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Harnessing Nanotechnology for Environmental Sustainability: Applications, Challenges, and Future Perspectives

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Abstract

Background: Nanotechnology has emerged as a transformative and rapidly advancing field with significant potential to address pressing environmental challenges. Owing to the unique properties of nanoparticles, particularly their high surface area-to-volume ratio and enhanced reactivity, nanotechnology offers innovative solutions across multiple environmental sectors. **Aim:** This review aims to explore the applications, advantages, challenges, and future perspectives of nanotechnology in promoting environmental sustainability. **Methods:** A comprehensive literature review approach was employed to examine the role of nanotechnology in key areas, including climate change mitigation, wastewater treatment, sustainable agriculture, food quality enhancement, and civil engineering. **Conclusion:** Nanotechnology provides cost-effective, efficient, and sustainable solutions for reducing environmental pollutants, improving resource management, and enhancing ecosystem resilience. However, concerns regarding environmental toxicity, long-term impacts, and regulatory challenges highlight the need for further research, risk assessment, and the development of robust regulatory frameworks to ensure its safe and widespread implementation.

Keywords: climate change mitigation; nanomaterials; nanopesticides; nano-fertilizers; wastewater treatment

1. Introduction

Nanotechnology is the branch of biotechnology that deals with the formation of nanoparticles, the size of which ranges from 1-100 nm. This increases their physical and chemical characteristics as well as biological efficiency. Nanoparticles have a high surface area to volume ratio (Chausali et al., 2023) . Nanotechnology can play a major role in accomplishing the goal of zero hunger, which is one of the 17 major goals proposed by the UN. Researchers can use agri-nanotechnology for the betterment of the agri-food sector around the world. Nano agrochemicals, including nano herbicides, nano pesticides, nano fertilizers, nano fungicides, and nano insecticides, can act as sustainable approaches that scientists should use for financially reasonable agriculture (Saritha et al., 2022; Khalid et al.,2025).

The present world is facing numerous challenges like population growth, climate crisis, and lack of resources. This calls for the use of advanced technology and methodology to augment performance by civil engineers. In these circumstances, most significant tool is nanotechnology that can reevaluate material functioning at the nanoscale. Nanotechnology allows remarkable improvement in durability, resilience, and environmental receptiveness of conventional building matter (Firoozi et al., 2025).

The major problems regarding climate change, like rapidly melting polar ice sheets, increasing greenhouse gases, desert encroachment, severe weather conditions, and global warming, are all a result of human activities such as the installation of industries and overdependence on fossil fuels. These practices are causing ecological destruction. Nanomaterials have the ability to counter these adverse climate changes by reducing pollution, allowing clean energy production, and encouraging viable agriculture. The combination of nanotechnology and green chemistry has thus resulted in the formation of a new discipline called green nanotechnology, which is very effective in this regard (Kodadi et al., 2025).

Nanotechnology includes many important areas like agriculture, environment, energy, food, material science, etc. With the advancement in agriculture, nanotechnology has provided nanofertilizers, nano-pesticides, and several other modern tools that enhance productivity and help in maintaining the ecosystem. Nanosensors play a key role in providing various advantages in agricultural farms by recognizing the climatic circumstances necessary for increasing the generative capacity of crops. Nanoproducts are most importantly involved in the efficient recycling of renewable energy resources. Moreover, nanomaterials like nanocoatings, nanocatalysts, nanolubricants, nanocomposites, etc. have a high ability to substitute traditional methods in an eco-friendly way (Chausali et al., 2023).

Utilization of nanotechnology in the field of agriculture is escalating enhanced food production, durability, and low-input agriculture. Nanotechnology involves many aspects, such as the cure of multiple diseases, microbial identification, the provision of safe food, and productive packing and delivering methods. Nanocoated fertilizers have high interfacial tension and encapsulate massive particles. Nanovesicles provide greater pathogen and disease protection in plants (Chand Mali et al., 2020) .

Nanopesticides provide greater protection to crops while minimizing pesticide use. Nanoparticles (NPs) that show phytosanitary activity include metalloids, metallic oxides, nonmetals, and carbon nanomaterials (Warghane et al., 2024).

Nano-titanium dioxide and nano-silica can be used to improve the functionality of concrete by conferring additional beneficial properties (Firoozi et al., 2025). The combination of bio-elements and green functionalization allows effective environmental surveillance (Aguilar-Pérez et al., 2020).

Lack of safe drinking water is a major issue in the developing world. Methods that were being used previously are expensive and inefficient. Now carbon-based nanomaterials are being used as biosensors. These include carbon black, graphene, and carbon nanohorns, etc. These substances are conductors of heat and electricity, have increased surface area, and are efficient catalysts (Wilson et al., 2021) .

Nanocatalysts are nanomaterials that have the ability to catalyze a reaction. Harmful environment pollutants like oils, pesticides, sewage, herbicides, industrial waste, and organic waste can be broken down by using nanocatalysts (Ningthoujam et al., 2022). There are three types of nanocoated materials that are identified by distinct dynamics and processes of transmutation. CeO_2, and Ag can be converted through redox reaction, and TiO_2 is chemically inert, which leads to a change in sensitivity and decomposition. These greatly affect nature and the ecosystem (Bottero et al., 2015). The benefits of environmental nanotechnology are presented in Figure 1. This review aims to explore the applications, advantages, challenges, and future perspectives of nanotechnology in promoting environmental sustainability.

