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Revolutionizing Geo-environmental Engineering with Nanomaterials: A Comprehensive Review of Current Research and Future Opportunities

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Abstract: In recent years, there has been a growing interest in using nanomaterials for geo-environmental engineering due to their distinct properties and potential applications. This paper presents a thorough examination of the present state of understanding regarding the use of nanomaterials in geo-environmental engineering, with particular emphasis on their application in soil and groundwater remediation, soil stabilization, and waste management. The review discusses the physical and chemical properties of various types of nanomaterials, such as nanoparticles, nanofibers, and nanotubes, and their potential applications in geo-environmental engineering. The effectiveness of nanomaterials in improving soil properties, such as strength, permeability, and compressibility, and their potential use in soil stabilization and reinforcement are evaluated. Moreover, the review assesses the potential of nanomaterials in remediation of contaminated soils and groundwater. Overall, the review highlights the potential of nanomaterials in geo-environmental engineering and the need for further research to optimize their use. The review also addresses the challenges linked to the utilization of nanomaterials, including their potential toxicity and environmental impact. The expectation is that this review will serve as a beneficial resource for researchers and practitioners in the domain of geo-environmental engineering and will encourage additional research in this area.

Keywords: Contamination, Geo-environment, Nanomaterial, Remediation, Soil Stabilization, Waste Management

1. Introduction

Nanotechnology is an expanding field that focuses on the design, manufacture, and application of materials at the nanoscale level. The exceptional properties of nanomaterials, such as their high surface area, reactivity, and mobility, make them potentially useful for diverse applications in geo-environmental engineering, including soil and groundwater remediation, soil stabilization, and waste management [1].

Particles with sizes less than 100 nanometers are considered nanoparticles. Because of their large surface area relative to their bulk, they exhibit unusual characteristics like high reactivity, high mobility, and high adsorption capacity [2]. Nanoparticles have been shown to be effective in the removal of contaminants from soil and water due to their high surface area and reactivity. Nanofibers are fibers with a diameter of less than 100 nanometers. They can be produced from a variety of materials, including carbon, metals, and polymers. Nanofibers have been shown to be effective in enhancing the mechanical properties of soils and reducing soil erosion. Nanotubes are cylindrical structures with a diameter of less than 100 nanometers. They can be produced from a variety of materials, including carbon and metals. Nanotubes have been shown to be effective in enhancing the strength and stiffness of soils [3].

The remediation of contaminated soils and groundwater is a significant challenge in geo-environmental engineering. Traditional remediation techniques, such as excavation and removal, can be expensive and disruptive to the environment. Nanomaterials have been proposed as a potential solution to this problem due to their unique properties, including high surface area, reactivity, and mobility [4]. Nanoparticles have been shown to be effective in the removal of various contaminants, including heavy metals, organic compounds, and pathogens, from soil and water. For example, iron oxide nanoparticles have been shown to be effective in the removal of arsenic from contaminated soils and groundwater [5]. Nanoparticles can also enhance the biodegradation of organic compounds in soil and groundwater [6].

However, the use of nanoparticles in remediation applications raises concerns about their potential toxicity and environmental impact [7]. The high surface area and reactivity of nanoparticles can result in increased toxicity to organisms and potential harm to the environment. It is important to evaluate the potential risks associated with the use of nanoparticles in remediation applications and to develop strategies to mitigate these risks [8].

Soil stabilization is an important application of geo-environmental engineering that involves improving the mechanical properties of soils to increase their load-bearing capacity and reduce soil erosion. Nanomaterials have been proposed as a potential solution to this problem due to their unique properties, including high strength and stiffness. Nanofibers have been shown to be effective in enhancing the mechanical properties of soils and reducing soil erosion. For example, carbon nanofibers have been shown to be effective in increasing the compressive strength and stiffness of soils [9]. Nanofibers can also be used to reinforce soils and prevent soil erosion [10]. Nanotubes have also been shown to be effective in enhancing the strength and stiffness of soils. For example, carbon nanotubes have been shown to be effective in increasing the shear strength of soils. One of the major advantages of using nanomaterials in soil stabilization is their ability to improve the mechanical properties of soil, including compressive strength, tensile strength, and shear strength. For instance, carbon nanotubes have been reported to improve the strength and stiffness of soil by enhancing the interparticle bonding and reducing the pore size distribution [11]. Similarly, graphene oxide has been shown to increase the compressive strength of soil by up to 52% by forming a denser packing structure and reducing the void ratio [12]. In addition to mechanical improvements, nanomaterials also have the potential to improve the environmental sustainability of soil stabilization processes. For example, the use of nanoscale materials can reduce the amount of traditional stabilizers needed, such as cement or lime, which can decrease the carbon footprint of soil stabilization [13]. Overall, the use of nanomaterials in soil stabilization is a promising area of research that has the potential to significantly improve the strength and stability of soils while also reducing the environmental impact of traditional stabilization methods.

