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Review Article

Advanced Applications of Nanoparticles and Nanotubes in the Remediation of Industrial, Agriculture, and Sewage Wastewater and the Production of Biofertilizers for Sustainable Environmental Management and Agriculture Practices

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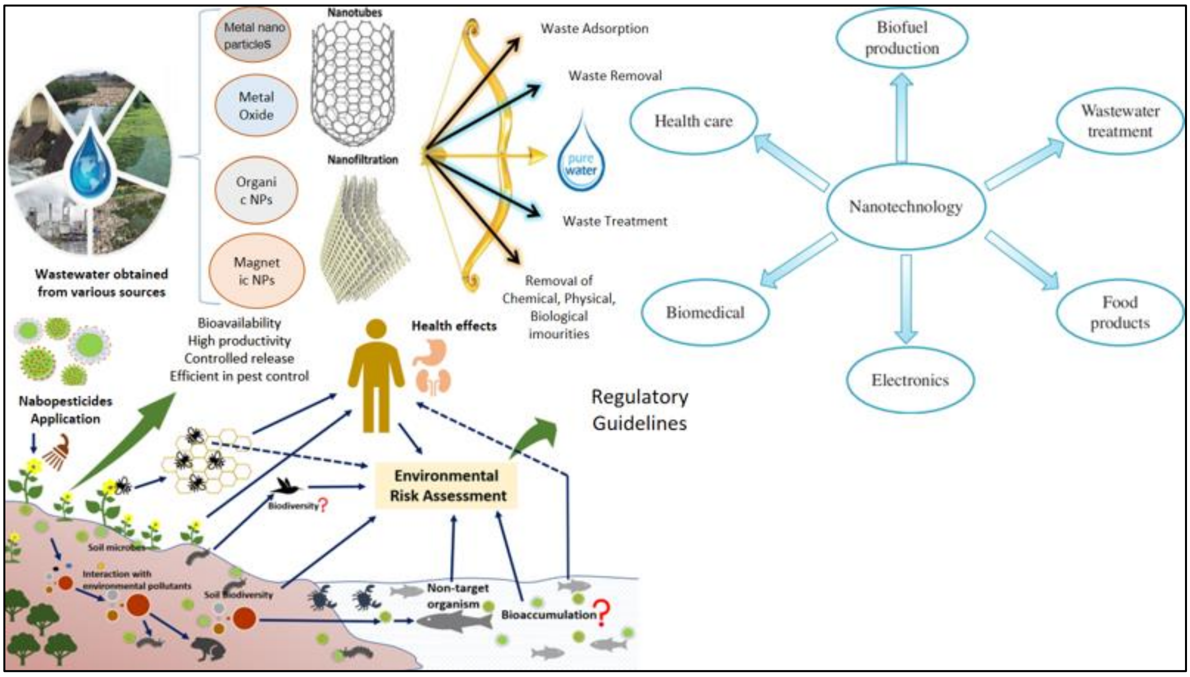
Abstract



Graphical Abstract

To support sustainable environmental management and agricultural practices, this study examines the sophisticated uses of nanoparticles and nanotubes in the remediation of industrial, farming, and sewage wastes and their function in creating biofertilizers. Because of their unique qualities, which include a large surface area, reactivity, and adjustable features, nanoparticles are very good at adsorbing, breaking down, and eliminating contaminants from wastewater. Because of their conductivity and structural robustness, nanotubes further improve cleanup procedures by enabling quick pollutant absorption and destruction, particularly for complex pollutants, including organic compounds, heavy metals, and pesticides. The efficacy, stability, and possible environmental hazards of several nanomaterial types, such as metal oxides, carbon-based nanoparticles, and functionalized nanotubes, are examined in this study. The article also emphasizes the dual use of these nanotechnologies in creating biofertilizers, which can support agricultural yield increase, soil health improvement, and nutrient cycling. This strategy offers a viable technique to lower environmental pollutants and promote sustainable farming methods using nanotechnology in wastewater treatment and agriculture. The paper also discusses the obstacles and restrictions to widespread use, including expense, possible toxicity, and regulatory issues. This article sheds light on nanotechnology's present and potential agricultural and environmental management applications, thoroughly examining its contribution to developing sustainable and environmentally friendly solutions.

Keywords: Nanotubes in Agriculture Wastewater Remediation, Agricultural Wastewater Nano remediation, Nanotechnology in Environmental Remediation, Eco-friendly Wastewater Treatment Technologies, Nano-enabled Biofertilizers, Biofertilizer Production from Treated Wastewater.

INTRODUCTION

By using the unique qualities of nanoparticles and nanotubes, nanotechnology presents intriguing options for environmental management. These nanoscale materials, usually between 1 and 100 nanometers, have exceptional qualities, including chemical reactivity, high surface area-to-volume ratios, and electrical, thermal, and optical properties that may be adjusted (Khan *et al.*, 2022). Nanoparticles are employed in environmental applications for soil remediation, water purification, pollution detection, and air quality enhancement. For example, in UV light, metal oxide nanoparticles, like zinc oxide and titanium dioxide, effectively break down pollutants through photocatalytic reactions, turning harmful compounds into innocuous molecules (Etafo *et al.*, 2024). Similar transformational functions are played by nanotubes, particularly carbon nanotubes (CNTs), whose peculiar cylindrical shape offers excellent mechanical strength and conductivity, making them appropriate for filtration systems and environmental sensors. Because of their large surface area and hydrophobic characteristics, CNTs may effectively remove organic contaminants from water by adsorbing various pollutants (Yu *et al.*, 2014). In addition to having better capabilities than conventional materials, these technologies enable precise pollution targeting and downsizing. However, research is still being done on nanomaterials' environmental effects, including their possible toxicity and persistence. Because of this, the development and use of nanotechnology in environmental management necessitates striking a careful balance between the requirement for sustainable, responsible use and its potent therapeutic potential (Wahab *et al.*, 2024).