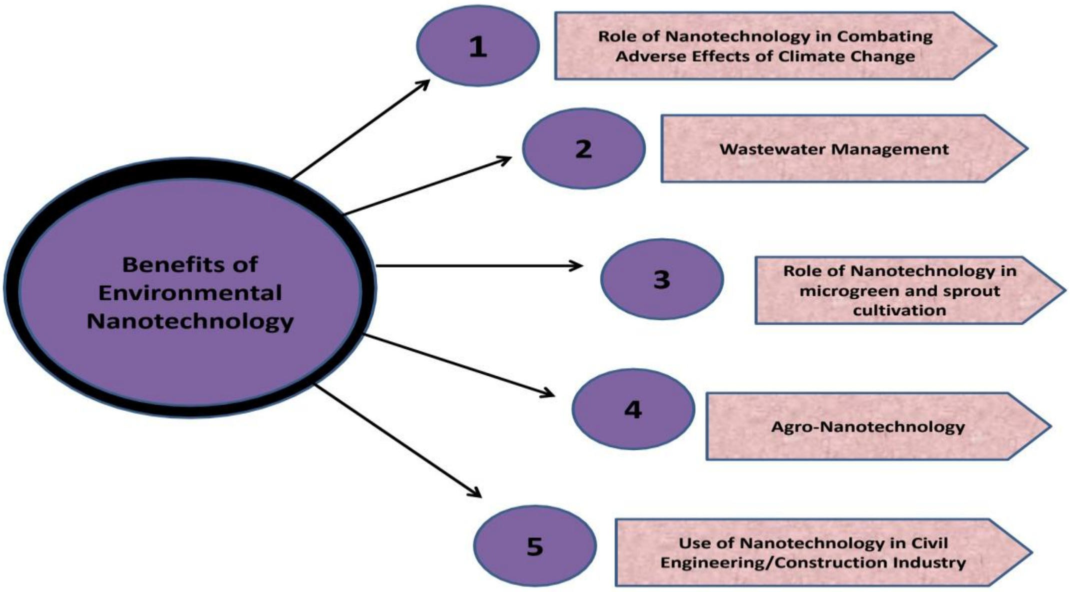

Figure 1. Benefits of environmental nanotechnology

2. Methods

This detailed literature review was carried out with the help of Google Scholar, ScienceDirect, and PubMed, which covered studies from 2015 to 2025. The search was done using the keywords "environmental nanotechnology", "nanopesticides", "nanoremediation", and "wastewater treatment". Out of approximately 250 articles, a total of 23 articles were used as a source of information for this review based on relevancy and applicability to the topic.

3. Results and Discussion

3.1. Role of Nanotechnology in Combating Adverse Effects of Climate Change

Presently, the world is going through numerous ecological problems, of which climate change is the most important. Over the previous 4 to 5 decades, Earth's temperature has been continuously rising and will keep doing so in the future (Chausali et al., 2023).

Pollution and the greenhouse effect that cause global warming are important contributors to climate change, which threatens the sustainability of the environment, eco-diversity, and poses adverse effects on mankind. This calls for an immediate approach to combat these harmful conditions. Green nanomaterials, the products of Nanotechnology, provide the ultimate evolutionary and environmentally friendly solution (Kodadi et al., 2025).

Nanomaterials, like nano catalysts, carbon nanomaterials, nano silica, nano level lubricants, nano coatings, nano zeolite, and nano composites have high ability in the generation of biofuels, wastewater management, bio-sequestration, and sanitation of the environment in a climate-friendly manner (Pandey et al., 2024).

3.1.1 Impacts of Climate Crisis

Some major effects of climate change that gravely damage the planet's climate system are increasing temperature of land, air, and water, melting of glaciers, causing rising sea level, floods, acidification, and extreme weather conditions. These affect all the aspects of human life, including health and wellbeing, agricultural, social, and financial circumstances (Pandey et al., 2024).

3.1.2 Agricultural Implications

Extreme weather resulting from climate change has a dreadful influence on agricultural yield. Hypersalinity and shortage of water are also significant contributing elements. Thus, the immediate demand is a supportable technology that mitigates risks, enhances crop yield, and strengthens the agricultural resistance against harmful agents (Chausali et al., 2023). Green nanotechnology minimizes water wastage, enhances soil fertility and nutrient uptake by plants, thus helping in the application of climate-friendly agriculture despite various challenges. These approaches encourage eco-friendly agriculture (Kodadi et al., 2025). A few nanomaterials and their beneficial role in agriculture are given below in Table 1.

Table 1. Nanomaterials and their beneficial role in agriculture

Nanomaterial	Agricultural Role	Climate Benefit	Source
Nano-pesticides	Microbial and insect control	Reduced chemical consumption	Silver NPs
Nano-fertilizers	Effective nutrient uptake by plants	Decreased fertilizer runoff	FeO NPs, ZnO
Nano-biochar	Water retention and soil conditioning	Drought tolerance	Agrowaste

3.1.3 Environmental Assessment Tools

Nano-biosensors are surfacing as advanced tools for the recognition of factors causing harsh weather, greenhouse gases, and environmental pollutants. These biosensors are entirely based on green nanotechnology. Green nanotechnology is an excellent tool in combating the current climate crisis by the use of these biosensors, which aid in the prediction of natural calamities, surveillance of climate patterns, and refinement of adaptation strategies. It is highly potent, adaptable, and ecologically sound in its action (Kodadi et al., 2025). Sensor type, green nanomaterial used, and parameter detected are shown in Table 2.