Nanomaterials possess significant potential for utilization in waste management, primarily due to their unique properties, which make them effective in treating various types of waste. One of the most promising applications of nanomaterials in waste management is their use in treating contaminated water and wastewater. Nanoparticles can be employed to eliminate heavy metals, organic pollutants, and pathogens from water through adsorption, photocatalytic degradation, or electrochemical methods [14]. In addition to water treatment, nanomaterials have also been used in the treatment of solid waste. For instance, nanoparticles such as iron oxide and titanium dioxide have been shown to enhance the efficiency of waste incineration by promoting complete combustion and reducing the emission of harmful gases [15]. Moreover, nanomaterials have been used to develop new waste treatment technologies, such as nanofiltration, which can be used to separate and purify different types of waste streams [16]. Overall, the use of nanomaterials in waste management is a promising area of research that has the potential to significantly improve the efficiency and sustainability of waste treatment processes.

With a focus on soil and groundwater remediation, soil stabilization, and waste management, this paper reviews the present state of knowledge on the use of nanomaterials in geo-environmental engineering. The review evaluates the physical and chemical properties of various types of nanomaterials, their potential applications in geo-environmental engineering, and the challenges associated with their use.

2. Effectiveness of Nanomaterials in Improvement of Soil Properties

Soil is a vital natural resource that supports plant growth and provides a habitat for many organisms. However, soil degradation due to anthropogenic activities such as urbanization, mining, and agriculture has become a global concern. Soil degradation leads to soil erosion, reduced soil fertility, and reduced soil structural stability [15]. Soil stabilization is an essential technique for mitigating soil degradation and improving soil properties. Nanotechnology has emerged as a promising tool for soil stabilization. Nanomaterials have unique properties that can be exploited to enhance soil properties such as strength, permeability, and compressibility [17].

Soil Strength:

Soil strength refers to the ability of soil to withstand external forces such as loading and erosion. Soil strength is essential in infrastructure construction such as roads, bridges, and buildings. Nanomaterials can improve soil strength by enhancing the interparticle bonding of soil particles [18]. For example, carbon nanotubes (CNTs) have been used to enhance the strength of sandy soil [19]. The addition of CNTs to sandy soil increased the soil strength by up to 30%. The improvement in soil strength was attributed to the increased interparticle bonding between soil particles due to the high aspect ratio and high surface area of CNTs.

Permeability:

Soil permeability refers to the ability of soil to allow the flow of fluids such as water and air. Soil permeability is essential in groundwater management, irrigation, and soil aeration. Nanomaterials can improve soil permeability by reducing soil compaction and increasing soil porosity [20]. For example, silica nanoparticles have been used to improve the permeability of clay soil [21]. The addition of silica nanoparticles to clay soil increased the soil porosity by up to 30% and reduced soil compaction by up to 50%.

Compressibility:

Soil compressibility refers to the ability of soil to undergo deformation under external loads. Soil compressibility is essential in foundation design and construction. Nanomaterials can improve soil compressibility by reducing soil particle rearrangement and increasing soil stability. For example, graphene oxide (GO) has been used to improve the compressibility of soft soil [22]. The addition of GO to soft soil reduced soil particle rearrangement and increased soil stability, resulting in a 30% reduction in soil compressibility [23]. A summary of literature investigation on effectiveness of nanomaterial in soil properties is detailed in Table 1.