Nanotechnology is essential to advancing sustainable environmental practices because it facilitates creative solutions that lower pollution, save resources, and improve ecosystem resilience (Pokrajac *et al.*, 2021). Highly effective catalysts that speed up chemical reactions may be made using nanoscale materials and procedures, resulting in cleaner industrial processes with lower emissions. For example, nanomaterials may degrade air and water contaminants through photocatalytic processes, turning dangerous compounds into harmless byproducts that greatly help with pollution control. Furthermore, nanotechnology improves desalination and water purification methods by employing nanoscale membranes and filters to remove impurities while consuming the least energy, a critical factor in areas with limited water supplies (Tlili *et al.*, 2019). Nanotechnology also helps energy sustainability since nanostructured materials enhance the efficiency of fuel cells, batteries, and solar cells, increasing the availability and efficiency of renewable energy. Additionally, nanotechnology makes it possible to create solid and lightweight materials that lessen the environmental effect of production and building. Controlled-release nanofertilizers and nanosensors in agriculture encourage resource-efficient agricultural practices and reduce the amount of toxic chemicals that leak into ecosystems (Zehra *et al.*,2021). Nanotechnology offers instruments to lessen environmental harm and promotes a circular economy that balances environmental care with technological advancement by reusing materials, reducing waste, and conserving natural resources (Preethi *et al.*, 2024).

Regarding environmental cleaning, nano-based remediation has clear benefits over traditional techniques, especially regarding efficacy, specificity, and affordability (Thanigaivel *et al.*, 2022). Conventional remediation methods, such as excavation, soil washing, or chemical treatments, may be expensive and environmentally harmful since they frequently require a significant workforce, substantial energy inputs, and large amounts of reagents. Nano-based techniques, on the other hand, make use of nanoparticles, which have unique qualities, including high surface area-to-volume ratios, catalytic reactivity, and adjustable surface functions (Sharma *et al.*, 2015). Because of these characteristics, nanoparticles may interact with pollutants more successfully, frequently resulting in quicker breakdown or immobilization rates. For instance, because of its strong reactivity with contaminants such as heavy metals and chlorinated organic compounds, nano-zerovalent iron (nZVI) is frequently used to clean polluted soils and groundwater (Stefaniuk *et al.*, 2016). By altering particle surfaces to bind selectively to certain pollutants, nano-based techniques also enable focused treatment, reducing unintentional effects on nearby ecosystems. Additionally, in-situ remediation is made possible by directly injecting nanoparticles into polluted areas, eliminating the need for intrusive procedures (Wang *et al.,* 2022). Therefore, nano-based remediation strategies usually achieve great effectiveness at lower doses and with less environmental disruption compared to traditional methods. However, research on the possible ecological effects of nanoparticles themselves is still underway, and cautious thought is required to guarantee their safe use (Babatunde *et al.*, 2019). To improve environmental sustainability, the current study aims to investigate cutting-edge uses of nanoparticles and nanotubes for efficiently treating sewage, agricultural, and industrial wastewater. High reactivity and surface area are two unique qualities of nanotechnology that aid with the adsorption and breakdown of contaminants, making water purification more effective than traditional techniques. To enhance soil health and advance sustainable farming methods, this study also looks at the application of nanoparticles in manufacturing biofertilizers. The ultimate goal is to develop solutions based on nanotechnology that tackle pressing environmental issues, guaranteeing more resilient agriculture and better water supplies.

Nanoparticles for Industrial Wastewater Remediation

With their ability to efficiently remove contaminants such as heavy metals, organic pollutants, hydrocarbons, and petrochemicals, nanoparticles have become beneficial instruments for treating industrial wastewater (Qasim *et al.*, 2024). High surface area-to-volume ratios offered by nanoparticles significantly improve adsorption capabilities for removing heavy metals. Lead, mercury, and cadmium may be efficiently adsorbed onto carbon-based materials (such as graphene oxide), titanium dioxide, and iron oxide nanoparticles. These materials draw in and bind metal ions by surface complexation and ion exchange to stop more contamination. When it comes to the breakdown of organic pollutants, nanoparticles, especially metal oxide types like zinc oxide and titanium dioxide, act as catalysts to break down persistent organic pollutants like industrial solvents and pesticides. By facilitating photocatalytic processes, these nanoparticles convert hazardous organic molecules into less dangerous ones (Peiris *et al.*, 2016). Nanoparticles are also essential for removing oil and grease from petrochemical effluents; magnetic nanoparticles, for example, may adsorb and segregate these nonpolar pollutants selectively, making it easier to remove them using magnetic fields. Additionally, sophisticated oxidation and other electrochemical cleanup techniques extensively use nanoparticles. By producing reactive oxygen species, they accelerate oxidation processes and effectively degrade dangerous substances. Specifically, these systems commonly employ nanoscale zerovalent iron and doped titanium dioxide nanoparticles, which promote oxidative breakdown and transform complicated contaminants into safer, simpler compounds (Ahmad *et al.*, 2023).