Table 2. Sensor type, green nanomaterial used, and parameter detected

Sensor Type	Green Nanomaterial Used	Parameter Detected
UV sensors	ZnO–TiO_2	UV rays levels
Gas sensors	SnO_2, ZnO NPs	CO_2, NOx
Biosensors	Enzyme-capped AuNPs	Pesticides in water

3.1.4 Greenhouse Gases

Greenhouse gases such as CH_4, SF_6, and CO_2 trap heat in the atmosphere, leading to an increase in the Earth's temperature known as global warming. Nanotechnology offers several greenhouse gas sequestration (GHGS) approaches to mitigate this effect, including: a) Capture of greenhouse gases, b) Minimizing utilization of natural fuels, and c) Improvement of procedure effectiveness

Nanofilms and Nanozeolites are used for the assimilation of greenhouse gases because they have a large surface area (Pandey et al., 2024).

3.1.5 Air Quality Management

Carbon dioxide is an important air pollutant as well as a major greenhouse gas, thus contributing to environmental pollution and global warming, respectively. Nanotechnology provides the solution for the sequestration of this harmful gas. Major green-synthesized nanomaterials that are now being used in the assimilation of CO_2 are graphene, carbon nanotubes, and metal-organic frameworks (MOFs). Plant-mediated nanoparticles also have a high capability of action in air purification systems because of their porous nature and large surface area (Kodadi et al., 2025).

3.2. Wastewater Management

Lack of safe drinking water is a major problem of developing world. The most important factors contributing to this are water pollution, increasing industrial installment and excessive population expansion. The importance of water can be highlighted by the fact that no form of life can exist without it. From the domestic to the global level, water is needed everywhere. This calls for an effective and practical approach to identify and handle all kinds of water pollutants (Wilson et al., 2021).

3.2.1 Potential Dangers from Wastewater

Toxic chemical substances that are released into water bodies from industries and other sources cause great distress to living beings. One disastrous effect of environmental pollutants on human health is cancer. Studies reveal that around $4/5^{th}$ of human cancers are caused by ecological factors, and organic pollutants make the major portion of these carcinogens. Certain substances, like nitrates, are not dangerous unless they are present in large amounts in water, when they cause diarrhea and other gastrointestinal issues (Wu et al., 2017).

3.2.2 Carbon-based adsorbents

Among various important techniques for treating wastewater, adsorption is the most productive and worth mentioning. It is used to eliminate inorganic and organic pollutants. For this purpose, many adsorbents are used, such as activated carbons and zeolite resin. In this procedure, carbon nanotubes are first made stable so that their surface adsorbing ability is preserved. Carbon nanotubes are dependable products in this technique, as they give excellent results in the elimination of pollutants (Wilson et al., 2021) . Carbon nanotubes make chemical bonds with metal cations and help to get rid of oil-based pollutants from water (Ningthoujam et al., 2022).

3.2.3 Role of Zeolite

Zeolites are materials having numerous small pores proving a large surface area which is taken up by water molecules and cations. They also have an electrostatic circular opening consisting of silica and alumina minerals. The basic principle of their action is hydration and ion exchange. Nano-zeolites are even more efficient and accurate than conventional zeolites in their action of adsorbing pollutants (Ningthoujam et al., 2022).

3.2.4 Other Nano-materials used in Wastewater Treatment

Nomaterials are instituted to polymeric membranes, and their efficacy is presented in Table 3.

Table 3. Nomaterials instituted to polymeric membranes and their efficacy

Nano-material	Nano-material characteristic	Nano-particles impact and membrane efficacy
Titanate	Porous structure	Increases hydrophilicity, Density. Increases salts retention and antifouling properties
ZnO	Hydrophilicity	High hydrophilicity Increases salts retention and antifouling properties
TiO2	Hydrophilicity photocatalysis	Increases hydrophilicity and antibacterial activity, Increases salts retention,
Silver	Antibacterial	Improves antibacterial Activity

Source: Bodzek et al. (2020)

3.2.5 Other Techniques Based on Nanotechnology

3.2.5.1 Deep Oxidation Technology

It is a latest technique relying on UV rays and photocatalysis. The most frequently used technology for wastewater management is photocatalytic oxidation technology. It helps to eliminate many water pollutants very efficiently. These include heavy metals, cyanide, phenols, halocarbons, and several carboxylic acids. The most important component of this technique is the photo catalyst. Currently, Titanium dioxide (TiO2) is thought to be the most efficient catalyst. Nano-TiO2 degrades chlorinated aromatic hydrocarbons, which are the major culprits in making pulp mill effluent. Hence, this technique is a revolutionary approach in the field of wastewater treatment (Wu et al., 2017).

3.2.5.2 Nano-Filtration

Membrane filtration is a conventional technique that has been in use for decades for the separation of solid impurities from liquids. Advanced variants of this old technique are now used for the purification of wastewater from various industries, including food, paper, oil, medicine, chemical, and nuclear industries. These advanced techniques are Nanofiltration, microfiltration, electrodialysis, reverse osmosis, and ultrafiltration (Wu et al., 2017).

3.2.5.3 Nano flocculation technology

Precipitation and flocculation greatly help to minimize saturation and cloudiness of polluted water and thus are considered among the most efficacious techniques in this regard. It helps to eliminate organic substances having high molecular weight, like heavy metals, and provides an improved sludge treatment method. Flocculation is the main tool used to eliminate colloidal dispersions from wastewater and to improve decantation (Wu et al., 2017).