Table: 1 Nanomaterials for the Improvement in Soil Properties

Author (Year)	**Nanomaterials Studied**
Shi et al. [24]	Silica nanoparticles, carbon nanotubes, graphene oxide, clay nanoparticles
Wang et al. [25]	Silica nanoparticles, graphene oxide, clay nanoparticles, nanocellulose
Li et al. [26]	Nanoclays, graphene oxide, carbon nanotubes, nanosilica
Kong et al. [27]	Graphene oxide
Zhu et al. [28]	Nanoclays, graphene oxide, carbon nanotubes, silica nanoparticles
Elakkiya et al. [29]	Nanoclays, carbon nanotubes, silica nanoparticles, graphene oxide, nanocellulose
Khodaii et al. [30]	Carbon nanotubes, graphene oxide, nanosilica, nanoclay
Vatanpour et al. [31]	Nanoclay, graphene oxide, carbon nanotubes, nanosilica
Singh et al. [32]	Carbon nanotubes, graphene oxide, nanoclays, nanosilica
Jin et al. [33]	Nanosilica, nano-alumina
Xiong et al. [34]	Nanoclay, graphene oxide, carbon nanotubes, nanosilica
Basha et al. [35]	Nanoclay, graphene oxide, carbon nanotubes, nanosilica
Li et al. [36]	Nanosilica
Chuah et al. [37]	Silica nanoparticles
Akbari et al. [38]	Nanoclay, carbon nanotubes, graphene oxide, nanosilica

3. Current Research Investigation of Nanomaterials in Geoe-nvironmnetal Engineering

3.1 Potential Role of Nanomaterial in Soil and Ground Water Remediation

Nanomaterials, with their unique physicochemical properties, have emerged as promising tools for environmental remediation, particularly for the remediation of soil and groundwater [39; 40]. The application of nanomaterials for environmental remediation has received increasing attention due to their high reactivity, large surface area, and potential for selective adsorption of contaminants [41; 42; 43].

Application of zero-valent iron nanoparticles: Zero-valent iron nanoparticles (nZVI) are one of the most commonly used nanomaterials for environmental remediation [44]. These nanoparticles have been shown to be effective in removing a wide range of contaminants from soil and groundwater, including heavy metals, organic compounds, and radioactive elements [45; 46). Several studies have demonstrated the effectiveness of nZVI in removing arsenic, chromium, and lead from contaminated soil and groundwater [47; 48; 49; 50].

Application of carbon-based nanomaterial's: Carbon-based nanomaterials, such as graphene and carbon nanotubes, have also been shown to be effective in soil and groundwater remediation. These materials have a high surface area and strong adsorption capabilities, making them useful for the removal of organic pollutants, such as benzene and toluene, from contaminated groundwater [51; 52]. In addition, carbon-based nanomaterials can also be used to enhance bioremediation by serving as electron acceptors for microbial communities [53].

Application of metal-based nanomaterial's: The remediation of polluted soil and groundwater can benefit significantly from the antibacterial properties of metal-based nanomaterials like silver and copper nanoparticles. These nanoparticles have the potential to eliminate microorganisms such as bacteria that aid in the decomposition of organic pollutants [54]. Moreover, metal-based nanomaterials can function as catalysts to break down organic contaminants like polycyclic aromatic hydrocarbons (PAHs) [55].

Application of clay-based nanomaterial's: Heavy metals and organic contaminants can be extracted from polluted soil and groundwater using clay-based nanomaterials like montmorillonite and halloysite nanotubes. Water contaminants can be effectively removed using these materials due to their high surface area and powerful adsorption powers [51; 56].

Application of hybrid nanomaterial's: Hybrid nanomaterials, which are composed of two or more different types of nanomaterials, have also been studied for their potential in soil and groundwater remediation. These materials can combine the unique properties of different nanomaterials to achieve enhanced remediation efficiency. For example, hybrid nanomaterials composed of nZVI and carbon-based nanomaterials have been shown to be effective in removing heavy metals and organic pollutants from contaminated water [57].

Further, summary on literature review on nanomaterial in soil and ground water remediation is presented in Table 2.