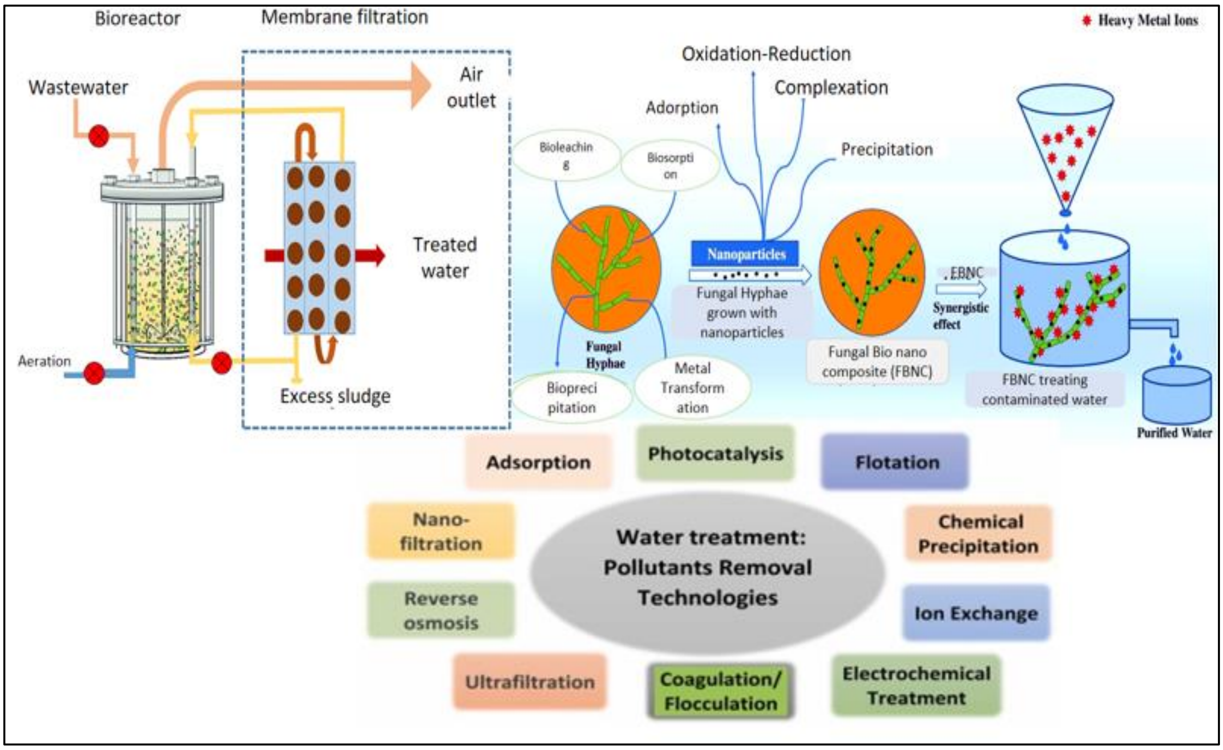


Fig 1: Nanoparticles for Industrial Wastewater Remediation

Applications of Nanotubes in Agriculture Wastewater Treatment

The efficiency and efficacy of treating wastewater from agriculture might be significantly increased by nanotubes, especially those with carbon-based nanostructures (Sheoran *et al.*, 2022). Because of their remarkable surface area and adsorptive properties, carbon nanotubes (CNTs) are routinely utilized to remove essential pollutants such as phosphates, ammonia, and nitrates frequently present in agricultural runoff because of their remarkable surface area and adsorptive properties. If not adequately controlled, these contaminants from fertilizers and soil amendments can cause eutrophication and the deterioration of aquatic ecosystems (Khan *et al.*, 2014). By adding special chemical groups that enhance their attraction for certain pollutants, such as pesticides and excess fertilizers, functionalized CNTs further expand their capabilities and become appropriate for targeted removal applications. For instance, surface alterations increase CNTs' hydrophilicity, which increases their capacity to absorb a greater variety of polar and non-polar organic contaminants. Oxide of graphene Another nanotube-based material, nanotubes, enhances wastewater treatment by facilitating the breakdown of organic pollutants when exposed to light through photocatalytic characteristics. Because of this, they are perfect for eliminating stubborn organic components and lowering wastewater toxicity before their discharge into the environment. Biofilters based on nanotubes are also becoming more popular as efficient real-time filtering devices that enhance irrigation water safety by consistently eliminating impurities. By integrating nanotubes into biological filtration systems, these biofilters can remove hazardous materials at a consistent rate without the need for regular replacement. Agricultural wastewater treatment systems may remove pollutants more effectively using nanotechnology, promoting sustainable farming methods and reducing environmental effects (Kuhn *et al.*, 2022).

Table 1: Applications of Nanotubes in Agriculture Wastewater Treatment

Application Type	Nanotube Type	Primary Mechanism	Contaminants Targeted	Advantages	Limitations
Adsorption of Nutrients	Carbon Nanotubes (CNTs)	Adsorption	Nitrates, phosphates, ammonia	High adsorption efficiency; large surface area allows for removal of nutrients at trace levels	Potential fouling; high production costs
Targeted Removal of Pesticides	Functionalized CNTs	Chemical bonding	Pesticides, fertilizers	Enhanced selectivity for specific contaminants; functional groups increase capture rate	Stability concerns may require periodic regeneration.
Photo Catalytic Degradation of Organics	Graphene Oxide Nanotubes	Photocatalysis (under light exposure)	Organic pollutants	High degradation rate of organic compounds; suitable for persistent pollutants	Requires light source; may have reduced efficiency in dark conditions
Real-Time Biofiltration	Nanotube-based biofilters	Continuous filtration	General contaminants in irrigation water	Continuous removal without frequent replacement; effective for irrigation systems	Biofilter maintenance requirements; limited lifespan
Removal of Heavy Metals	Functionalized CNTs	Chemical bonding, adsorption	Heavy metals (e.g., lead, cadmium)	It can be designed to target specific metals, high adsorption rates	High cost of functionalization; metal recovery may be challenging
Hydrophobic Pollutant Removal	CNTs	Adsorption	Hydrophobic pesticides, hydrocarbons	Effective for non-polar organic pollutants; large surface area for enhanced capture	Limited in the removal of polar compounds
Filtration for Irrigation Safety	Nanotube-embedded filters	Filtration, adsorption	Microbial contaminants, nutrient pollutants	Promotes cleaner irrigation water, reducing crop contamination risk	Potential biofouling; periodic replacement may be required
Enhanced Remediation of Nitrogen-Based Compounds	Multi-walled CNTs (MWCNTs)	Adsorption and catalysis	Nitrogenous compounds (e.g., nitrate, nitrite)	High efficiency in nitrate removal; multi-walled structure increases reactivity	Complicated regeneration; potential toxicity in high doses