3.2.6 Heavy Metals Detection in Water

There are certain chemical substances in our surroundings that, even if present in small amounts, are extremely hazardous to human health. Some of these are cationic heavy metals like mercury, copper, lead, and chromium, while others are anionic, which cause various major diseases like blue baby syndrome, which is characterized by high nitrate concentration in blood, and fluorosis, which is high fluorine in blood. As heavy metals are not decomposable, they tend to pile up in our food chain and cause major damage to human health as well as the environment. Keeping in view of this problem, nano-biosensors are being used to treat these hazardous heavy metals, which are present excessively in industrial wastewater. Most used are combinations of gold and silver nanoparticles with biomolecules because they are budget-friendly, simple, safe to use, and target-specific (Aguilar-Pérez et al., 2020).

3.3. Agro-Nanotechnology

Agro-Nanotechnology is the branch that is formed by the combination of nanotechnology and agriculture. It emphasizes enhancing crop productivity by increasing the nutrient content of soil and promoting perpetual plant growth. This technology can be applied in all the developmental stages of a plant, including seeding, germination, budding, maturation, and control of plant diseases. Through proper handling and provision of suitable conditions, nanotechnology can help minimize soil contamination, loss of essential nutrients, and use of toxic chemicals, thus increasing crop productivity (Bala et al., 2023) .

Nano enzymes make plants more resilient against environmental stresses by acting as antioxidants, and are popularly used against halotolerance nowadays (Saritha et al., 2022).

3.3.1 Nano-Fertilizer

Another name given to nano-fertilizers is ‘smart fertilizers’ because of their certain properties that make them superior to conventional fertilizers. These include better delivery and uptake of nutrients by plants and aim specificity. These properties confer nano fertilizers diverse and numerous functions such as time and budget friendliness, enhanced productivity, production of nutrient-enriched foods, and high nourishment. This has been proved by many experimental analyses, such as the use of SiO2-based nano-fertilizer, which enhanced the rate of germination of tomatoes, and recently, nano-composites have shown better nutrient uptake and distribution by the plants. Also, carbon nanoparticle-based fertilizers are found to be more efficient in the tobacco industry than traditional fertilizers (Saritha et al., 2022). Agricultural applications of nanotechnology is presented in Figure 2.

3.3.2 Nano-Pesticides

The function of pesticides is to eliminate and kill microbes and pests. But one undesirable effect of these is that they adversely impact human health as well as the environment. This has been a major concern over the years. Another problem related to excess use of pesticides is increased tolerance to them, which is called pesticide resistance. To resolve this major issue, there is a requirement for more advanced and effective pesticides. Nanotechnology provides the perfect answer to this by minimizing the need for traditional pesticides. In this way, agriculture is more economical as well as highly productive (Chand Mali et al., 2020).

Nanoformulated pesticides that use various nanoparticles are called nanopesticides, which have proven to be a landmark achievement in this regard because they are safer and more compelling than conventional pesticides. The main feature that distinguishes nanopesticides from older pesticides is their capability to give a sustained supply of active principle, which is beneficial because it increases the target specificity and reduces adverse ecological effects as well. All in all, this increases the lifespan of the active constituent (RODRÍGUEZ-SEIJO et al., 2025).