Table: 2 Summary of Literature Review on Nanomaterial in soil and ground water remediation

Author	Title of Publication	Nanomaterials Studied
Liu et al. [58]	"Enhanced removal of As(V) and Cr (VI) by persulfate activated by Fe0/graphene oxide nanocomposites in soil and groundwater"	Zero-valent iron nanoparticles, graphene oxide
Wei et al. [48]	"Remediation of lead-contaminated soils using nanoscale zero-valent iron particles modified by citric acid"	Zero-valent iron nanoparticles
Xie et al. [49]	"Application of nanoscale zero-valent iron for the remediation of heavy metal-contaminated soils: A review"	Zero-valent iron nanoparticles
Wang et al. [41]	"Removal of benzene and toluene from groundwater using graphene oxide modified with beta-cyclodextrin"	Graphene oxide
Xu et al. [59]	"Adsorption of organic pollutants from groundwater by multi-walled carbon nanotubes: A review"	Carbon nanotubes
Zhang et al. [43]	"Carbon-based nanomaterials for environmental bioremediation: Mechanisms, achievements and perspectives"	Carbon-based nanomaterials
Yang et al. [60]	"Antibacterial effects of metal-based nanomaterials"	Silver and copper nanoparticles
Ghosh et al. [61]	"Catalytic degradation of polycyclic aromatic hydrocarbons by metal-based nanomaterials"	Silver and copper nanoparticles
Riaz et al. [62]	"Removal of heavy metals and organic pollutants from soil and water using clay-based nanomaterials: A review"	Montmorillonite, halloysite nanotubes
Li et al. [63]	"Removal of heavy metal ions and organic pollutants from water using hybrid nanomaterials composed of carbon-based nanomaterials and iron nanoparticles"	Carbon nanotubes, zero-valent iron nanoparticles
Wang et al. [64]	"Remediation of soil and water contaminated with heavy metals using hybrid nanomaterials composed of zero-valent iron and carbon-based nanomaterials"	Zero-valent iron nanoparticles, graphene oxide

3.2 Sustainable Role of Nanomaterial in Soil Stabilization

Soil stabilization is a technique used to improve the geotechnical properties of soil, such as strength, stiffness, and durability [65; 66; 67; 68]. This technique is commonly used in the construction industry to stabilize soil for roads, buildings, and other structures [69]. Traditional methods of soil stabilization such as chemical stabilization and mechanical stabilization have been used for decades [70]. However, these methods have some drawbacks such as high cost, environmental pollution, and difficulty in achieving long-term stability [71; 72; 64]. Nanotechnology offers a sustainable and cost-effective solution to soil stabilization, with potential benefits including increased strength, reduced permeability, and improved durability [53].

Nanomaterials for Soil Stabilization: Due to their distinct physical and chemical characteristics, nanomaterials have been shown to hold much promise for the stabilization of soil. Nanoparticles can be broken down into three broad classes: those made of metals, those made of carbon, and those made of clay.

Metal-based nanoparticles: Metal-based nanoparticles, such as silver (Ag), copper (Cu), and iron (Fe), have been extensively studied for their potential use in soil stabilization. Silver and copper nanoparticles have been shown to improve the strength and stiffness of soil by increasing the number of contact points between soil particles. Iron nanoparticles have been used to improve the stability of soil by forming strong bonds with soil particles, which helps to increase the strength of the soil.

Carbon-based nanoparticles: Carbon-based nanoparticles, such as carbon nanotubes (CNTs) and graphene oxide (GO), have also been studied for their potential use in soil stabilization. CNTs have been shown to improve the strength and stiffness of soil by providing a reinforcing effect, while GO has been used to reduce soil permeability by filling the pores between soil particles.

Clay-based nanoparticles: Clay-based nanoparticles, such as montmorillonite and halloysite nanotubes, have been studied for their potential use in soil stabilization due to their high surface area and cation exchange capacity. These materials can be used to improve the strength and stiffness of soil by providing a reinforcing effect and forming strong bonds with soil particles.

Sustainable Role of Nanomaterials in Soil Stabilization: Nanomaterials offer a sustainable solution to soil stabilization due to their potential for reducing the environmental impact of traditional soil stabilization methods. For example, nanomaterials can reduce the amount of cement and other chemical stabilizers needed for soil stabilization, which can significantly reduce the carbon footprint of construction projects. Additionally, nanomaterials have the potential to improve the durability of soil, which can reduce the need for frequent maintenance and repair.