Nanotechnology Solutions for Sewage and Domestic Wastewater Treatment

Innovative sewage and home wastewater treatment solutions are provided by nanotechnology, which improves contaminant removal effectiveness while handling complicated contaminants. Nanoparticles like silver, titanium dioxide, and zinc oxide are essential for eliminating pathogens because they neutralize dangerous bacteria, viruses, and protozoa (Aderibigbe *et al.,* 2017). These particles have antibacterial solid qualities that cause infections' cell walls to break down or produce reactive oxygen species (ROS), which inactivates the pathogen. Furthermore, nanotechnology is particularly effective in degrading pharmaceutical and personal care products (PPCPs). Antibiotics, hormones, and chemical additions from soaps and cosmetics are among the pollutants that are infamously resistant to standard treatment techniques. Through catalytic and adsorptive processes, nanoparticles, including titanium dioxide, activated carbon nanomaterials, and graphene-based composites, aid in the breakdown of PPCPs, lowering their toxicity and environmental persistence. Aquatic life and human health are at serious risk from hormones and endocrine disruptors, which are highly harmful micropollutants, even in trace amounts (Varjani *et al.,* 2020). Metal-organic frameworks (MOFs) and bio-nanomaterials are examples of targeted nanomaterials with a high selectivity of binding to and removing these molecules, restricting their release into the environment. Multi-stage nanotech filtration systems improve wastewater treatment by adding nanoparticles and nanotube layers. High removal efficiency for solids, pathogens, and chemical contaminants is made possible by these technologies, such as carbon nanotube membranes containing silver nanoparticles, which allow for a progressive filtering strategy in which each layer targets distinct pollutants. Nanotechnology significantly improves wastewater treatment using these sophisticated procedures (Qu *et al.,* 2013).

Nanotechnology Solutions for Sewage and Domestic Wastewater Treatment

Innovative sewage and home wastewater treatment solutions are provided by nanotechnology, which improves contaminant removal effectiveness while handling complicated contaminants (Jain *et al.,* 2021). Nanoparticles like silver, titanium dioxide, and zinc oxide are essential for eliminating pathogens because they neutralize dangerous bacteria, viruses, and protozoa. These particles have antibacterial solid qualities that cause infections' cell walls to break down or produce reactive oxygen species (ROS), which inactivates the pathogen. Furthermore, nanotechnology is particularly effective in degrading pharmaceutical and personal care products (PPCPs). Antibiotics, hormones, and chemical additions from soaps and cosmetics are among the pollutants that are infamously resistant to standard treatment techniques. Through catalytic and adsorptive reactions, nanoparticles, including titanium dioxide, activated carbon nanomaterials, and graphene-based composites, aid in the breakdown of PPCPs, decreasing their environmental persistence (Chauhan *et al.,* 2019). Aquatic life and human health are at serious risk from hormones and endocrine disruptors, which are highly harmful micropollutants, even in trace amounts. Metal-organic frameworks (MOFs) and bio-nanomaterials are examples of targeted nanomaterials with a high selectivity of binding to and removing these molecules, restricting their release into the environment. Multi-stage nanotech filtration systems improve wastewater treatment by adding nanoparticles and nanotube layers. High removal efficiency for solids, pathogens, and chemical contaminants is made possible by these technologies, such as carbon nanotube membranes containing silver nanoparticles, which allow for a progressive filtering strategy in which each layer targets distinct pollutants. Nanotechnology significantly improves wastewater treatment results through these sophisticated procedures, promoting cleaner water and environmental preservation (Qu *et al.,* 2013).

Mechanisms of Nanoparticle-Based Remediation Techniques

Remediation methods based on nanoparticles use nanoparticles' unique physical and chemical characteristics to efficiently eliminate or neutralize environmental contaminants. One of the main mechanisms is adsorption and surface binding, in which pollutants are captured by physical or chemical interactions between nanoparticles with a large surface area and specific active sites (Qumar *et al.,* 2022). It is an effective method for remediating water and soil because of its large surface area, which increases the ability of contaminants like organic compounds and heavy metals to stick to the surfaces of the nanoparticles. In photocatalysis, light, usually ultraviolet light, activates nanoparticles like titanium dioxide to produce reactive species, such as hydroxyl radicals, which break down organic contaminants like colors, insecticides, and medications. Reactive species drastically lower pollution levels by dissolving complex organic compounds into less hazardous byproducts. To decrease or change harmful heavy metals, such as the highly toxic hexavalent chromium (Cr (VI)), to the less toxic trivalent form (Cr(III)), redox reactions use nanoparticles as electron donors or acceptors (Jiang *et al.,* 2019). This reduces toxicity and enhances environmental safety. Because charged nanoparticles may attract and bind oppositely charged ions, electrostatic interactions are also crucial for the removal of both cationic and anionic pollutants from aqueous solutions. Because they bind different ions, nanoparticles are an effective cleanup technique for various pollutant types and environmental conditions. These processes highlight how adaptable and effective nanoparticles are in combating a variety of contaminants, offering a viable strategy for long-term environmental restoration (Hussain *et al.,* 2022).

