S., Shabir, T., Shah, A., Nisar, J., Shah, I., Muhammad, H., & Shah, N.S. (2022) Highly efficient visible light active doped ZnO photocatalysts for the treatment of wastewater contaminated with dyes and pathogens of emerging concern. *Nanomaterials*, 12(3), 486.