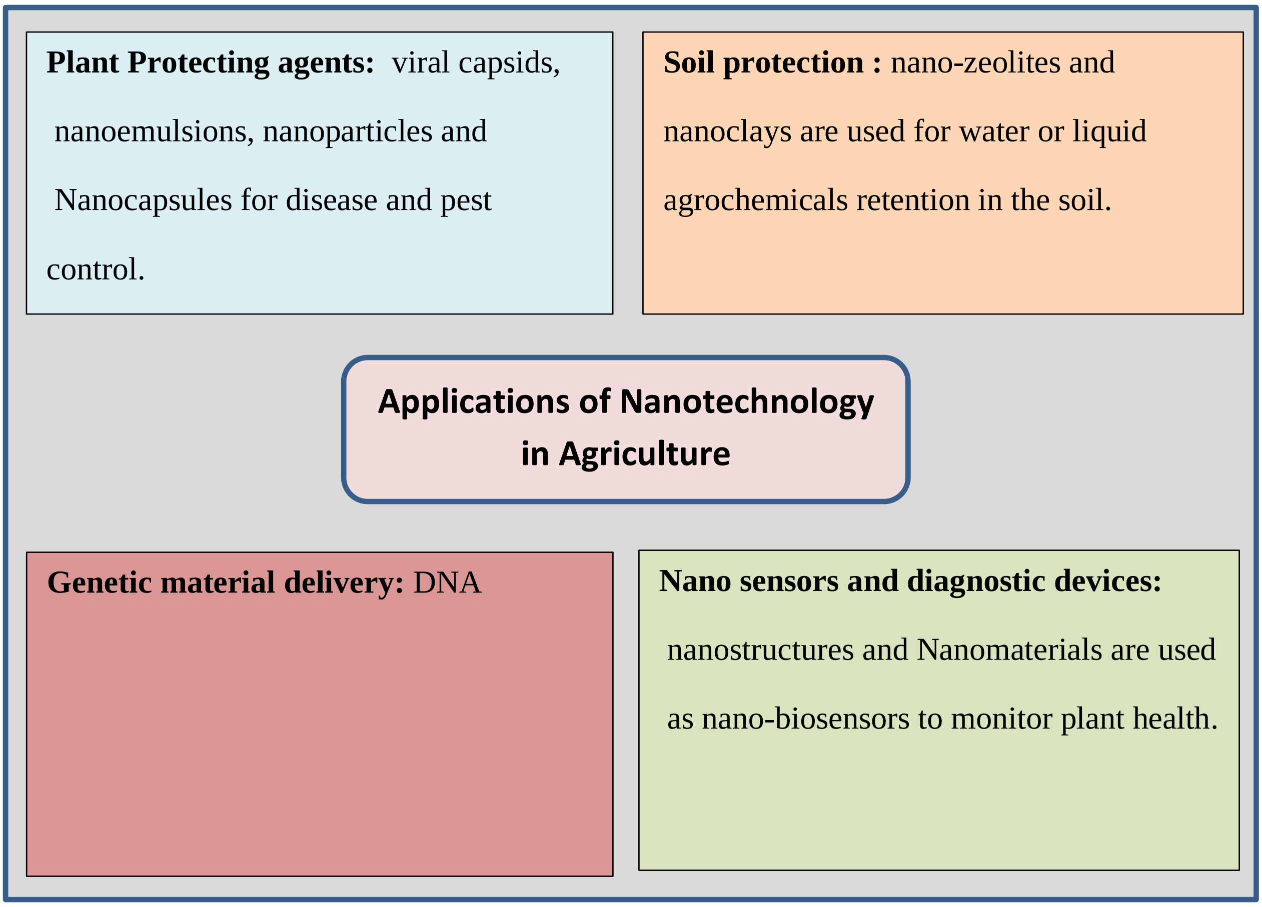

Figure 2. Agricultural Applications of Nanotechnology (Chand Mali et al., 2020)

3.3.3 Nano-Biosensors

Another term we come across while studying the role of nanotechnology in agriculture is nano-biosensors. A nanosensor is a substance that utilizes nanoparticles to evaluate a sample. Quantum dots, carbon nanotubes, and gold nanoparticles have been used in nano-biosensors. They are employed to detect pathogens like *Salmonella typhi* and *E. coli* (Saritha et al., 2022).

3.3.4 Nano-Herbicide

As occurs with pesticides, continual and prolonged use of herbicides also leads to the development of tolerance in the weed against that specific herbicide. Nanotechnology helps to prevent this from happening by targeted and controlled supply of nanoherbicides in such a way that it avoids excess accumulation of active constituents in the soil and environment. So, it acts as an eco-friendly solution to this problem. Nano-herbicides that are expected to be used most frequently in the future are carboxy methyl cellulose nanoparticles (Chand Mali et al., 2020).

3.3.5 Nano-Bionics

Nano-bionics involves the use of nanomaterials for the betterment of the functioning of living organisms. In agriculture, it refers to the enhancement of crop yield. Various carbon and metal-based nanomaterials are widely used in agriculture industry because of their special properties, such as transportation, assimilation, aggregation, and encouraging impacts on plant growth and maturation. This technology has been applied to many crops, which have shown major benefits in return as well. Aside from physical growth, it also amplifies functional processes like nitrogen balance and photosynthesis. This has been seen in peanut, soybean, and spinach crops (Chand Mali et al., 2020).

3.3.6 Role of Nanotechnology in microgreen and sprout cultivation

The use of nanosensors, nanofertilizers, and nanoparticle seed priming has been broadly accepted in microgreens, sprouts, and cultivation media over the past few years. It greatly helped in increasing the quality and productivity of crops. However, some nanotechnological tools like nanocoatings and nanopesticides have not been used for microgreens and sprouts yet, although they have shown beneficial effects of amplifying disease resilience and increasing lifespan in other agricultural products. Their ability to maintain the wholesomeness of vegetables and fruits and render them resistant to pathogens suggests a potential chance of their use in microgreens and sprouts as well (Zhu et al., 2025).

3.3.7 Pathogen Detection and Phytosanitary Action

Another application of nanotechnology in the field of agriculture is in the detection and management of viral diseases of plants. The branch that deals with this action is called nanophytovirology. It includes drug administration, bioactivation, activated defense response, genetic manipulation, and curative science. Nanoparticles have the marked ability to communicate more freely and readily, and even have the potential to kill many viruses. Nano-biosensors are used for the identification of vectors that serve as a vehicle for disease transmission. Metal-based nanomaterials also have a broad capacity for the treatment of plant disorders (Warghane et al., 2024).

Use of nanopesticides, nanofungicides, nanoherbicides, and nanoemulsions has been widely emphasized for managing many plant-related diseases and controlling pests, as they are highly superior to conventional pesticides in their action (Saritha et al., 2022).

Nanosensors can be very diverse in the field of observing, recognizing, and identifying. They help in the diagnosis of various harmful factors like microorganisms, irritants, and other environmental tensions like extremes of weather, lack of water, and nutrients (Chand Mali et al., 2020).

3.4. Use of Nanotechnology in Civil Engineering/Construction Industry

Nanotechnology is applicable in nearly all disciplines of engineering, but its role is highly superior in the construction industry, as it is used in the manufacture of several building materials. The knowledge of nanotechnology has elevated the quality of construction material in terms of sustainability and cost-effectiveness. Its main advantage that has restructured this industry and has shown many positive impacts is use of protective coatings that help to resist erosion, minimize heat transduction, and prevent attack of humidity on pipes. The significance of nanotechnology has been unremarkable in the manufacture of concrete products (Rao et al., 2015).