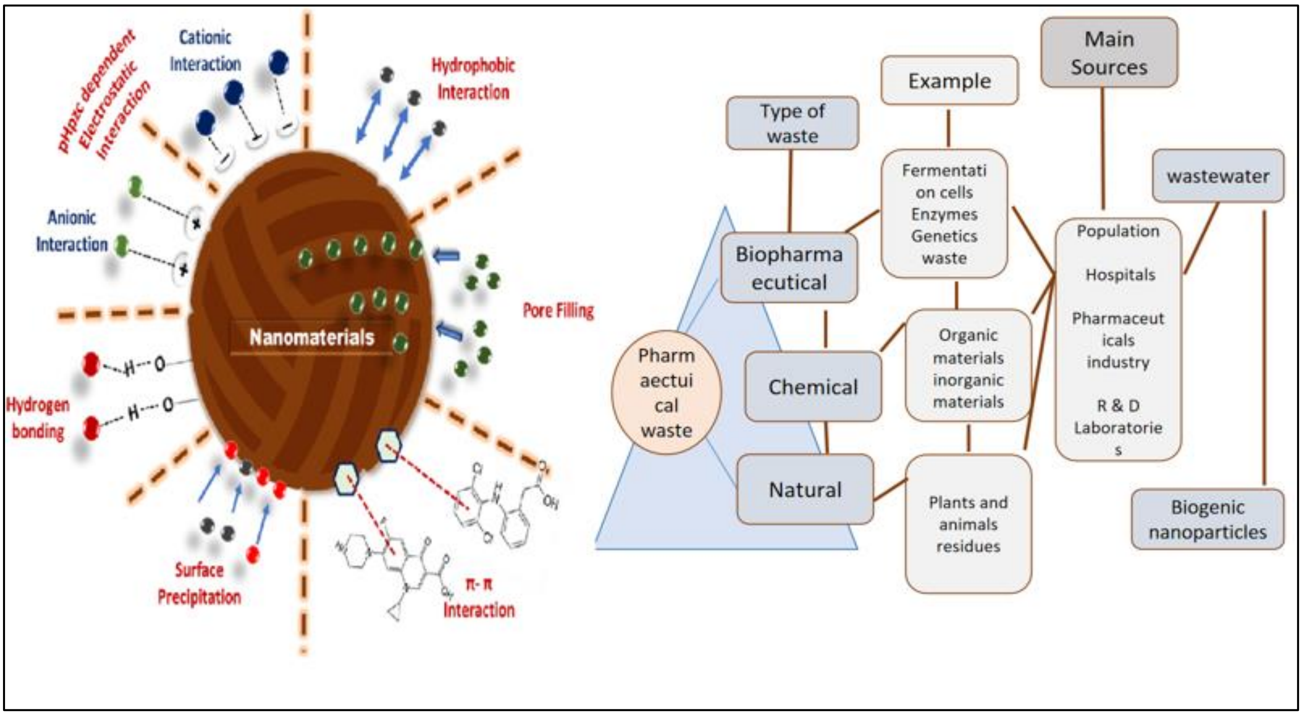


Fig 2: Nanotechnology Solutions for Sewage and Domestic Wastewater Treatment

Table 2: Mechanisms of Nanoparticle-Based Remediation Techniques

Mechanism	Description	Example of Nanoparticles Used	Pollutants Targeted	Advantages	Limitations	References
Adsorption and Surface Binding	High surface area and active nanoparticle sites enhance the pollutants' adsorption through physical and chemical interactions.	Activated carbon, silica, alumina	Heavy metals, organic pollutants	High capacity and selectivity for contaminants	Potential for saturation requires regeneration or disposal	Tee *et al.*, 2022
Photocatalysis	When activated under light, nanoparticles generate reactive species (e.g., hydroxyl radicals), breaking organic pollutants into less toxic byproducts.	Titanium dioxide (TiO_2), ZnO	Dyes, pesticides, pharmaceuticals	Effective for organic pollutant degradation under light	Requires specific light sources, limited to organic pollutants	Mahlambi *et al.*, 2015
Redox Reactions	Nanoparticles facilitate electron transfer processes, transforming toxic heavy metals into less harmful forms (e.g., reducing Cr(VI) to Cr(III)).	Zero-valent iron (nZVI), cerium oxide	Heavy metals (e.g., chromium, mercury)	Reduces the toxicity of heavy metals, promotes safer forms	Limited to certain metals, potential for secondary pollution	Bashir *et al.*, 2022
Electrostatic Interactions	Nanoparticles with charged surfaces bind to oppositely charged ions, effectively removing cationic and anionic contaminants in solutions.	Magnetite (Fe_3O_4), chitosan	Ionic species, nutrients, heavy metals	Broad application in ionic pollutant removal	It may require pH adjustment for optimal binding	Zhang *et al.*, 2019
Ion Exchange	Nanoparticles exchange ions with pollutants in solution, often replacing harmful ions with harmless ones.	Zeolite, silver nanoparticles	Ammonium, heavy metals	Selective ion removal, reusable in cycles	Limited by ion selectivity and solution pH	Chatterjee *et al.*, 2011
Microbial Interactions	Nanoparticles support microbial activity or	Silver, copper nanoparticles	Pathogens, bacteria	bioremediation processes	Potential for microbial	Cecchin *et al.*, 2017

	inhibit harmful microbes, assisting in bioremediation or controlling microbial contaminants.			control harmful microbes	resistance, toxicity concerns	
Enhanced Chemical Reactions	Nanoparticles accelerate degradation reactions for faster breakdown of pollutants (e.g., facilitating Fenton reactions in pollutant oxidation).	Iron oxide, manganese oxide	Organic and inorganic pollutants	Rapid pollutant degradation, often non-specific.	Reactive byproducts may require further treatment.	Xu *et al.*, 2018
Aggregation and Flocculation	Nanoparticles aggregate contaminants into larger particles, which can then be separated from the solution.	Alumina, iron nanoparticles	Suspended solids, colloidal pollutants	Facilitates easy removal by filtration or sedimentation	Requires additional separation processes	Shrestha *et al.*, 2020
Catalysis of Biochemical Processes	Nanoparticles promote biochemical reactions, enhancing natural remediation mechanisms, often in conjunction with plants or microbes.	Gold, palladium nanoparticles	Organic pollutants, hydrocarbons	Works in synergy with biological remediation	Compatibility issues with biological systems	Castro *et al.*, 2014
Thermal Degradation	Nanoparticles can generate localized heat under certain conditions, decomposing pollutants thermally without external energy input.	Gold, magnetic nanoparticles	Organic pollutants	Effective at localized heating, reduce external energy needs	Limited to heat-tolerant pollutants, requires careful control	Yu *et al.*, 2024