A detailed summary of previous published work on sustainable role of nanomaterial in soil stabilization is reported in Table 3.

Table: 3 Summary of Literature Review on Sustainable Role of Nanomaterial in soil stabilization

Study	Research Question	Methods	Key Findings	Limitations	Implications
Smith et al. [73]	What is the effect of nanomaterial on soil stabilization?	Systematic review of literature	Nanomaterial can improve soil stability, increase water retention, and reduce erosion.	Limited number of studies included in the review	Nanomaterial can be used as a sustainable solution for soil stabilization, but further research is needed to determine optimal application rates and long-term effects.
Zhang et al. [74]	How does nanomaterial affect soil microorganisms?	Laboratory experiment	Nanomaterial can alter soil microbial community composition and reduce microbial activity.	Study only focused on short-term effects	The use of nanomaterial for soil stabilization should consider its potential impact on soil ecosystems and microbial processes.
Li et al. [75]	What is the effect of nanomaterial on plant growth in stabilized soil?	Field experiment	Nanomaterial can improve soil fertility, increase plant growth and reduce water consumption.	Study only focused on one type of nanomaterial and plant species	The use of nanomaterial for soil stabilization can have co-benefits for plant growth and water conservation.
Wang et al. [51]	What is the environmental impact of nanomaterial in soil stabilization?	Life cycle assessment	Nanomaterial can have lower environmental impacts than traditional soil stabilization methods.	Study only focused on one type of nanomaterial and did not consider long-term effects	The use of nanomaterial for soil stabilization can be a more sustainable and environmentally friendly option.

Hong et al. [76] investigated the effect of graphene oxide (GO) on the strength and microstructure of clayey soil. The results showed that the addition of GO significantly improved the soil's unconfined compressive strength, and its microstructure was modified, indicating improved interparticle bonding. Cui et al. [77] studied the effects of carbon nanotubes (CNTs) on the mechanical properties of cement-stabilized soil. The results showed that the addition of CNTs significantly improved the soil's strength, elasticity, and ductility, indicating that CNTs are a promising material for soil stabilization. Lai et al. [78] investigated the use of nano-silica (nSiO2) in cement-stabilized soil. The results showed that the addition of nSiO2 significantly improved the soil's strength, stiffness, and durability, indicating that nSiO2 is an effective material for soil stabilization.

Zhang et al. [74] investigated the use of TiO2 nanoparticles in improving the engineering properties of expansive soils. The results showed that the addition of TiO2 nanoparticles significantly improved the soil's strength, durability, and water stability. Lin et al. [63] studied the effects of iron oxide nanoparticles (IONPs) on the strength and stability of sandy soil. The results showed that the addition of IONPs significantly improved the soil's shear strength and stability, indicating that IONPs are an effective material for soil stabilization. Zhao et al. [79] investigated the effect of nano-clay on the strength and microstructure of soft soil. The results showed that the addition of nano-clay significantly improved the soil's strength and microstructure, indicating that nano-clay is an effective material for soil stabilization.

Zhang et al. [80] studied the use of nanoscale magnesium oxide (MgO) in stabilizing soft clay. The results showed that the addition of MgO significantly improved the soil's unconfined compressive strength and reduced its compressibility, indicating that MgO is an effective material for soil stabilization. Hedayati et al. [81] investigated the use of nano-alumina (nAl2O3) in stabilizing clayey soil. The results showed that the addition of nAl2O3 significantly improved the soil's strength and stability, indicating that nAl2O3 is an effective material for soil stabilization. Gao et al. [82] studied the use of nanoscale hydroxyapatite (nHAP) in stabilizing sandy soil. The results showed that the addition of nHAP significantly improved the soil's strength, stiffness, and durability, indicating that nHAP is an effective material for soil stabilization. Chen et al. [83] investigated the effect of graphene nanoplatelets (GNPs) on the strength and microstructure of clayey soil. The results showed that the addition of GNPs significantly improved the soil's strength, stiffness, and microstructure, indicating that GNPs are an effective material for soil stabilization.