3.4.1 Impact of Nano $CaCO_3$ on Cement Mortars

Cement-based materials are supplemented with nano calcium carbonate, as it has strong potential in this regard. $CaCO_3$ can be obtained from carbon dioxide that is released during the production of cement. It has been proven experimentally that this supplementation enhances the bending strength of cement mortars, but a limitation in this regard is that if nano $CaCO_3$ is used in excess of its optimal quantity, it fails to enhance the physical characteristics of mortars up to the target. The reason behind this is the deficient dissemination of nanoparticles. Nano $CaCO_3$ speeds up the hydration of cement and thus quickens its setting. The best action is seen with samples having 2% of nano $CaCO_3$. Another benefit is that this practice recycles CO_2, which results in the betterment of the economy (Cosentino et al., 2020) .

3.4.2 Carbon Nano-materials in Enhancing the Quality of Concrete and Cement

Water and cement constitute a binder, which is an important component of concrete, along with fine and coarse aggregate. So cement is a component of concrete. The applications of nanomaterials in construction and the concrete industry are very vast. They enhance various properties, including cohesiveness, cement reaction with water, durability, compressibility, bond performance and adhesion, prevention of breaks and cracks, and self-repair (Liu et al., 2023). The effect of CNTs on concrete and cement is shown in Table 4.

Table 4. The effect of CNTs on concrete and cement

Properties	**Explanation**
Sturdiness, compressibility, power dissipation, nanostructure	Both the sturdiness and compressibility of concrete are enhanced by using carbon nanotubes.
Physical properties and ultra-high performance concrete (UHPC)	Physical properties and UHPC are improved by using MWCNTs
Erosion	CNTs resulted in an increased rate of corrosion in the concrete-steel matrix
Bending strength, tensile bond strength, and crack resistance	All these properties showed improvement as well
Interfacial transition zone (ITZ)	ITZ and splintering were found to be decreased
Change in binding energy of concrete and steel after adding multi-walled carbon nanotubes	The binding energy was enhanced by 14%
Conduction of heat	favorable effect on the conduction of heat
Overall Behavior of Concrete	Enhanced compressibility and diminished bleed were beneficial outcomes in this study of CNTs use

Source: Liu et al. (2023)

3.4.3 Nano-materials used in Civil Engineering

Examples of nanoparticles and their use in civil engineering is presented in Figure 3 (Firoozi et al., 2025).

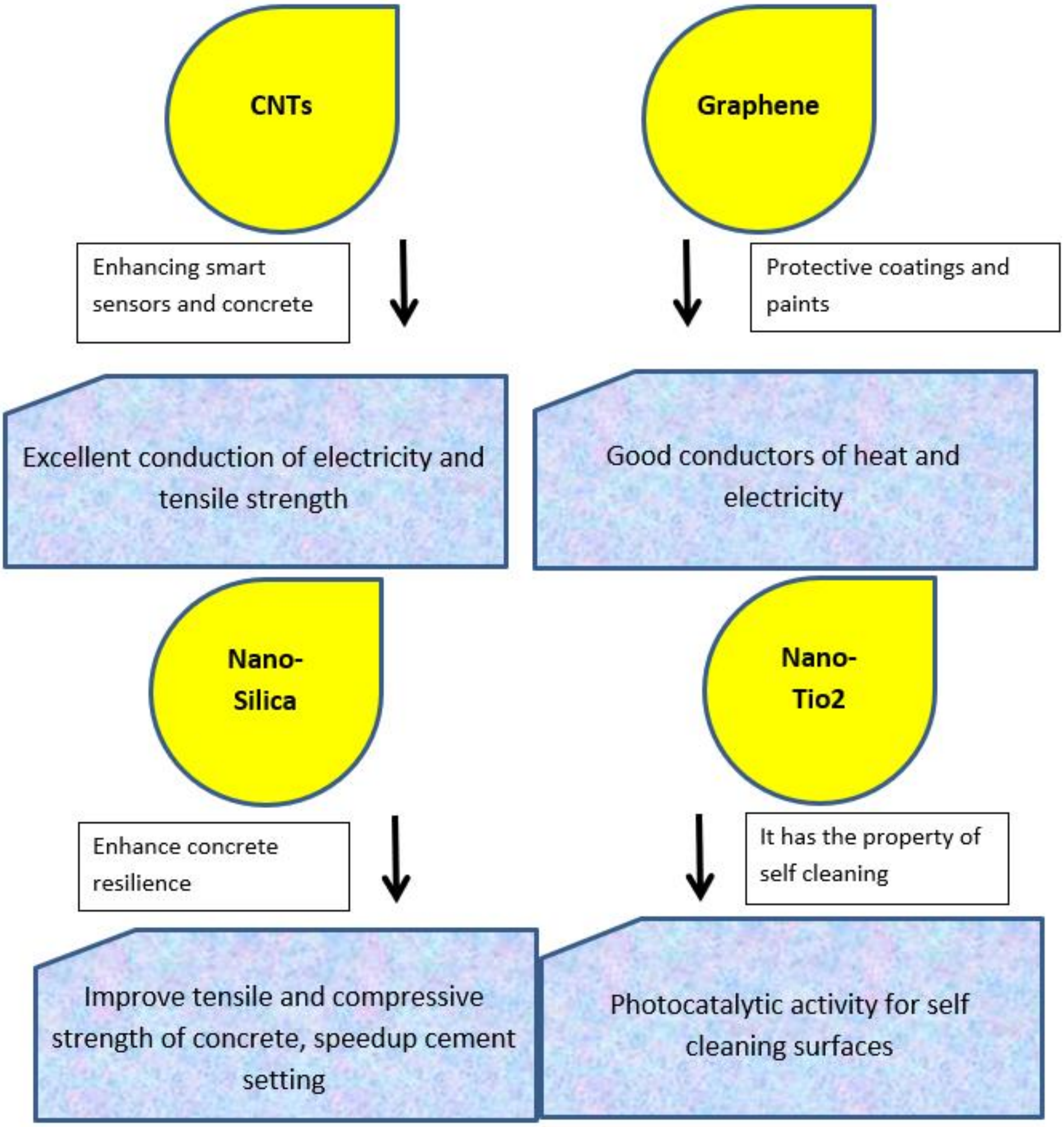

Figure 3. Examples of nanoparticles and their use in civil engineering (Firoozi et al., 2025).