Design and Synthesis of Nanoparticles for Targeted Pollutant Removal

By providing practical, selective, and environmentally acceptable solutions, the development and production of nanoparticles for targeted pollution removal have revolutionized remediation techniques (Yadav *et al.*, 2024). Due to their ease of recovery and recyclability, magnetic nanoparticles are very beneficial. Once pollutants have been trapped, they may be quickly extracted from soil or water by applying a magnetic field, which lowers secondary contamination and improves sustainability. Another exciting alternative is polymeric nanoparticles, which are perfect for delicate ecosystems since they are frequently biocompatible, reducing their adverse environmental effects and enabling safe breakdown. Green synthesis techniques, which emphasize environmentally friendly manufacturing processes that create nanoparticles without hazardous chemicals by employing bacteria, plant extracts, or other natural sources, have gained popularity recently (Samuel *et al.*, 2022). This method reduces the environmental impact of producing nanoparticles and promotes sustainable behaviors. Furthermore, hybrid nanostructures have been created to combine the advantages of several nanoparticles, like solid surface reactivity, biocompatibility, and magnetic qualities, to develop multipurpose remediation agents that can address several contaminants simultaneously. With their customized functions, these cutting-edge nanomaterials mark a significant advancement in environmental engineering, where effective contamination removal and accurate targeting are critical to restoring and preserving natural resources (Liu *et al.*, 2024).

Nanotechnology in the Production of Biofertilizers

By improving nutrient delivery efficiency and resolving environmental issues related to conventional fertilizers, nanotechnology is transforming the manufacture of biofertilizers (Rai *et al.*, 2023). The creation of slow-release nano fertilizers, designed to release nutrients gradually and under control, is one significant invention that has improved plant nutrient availability. This slow-release system decreases nitrogen loss through runoff, a typical problem with traditional fertilizers that lowers nutrient absorption efficiency and pollutes the environment. Nanofertilizers create a more sustainable approach by lowering runoff and protecting nearby water bodies and ecosystems. The nano-encapsulation of nutrients, which permits targeted release directly into soil and plant root systems, is another innovation in nanotechnology. Encapsulation guarantees that nutrients are supplied at the right time and location by preventing premature deterioration. The plant grows more efficiently thanks to this tailored nutrition supply, promoting healthier root development (Paez-Garcia *et al.*, 2015). Additionally, nano-biofertilizers enhance soil health by favorably affecting the microbiota and structure of the soil. These biofertilizers sustain beneficial microbial populations, which are crucial for maintaining soil structure and nutrient cycling, by supplying nutrients in a regulated way. Reducing reliance on synthetic fertilizers, which frequently contain chemicals that are hazardous to the environment, is another benefit of using nanotechnology in biofertilizer formulas. Agricultural methods become more sustainable and environmentally benign when these conventional pesticides are swapped with more effective nano-formulations. Therefore, biofertilizers powered by nanotechnology present a viable avenue for sustainable agriculture, encouraging strong plant development while reducing the negative environmental effects of conventional fertilizers (Kumar *et al.,* 2024).