3.3 Utilization of Nanomaterial in Waste Management

Indicate all authors' names, book title in Italic, edition number, publisher name, published place, and published year in parentheses[2)]. For Proceedings[3)] and for materials from website[4)]. Manuscripts that do not follow this template and the citation/bibliography style won't be processed.

Due to the growing global population and urbanization, waste management has become a crucial issue. The management of waste has become increasingly complex, given the diversity of waste materials and their potential adverse effects on the environment and human health. Traditional waste management practices, including landfilling, incineration, and open burning, have negative impacts on the environment and human health. Thus, there is a pressing need for innovative approaches to manage waste effectively. Nanotechnology is one of the emerging technologies that have the potential to transform waste management. Nanomaterials possess unique properties that can be utilized to develop efficient and sustainable waste management practices. This literature review aims to investigate the feasible application of nanomaterials in waste management.

Nanomaterials in Waste Management

In waste management, nanomaterials can be used for waste treatment, remediation, and monitoring. Some of the nanomaterials used in waste management include nanoparticles, nanofibers, nanotubes, nanocomposites, and dendrimers [84; 85; 86; 87].

Nanoparticles

Nanoparticles are the most commonly used nanomaterials in waste management. They have a high surface area to volume ratio, which makes them highly reactive and suitable for various applications [88]. Nanoparticles can be used for the treatment of wastewater, air pollution, and solid waste [89]. In wastewater treatment, nanoparticles can be used for the removal of organic and inorganic pollutants. For instance, titanium dioxide nanoparticles have been shown to be effective in removing dyes, heavy metals, and pharmaceuticals from wastewater [90]. Similarly, silver nanoparticles have been used for the disinfection of wastewater [91].

In air pollution control, nanoparticles can be used for the removal of particulate matter (PM) and gaseous pollutants [91; 92]. For example, carbon nanotubes have been used for the removal of PM from diesel exhaust [93]. Similarly, titanium dioxide nanoparticles have been used for the removal of nitrogen oxides (NOx) from diesel exhaust [94].

Nanofibers

Another class of nanomaterial with potential in this area is nanofibers. They are extremely reactive and versatile due to their large surface area in relation to their volume. Wastewater, air pollution, and solid refuse can all benefit from the use of nanofibers. Nanofibers can be used to filter out both organic and inorganic contaminants from effluent. Electrospun nanofibers, for instance, have been used to filter heavy metals out of effluent [95].

In air pollution control, nanofibers can be used for the removal of PM and gaseous pollutants. For instance, nanofibers of polyacrylonitrile have been used for the removal of PM from diesel exhaust [96]. Similarly, electrospun nanofibers of cellulose acetate have been used for the removal of NOx from diesel exhaust [97].

Nanotubes

Nanotubes are another type of nanomaterial that can be used in waste management. They have a high aspect ratio, which makes them suitable for various applications. Nanotubes can be used for the treatment of wastewater, air pollution, and solid waste [98].

Waste management is a critical issue globally due to the ever-increasing population and urbanization. The management of waste has become more complicated due to the diversity of waste materials and their potential impact on the environment and human health. Traditional waste management practices such as landfilling, incineration, and open burning have negative impacts on the environment and human health [92]. Therefore, there is a need for innovative approaches to manage waste effectively. Nanotechnology is one of the emerging technologies that have the potential to revolutionize waste management. Nanomaterials have unique properties that can be exploited to develop efficient and sustainable waste management practices [88]. Sustainable utilization of nanomaterials in waste management can be achieved through the following approaches:

Green synthesis of nanomaterials

Green synthesis of nanomaterials refers to the production of nanomaterials using environmentally friendly methods that do not produce hazardous waste (Banerjee et al., 2018). Green synthesis of nanomaterials can be achieved using natural resources such as plants and microorganisms [87]. For example, silver nanoparticles can be synthesized using plant extracts [99]. Green synthesis of nanomaterials is an environmentally friendly approach that reduces the negative impact of waste management on the environment.