3.4.4 Use of Nanotechnology in Steel and Glass

Steel is among the most important and common substances used in the construction industry. It has great tensile strength but is highly fatigable, which creates a critical challenge during dynamic loading. Copper nanomaterials can be used to resolve this issue. These, when added to steel, cause its surface to become sleek and plain, which minimizes the fatigue breakage and excessive stain. Steel with resilience against erosion has also been developed. Stainless steel that is used in a low-weight framework is also the product of nanotechnology (Rao et al., 2015).

Glass is a widely used construction material, but it is required to be kept clean constantly, which is a significant issue. Nanotechnology is also used in this regard. Nano TiO2-based glass is being utilized now instead of plain glass. This type of glass attracts rainwater, which helps in its own cleaning, while TiO_2 eliminates bio waste. It also avoids the accumulation of pollutants on the buildings when coated outside them and shows antifogging properties. Fireproof glass is a provision of nanotechnology as well (Rao et al., 2015).

3.5 Impact of Nanobiotechnology on Plants and Forest

3.5.1 Nano-biotechnology role in abiotic stress management in plants

Plant abiotic stress tolerance has been enhanced by employing nanotechnology. Nanomaterials are very potent in this regard. They bring about this enhancement by modification in omics (like proteomics, transcriptomics, and microRNAs) and epigenetics. Extremes of temperature, moisture, and salinity of soil are the abiotic stresses that adversely affect agricultural yield. Several methods have been employed to overcome these stresses, of which nanobiotechnology is the most effective and is used on a large scale (Chen et al., 2024).

Nanomaterials stimulate changes in metabolism that allow plants to withstand abiotic stresses. They affect both primary and secondary metabolites, and thus, stress tolerance is improved. The extent to which this practice is favourable depends on many factors related to both plants and nanomaterials. These include the concentration, size, and shape of nanomaterials and species, and other characteristics of plants. NMs modify the expression of genes required for photosynthesis and those involved in responses to oxidative stress. Some of these modifications include downregulation of photosystem II lipoprotein and upregulation of Ferredoxin- NADP reductase, which enhances the stress tolerance by increasing protein content. Epigenetic changes include modifications in histones and DNA methylation, both of which also give the same outcome. Although NMs have evidently modified DNA methylation in animals and humans, their role in plants is rarely understood. Some plants that do support these studies include *Allium cepa, Lepidium sativum,* and tobacco (Chen et al., 2024).

3.5.2 Role of nanobiotechnology in protecting plants against viruses

Silver nanoparticles have been used to free plants from plum pox virus (PPV). This is achieved by treating virus-infected apricot plants with Argovit™. Nanomaterials are cheaper and safer than antiviral drugs. Argovit™ may have a role against other pathogens, but this is still to be proved by further studies. Another approach emerging nowadays is the use of metallic nanoparticles as antimicrobials in agriculture industry. They reduce the severity and duration of symptoms caused by several plant-infecting viruses (Pérez-Caselles et al., 2025).

3.5.3 Improvement of Salt Tolerance in Plants

One of the most important damaging factors to crop yield and quality is salt stress. Nanotechnology is also providing a solution to this problem with the help of a technique known as nano priming. This technique involves combining seedlings or seeds with nanoparticles, and as a result of this, they become resistant to many environmental stresses such as temperature, salt, drought, and greatly improve the germination process. Nanoceria is also known as cerium oxide nanoparticles, and their function is to induce salt tolerance in *Arabidopsis.* When scientists treated nanoceria coated with polyacrylic acid and applied it to *Arabidopsis plants*, the baby plants born were more salt-tolerant than the plants that were left untreated (Li et al., 2025).

3.5.4 Applications of Forest Fungi Nanotechnology

Forest fungi nanotechnology is the branch of nanotechnology that deals with the application of fungi-based nanomaterials. As the name suggests, forest fungi are those that live in forests and play an important role in sustaining the forest ecosystem by managing nutrient provision as well as the degradation process. Incorporation of these organisms with nanotechnology can bring about beneficial changes in many sectors. Fungal nanoparticles can be employed in the detection as well as degradation of environmental pollutants, as they have physical properties conducive to this cause. In the pharmaceutical industry, they help increase patient compliance and reduce adverse effects by controlled release of the active agent. In agriculture industry, fungal nanoparticles greatly improve soil health and nutrient uptake, thus increasing overall productivity from crops. Fungus-based nanotechnology is used in the manufacturing of biofertilizers and biopesticides. In biomedical engineering, these types of nanoparticles have shown great potential for better wound healing, diagnostics, and tissue engineering (Bhandary et al., 2025).

3.6 Potential Risks and Future Prospects of Environmental Nanotechnology

Any technology that is being used has its pros and cons. If any technology has many strengths, then it also has some weaknesses, and we cannot sideline this fact; the same is the case with nanotechnology. Nanotechnology shows lasting consequences and a bad effect on organisms and the environment. So, deeper research and study is required to properly understand the negative outcomes of this technology (Saritha et al., 2022) .