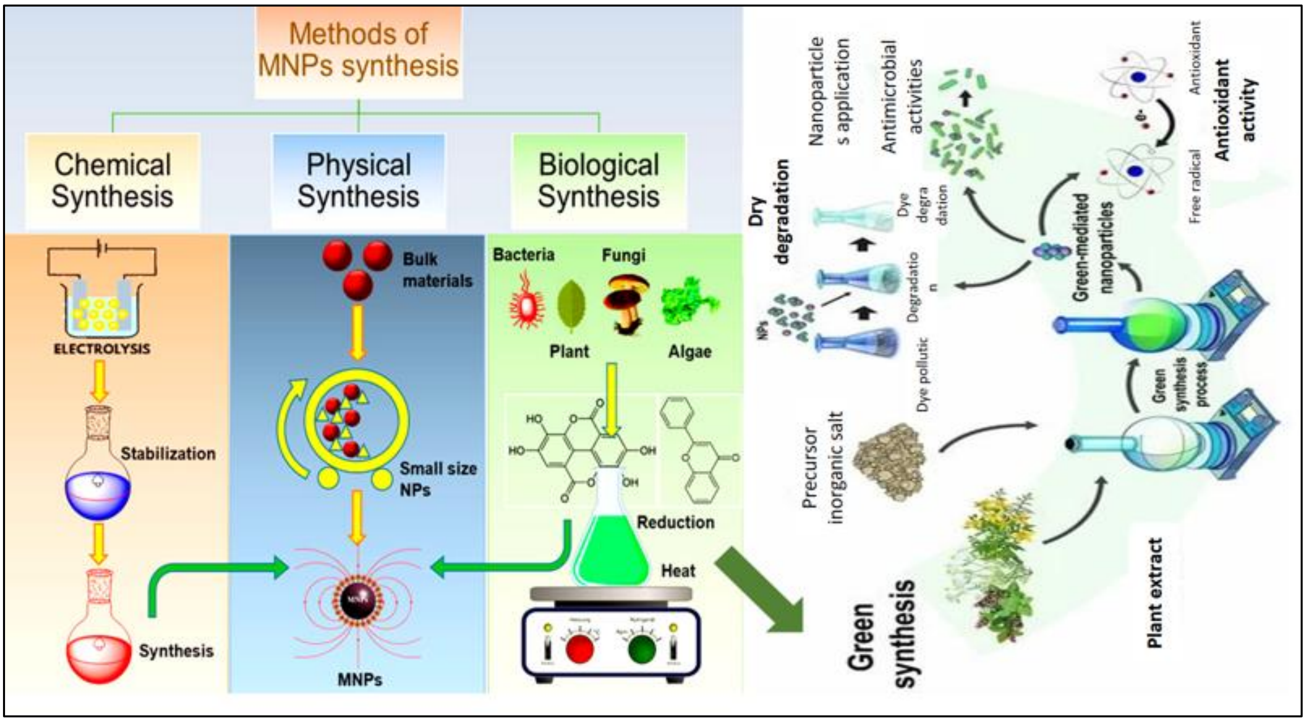


Fig 3: Design and Synthesis of Nanoparticles for Targeted Pollutant Removal

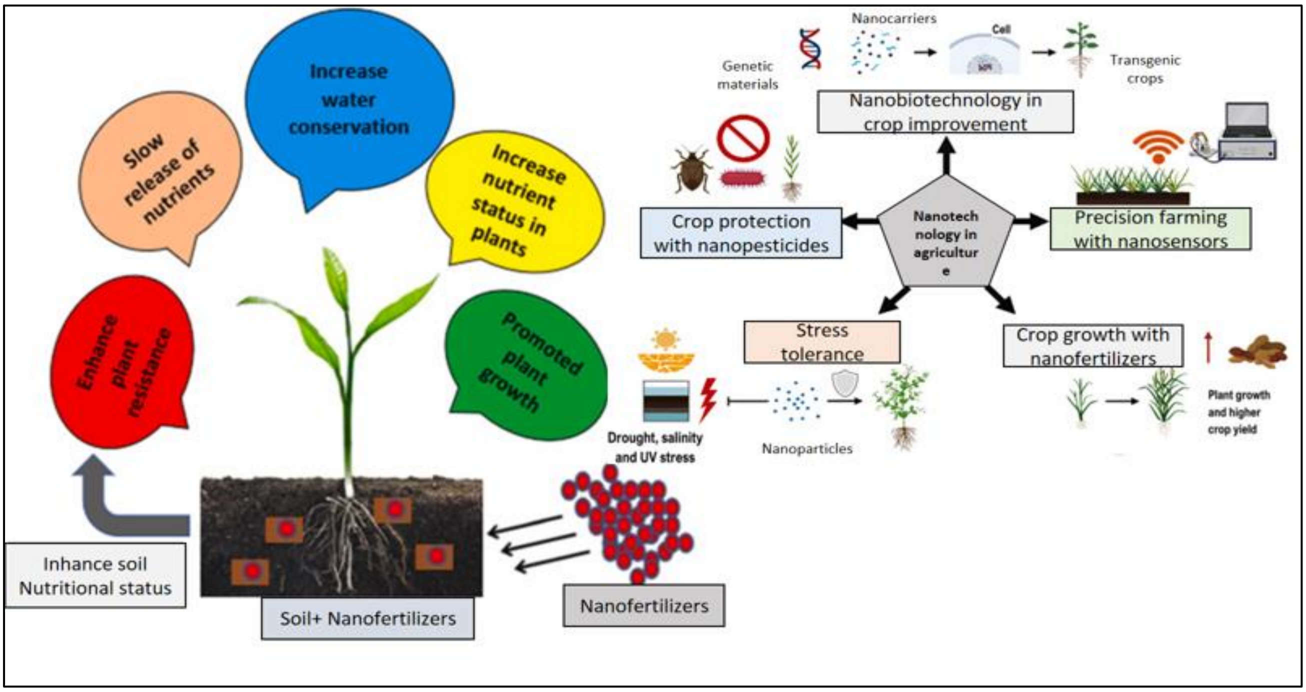


Fig 4: Nanotechnology in the Production of Biofertilizers

Interdisciplinary Applications of Nanotechnology in Agriculture and Wastewater Management

Crop production, environmental preservation, and resource efficiency are revolutionized by nanotechnology's multidisciplinary uses in wastewater treatment and agriculture. One important advancement is using nano biosensors for real-time pollution detection and water quality monitoring (Thakur *et al.*, 2022). With the extreme sensitivity of these nanoscale sensors, farmers and environmental managers may quickly respond to pollution and receive real-time input on the safety of their water. Examples of these toxins include pesticides and heavy metals. Furthermore, nano-enhanced irrigation systems increase water efficiency by accurately supplying water to crops and reducing water waste. By screening out contaminants and pathogens, nanomaterials used in irrigation systems can also assist in avoiding contamination and producing safer and cleaner agricultural water (Dasgupta *et al.,* 2017). In precision agriculture, Nanotechnology is used to evaluate soil quality and maximize nutrient delivery, improving crop output and health. For instance, fertilizer nano-formulations are being developed to release nutrients gradually, improving plant nutrient uptake and lowering pollution and nutrient runoff. Furthermore, nanotechnology is integrated with IoT-based platforms in smart agricultural systems, enabling constant, remote monitoring of soil temperature, moisture content, and nutrient levels. Thanks to this connection, farmers can now make data-driven decisions that maximize crop productivity, reduce waste, and advance sustainable practices. When taken as a whole, these developments show how nanotechnology may be used to solve important problems in wastewater treatment and agriculture, paving the way for resource stewardship and sustainable farming in the future (Sharma *et al.,* 2024).