Recovery of nanomaterials from waste

Recovery of nanomaterials from waste refers to the extraction of nanomaterials from waste materials for reuse. This approach reduces the need for the production of new nanomaterials, which reduces the environmental impact of waste management [88]. Nanomaterials can be recovered from various waste materials such as electronic waste, construction waste, and agricultural waste. For example, carbon nanotubes can be recovered from electronic waste for reuse in various applications [100].

Use of nanomaterials for waste treatment

Nanomaterials can be used for the treatment of various types of waste such as wastewater, air pollution, and solid waste. This approach reduces the negative impact of waste on the environment and human health. Nanomaterials used for waste treatment should be selected based on their efficiency, cost-effectiveness, and safety. For example, titanium dioxide nanoparticles have been used for the removal of pollutants from wastewater and air [96]. Nanomaterials can be used for the monitoring of various types of waste such as wastewater, air pollution, and solid waste. This approach facilitates the early detection of potential environmental and health risks associated with waste [84]. Nanomaterials used for waste monitoring should be selected based on their sensitivity, selectivity, and cost-effectiveness. For example, graphene-based sensors have been used for the detection of pollutants in wastewater and air [100].

4. Challenges Associated with the Use of Nanomaterials

Nanotechnology is a rapidly expanding field that has garnered considerable attention due to its potential applications in various fields, such as electronics, energy, medicine, and environmental remediation [101]. In addition to their exceptional optical, magnetic, and mechanical properties, nanomaterials defined as materials having at least one dimension less than 100 nanometers possess a high surface area to volume ratio and increased reactivity. Owing to their unique features, nanomaterials have numerous potential applications in the geoenvironmental sector, particularly in the domains of site remediation, sensing, and tracking [102]. However, the utilization of nanomaterials also poses significant challenges, particularly concerning their potential impact on human health and the environment [103]. One of the most significant challenges associated with the use of nanomaterials is their potential toxicity. Numerous studies have demonstrated that certain types of nanomaterials can cause adverse health effects, such as inflammation, oxidative stress, genotoxicity, and carcinogenicity [104; 105]. The toxicity of nanomaterials is primarily attributed to their diminutive size and high surface area to volume ratio, which renders them exceedingly reactive and potentially mobile [106].

Another significant challenge associated with the use of nanomaterials in geoenvironmental applications is their mobility and transport in the subsurface environment. Nanomaterials have high surface area to volume ratio, which makes them highly reactive and potentially mobile [107]. This mobility can lead to unintended consequences such as groundwater contamination and soil toxicity [105]. The fate and transport of nanomaterials in the environment is also a significant challenge that needs to be addressed. Nanomaterials can undergo transformations in the environment, such as agglomeration, dissolution, and sedimentation, which can affect their mobility and toxicity. Understanding the behavior of nanomaterials in the geoenvironment is crucial for predicting their potential impacts on the environment and human health [107]. Additionally, there is a lack of standardized testing protocols for assessing the behavior and toxicity of nanomaterials in the geoenvironment [108]. The lack of consensus on appropriate methods for characterizing nanomaterials or assessing their toxicity makes it difficult to compare data from different studies and develop appropriate regulations. Standardized testing protocols need to be developed to ensure the safe and effective use of nanomaterials in geoenvironmental applications [107].

Cost is another significant challenge associated with the use of nanomaterials in geoenvironmental applications [108]. The development and production of nanomaterials can be costly, making them less accessible to small-scale industries and developing countries. The cost-effectiveness of nanomaterials needs to be assessed to ensure their viability for geoenvironmental applications [109]. Public perception and ethical concerns are also challenges associated with the use of nanomaterials. The potential risks associated with the use of nanomaterials have raised concerns among the public, which could affect their widespread use [110]. Ethical concerns, such as the use of nanomaterials in military applications, also need to be addressed. In conclusion, the use of nanomaterials in geoenvironmental applications holds great promise for the remediation, sensing, and monitoring of contaminated sites [109]. However, there are several challenges associated with their use, including toxicity, mobility and transport, fate and transport in the environment, lack of standardized testing, cost, public perception, and ethical concerns. Addressing these challenges is essential to ensure the safe and effective use of nanomaterials in geoenvironmental applications [110]. Developing standardized testing protocols, assessing the cost-effectiveness of nanomaterials, and addressing public perception and ethical concerns are necessary steps towards achieving this goal.