As nanotechnology shows major hazards due to the specific behavior of nanoparticles, scientists are doing more thoughtful evaluations for the sake of public interest. Different organizations are also working to optimize nanotechnology to mitigate risks that cause harm to society (Bottero et al., 2015).

Nanoparticles can be toxic and usually show their toxicity effect when there is a sudden change in their sizes means when the material is broken down into nanoscale. The small nanoparticles could be more dangerous than the corresponding larger parts and protective measures should be taken to minimize the effect. For instance, Asbestos cannot be dangerous when present in macro size, but when it is reduced to nano size can cause cancer of the lungs (Chausali et al., 2023).

In the construction industry, nanoparticles can also show their prolonged effects, and to avoid this problem, we have to ensure that nanomaterials used for this should fulfill international safety criteria for the best interest of people as well as the environment. Due to a lack of research in this regard, the toxicity is still a worry (Firoozi et al., 2025)

Nanotechnology also has a major application in wastewater cleaning, and the technique used for this is nanofiltration, but the high cost and efficiency of the membrane are issues that bring hurdles in the way. In the treatment of papermaking wastewater, more advanced practices are required to get the best results. While inorganic and organic nanoparticles show promising results, more study is required to address their full potential. Increased research is being done on nanotechnology benefits at this time, but no one is too concerned about their drawbacks, so a more focused and thorough evaluation should be done on this (Wu et al., 2017).

Nanotechnology is bringing a great revolution in agriculture industry as well as in the manufacturing of food, but the negative long-term outcomes of nanoparticles raise a big question. The scattering of nanoparticles in soil or the environment is greatly damaging the surroundings, and to combat this issue, protective measures should be taken (RODRÍGUEZ-SEIJO et al., 2025).

Nanopesticides and nanofertilizers have shown encouraging results for crops and pathogens control, but piling up of nanoparticles in plants greatly damages plants' biological functions, including nutrient uptake kinetics, formation of roots, and change is photosynthesis efficiency. The toxicity of nanoparticles is very harmful for the ecosystem as well as for human biological functions (Zhu et al., 2025).

4. Limitations and Future Directions

The current body of research on environmental nanotechnology remains constrained by several critical limitations that hinder its large-scale and safe implementation. One of the foremost challenges is the insufficient understanding of nanoparticle toxicity and long-term ecological impacts, particularly their accumulation in soil, water, and biological systems. Evidence indicates that nanoparticles may disrupt plant physiology, alter nutrient uptake mechanisms, and pose risks to human health through bioaccumulation in food chains. Furthermore, economic and technical barriers—such as the high cost of nanomaterial production, limited efficiency and durability of nanofiltration membranes, and scalability issues—restrict practical deployment, especially in developing regions. The lack of standardized regulatory frameworks and safety assessment protocols further exacerbates uncertainty, creating a gap between laboratory innovation and real-world application.

Future research must adopt a more interdisciplinary and precautionary approach to unlock the full potential of nanotechnology while minimizing its risks. Priority should be given to developing robust, standardized toxicity evaluation methods and lifecycle assessments to better understand the environmental interactions of nanomaterials. Advancements in green nanotechnology, including biodegradable and eco-friendly nanoparticles, offer a promising pathway toward safer applications. In parallel, efforts should focus on improving cost-efficiency and scalability through material innovation and process optimization. Strengthening collaboration among scientists, policymakers, and industry stakeholders will be essential to establishing comprehensive regulatory guidelines and promoting responsible innovation. Ultimately, integrating ethical considerations, environmental monitoring, and public awareness into future research agendas will be key to ensuring that nanotechnology contributes sustainably to global environmental management.

5. Conclusion

Nanotechnology has emerged as a transformative force in addressing some of the most pressing environmental challenges of the 21st century. This review has highlighted its pivotal role in combating climate change through green nanomaterials, enhancing agricultural productivity via nano-fertilizers and nano-pesticides, revolutionizing wastewater treatment with nanocatalysts and nano-adsorbents, and advancing civil engineering through stronger, smarter, and more sustainable materials. The integration of nanotechnology across these sectors offers unparalleled benefits in terms of efficiency, specificity, cost-effectiveness, and ecological sustainability.

However, the widespread adoption of environmental nanotechnology is not without risks. The potential toxicity of nanoparticles, their long-term ecological impacts, and the challenges of scalability and economic feasibility necessitate cautious and responsible implementation. Future research must focus on developing standardized toxicity assessment protocols, promoting interdisciplinary collaborations among material scientists, ecologists, and policymakers as well as enhancing public awareness and regulatory oversight to ensure safe and equitable deployment.

In conclusion, while nanotechnology holds immense promise for building a more sustainable and resilient future, its successful integration into environmental management will depend on a balanced approach that prioritizes both innovation and safety. Through continued research, ethical governance, and global cooperation, nanotechnology can indeed become a cornerstone of sustainable development in the decades to come.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

In the preparation of this article, the authors did not use artificial intelligence (AI) assistance.

Authors' Contributions

Areeba Sagheer and Muhammad Iqbal: conceived the study design and research objectives. Duaa Sagheer and Areesha Sagheer: collected the data. Muhammad Madnee: performed data analysis. Intazar Ali and Nugraha Akbar Nurrochmat: contributed to the interpretation of results. Hussain Ahmed Makki: prepared the figures. Areeba Sagheer and Muhammad Madnee: writing, review and editing. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interests

The authors stated that they had no interest that might be perceived as posing a conflict or bias.

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