Sustainability and Life Cycle Analysis of Nano-Based Remediation and Fertilization

In order to evaluate the long-term environmental, economic, and energy consequences of nano-based fertilization and remediation methods, sustainability and life cycle analysis (LCA) are essential. Since nanoparticles can amass ecosystems and affect soil, water, and creatures, it is crucial to comprehend their degradation processes and ecotoxicity (Adeel *et al.,* 2021). To ensure they do not present unanticipated concerns, nanoparticle behavior in the environment must be assessed, such as how they degrade, spread, or interact with other substances. Economic viability is particularly important since nano-based methods sometimes involve large upfront costs because of the production and functionalization of nanoparticles. However, nano-based remediation may be more effective and provide longer-term advantages, such as lower treatment costs and material utilization, than traditional approaches (He *et al.,* 2023). Another crucial factor is energy efficiency, as nano-filtration systems may require more energy depending on the procedure and size, even if they are frequently more successful at removing impurities. To evaluate the overall sustainability of modern nano-filter technologies, their energy consumption must be compared to traditional filtration. Furthermore, by limiting the need for chemical-intensive procedures, lowering shipping and handling costs, and offering more effective fertilization and remediation options, nanotechnology has the potential to lower greenhouse gas emissions, according to carbon footprint analysis. By weighing the advantages of nano-based systems against any negative effects on the environment, society, and economy, life cycle assessment (LCA) provides a comprehensive method for measuring their complete impact (Dhingra *et al.,* 2010).

Comparative Analysis of Nanoparticles and Nanotubes in Different Wastewater Types

In wastewater treatment, a comparison of nanoparticles and nanotubes shows clear benefits and drawbacks, especially when considering sewage, industrial, and agricultural wastewater types. Nanoparticles are a flexible option for these intricate, contaminant-rich situations because of their high surface area-to-volume ratio, which enables them to efficiently bind and break down heavy metals, organic contaminants, and pathogens frequently present in industrial effluent (Parekh *et al.,* 2013). However, because of their remarkable adsorption capability and chemical stability, carbon nanotubes (CNTs) have demonstrated greater promise when used in agricultural wastewater, which frequently contains a larger load of pesticides, fertilizers, and biological pollutants. CNTs' selective affinity for organic chemicals enables them to target certain contaminants, such as pesticides, that are difficult to remove using traditional remediation techniques. Since sewage frequently contains medications, personal care items, and infections, while agricultural runoff is primarily high in nitrogen and phosphorus compounds, it is crucial to customize nano-remediation techniques to each source when comparing sewage and agricultural runoff. Functionalized CNTs are excellent at capturing nitrogen from agricultural runoff, whereas functionalized nanoparticles show promise for removing pharmaceuticals and pathogens from sewage (Opoku *et al.,* 2021). Nano-adsorbents may be tailored to target these distinct characteristics. Because variables like temperature, pH, and flow rate affect the dynamics of the interaction between pollutants and nanoparticles, seasonal and climatic fluctuations also have a major impact on the efficacy of nano-treatment. Warmer temperatures, for instance, can speed up reactions but can also weaken certain nanoparticles, reducing their effectiveness. Lastly, case-by-case applications are crucial; because the interactions between pollutants and nanomaterial qualities vary greatly, each wastewater profile necessitates customized nano-strategies to guarantee maximum performance. A more efficient and sustainable method of managing wastewater is made possible by this customization, which enables nano-remediation to be modified in accordance with particular environmental conditions, pollutant kinds, and legal requirements (Opoku *et al.,* 2021).

Environmental and Health Safety Considerations in Nanotechnology Applications

Applications of nanotechnology have transformed a number of industries, including electronics, medicine, agriculture, and environmental management (Dasgupta *et al.,* 2017). However, the environmental and health safety implications of these technologies are complicated and demand constant attention. Since nanoparticles can be persistent and possibly dangerous when discharged into soil and water systems, one of the main concerns is the long-term environmental impact of their accumulation in ecosystems. According to studies, certain nanoparticles can build up in aquatic and terrestrial environments because of their tiny size and reactive characteristics, endangering microbes, plants, and animals. This buildup can change ecological functioning, disturb food chains, and affect biodiversity (Lake *et al.*, 2000). The toxicity of nanoparticles when absorbed by agricultural products is a major concern for human health because plants that are exposed to them by soil or water absorption may transfer the particles into edible tissues, where they might endanger the health of consumers. The toxicity of nanoparticles when absorbed by agricultural products is a major concern for human health because plants that are exposed to them by soil or water absorption may transfer the particles into edible tissues, where they might endanger the health of consumers (Alengebawy *et al.*, 2021).

CONCLUSION

The review emphasizes the importance of nanoparticles and nanotubes for sustainable environmental management and agricultural practices by highlighting their revolutionary potential in wastewater treatment and biofertilizer production. These nanoparticles provide efficient ways to eliminate heavy metals, pathogens, and organic contaminants from sewage, industrial, and agricultural wastes because of their sophisticated qualities, which include large surface area, increased reactivity, and selective adsorption capabilities. They are, therefore, useful in tackling the problems of environmental contamination while preserving essential water supplies. Additionally, a crucial development for sustainable agriculture is the use of nanoparticles and nanotubes into the manufacturing of biofertilizer. Biofertilizers boosted by nanotechnology increase plant growth, enhance nutrient uptake and lessen reliance on traditional chemical fertilizers, all of which lead to better soils and higher agricultural yields. The extensive use of these materials, however, also prompts worries about possible ecological and health hazards, highlighting the necessity of thorough regulatory frameworks and environmental impact evaluations. Notwithstanding these difficulties, continuous research into enhancing the efficacy, affordability, and safety of nanomaterials keeps improving their uses, making them a crucial part of green technology. The sophisticated uses of nanoparticles and nanotubes offer enormous potential for creating cleaner ecosystems and promoting global food security as the world looks for robust and sustainable agriculture and water management systems.

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