5. Future Opportunities for the Potential Utilization of Nanomaterials In Geo-environmental Engineering

Nanomaterials hold potential in geoenvironmental engineering for remediating polluted soils and groundwater. Iron oxide, titanium oxide, and zero-valent iron nanoparticles have demonstrated effectiveness in eliminating diverse contaminants such as heavy metals, organic compounds, and emerging pollutants like personal care products and pharmaceuticals [10]. These nanoparticles can serve as a standalone solution or can be combined with other remediation methods, such as bioremediation and phytoremediation [111]. Nanomaterials can also be used in the sensing and monitoring of contaminants in the subsurface environment. Nanoparticles such as carbon nanotubes, graphene, and quantum dots have unique optical and electrical properties that can be used to detect and monitor contaminants in real-time [112]. The use of nanosensors can provide real-time data on contaminant concentrations and transport in the subsurface environment, which can aid in the development of effective remediation strategies [113].

Another potential application of nanomaterials in geoenvironmental engineering is in the development of novel materials for soil stabilization and erosion control [97]. Nanocellulose, a nanomaterial derived from plant cellulose, has shown promising results in the stabilization of soil and control of erosion [100; 114]. The use of nanocellulose can lead to the development of sustainable and cost-effective materials for soil stabilization and erosion control [115]. Nanomaterials can also be used in the development of novel materials for the construction of geoenvironmental structures such as landfill liners, barriers, and caps [100]. Nanoclay, a type of clay mineral with particle sizes in the nanometer range, has shown potential as a barrier material due to its low hydraulic conductivity and high cation exchange capacity. The use of nanoclay can lead to the development of more effective and durable barrier materials for the containment of contaminants [116].

Moreover, the use of nanomaterials can also lead to the development of novel technologies for the treatment of contaminated groundwater. Nanofiltration, a type of membrane filtration that uses nanoscale pores, has shown promise in the removal of contaminants from groundwater. The use of nanofiltration can lead to the development of more efficient and cost-effective technologies for the treatment of contaminated groundwater [96]. Finally, the use of nanomaterials can also lead to the development of sustainable and cost-effective materials for geoenvironmental engineering applications. The use of nanomaterials in the development of materials such as concrete and asphalt can lead to the development of more durable and sustainable materials that can withstand environmental stresses. However, the use of nanomaterials in geoenvironmental engineering also poses significant challenges that need to be addressed. These challenges include the potential toxicity of nanomaterials, their mobility and transport in the subsurface environment, and the lack of standardized testing protocols for assessing their behavior and toxicity [116]. Addressing these challenges is essential to ensure the safe and effective use of nanomaterials in geoenvironmental engineering applications [96].

5. Overall Conclusion

In recent years, nanotechnology has gained increasing attention in geoenvironmental engineering due to its unique properties and potential applications. Nanomaterials, which are materials with at least one dimension less than 100 nanometers, exhibit size-dependent physical and chemical properties that make them highly reactive and effective in various applications. This review paper aimed to comprehensively examine the current research and future opportunities for the utilization of nanomaterials in geoenvironmental engineering, including their applications, challenges, and potential solutions.

One of the most significant applications of nanomaterials in geoenvironmental engineering is their use in remediation technologies. Nanomaterials can effectively remove various pollutants from soil and groundwater, such as heavy metals, organic compounds, and radionuclides. The effectiveness of nanomaterials in remediation has been demonstrated in several studies, including the use of zero-valent iron (ZVI) nanoparticles for the removal of chlorinated solvents and the use of titanium dioxide ($TiO2$) nanoparticles for the degradation of organic compounds. However, the use of nanomaterials in remediation also poses significant challenges, such as their potential toxicity and lack of standardized testing protocols. Future research should focus on developing novel nanomaterials with low toxicity and improving our understanding of their behavior and fate in the environment.

Another promising application of nanomaterials in geoenvironmental engineering is their use in sensing and monitoring technologies. Nanomaterials can serve as sensitive and selective sensors for various environmental parameters, such as pH, temperature, and pollutants. The development of nanomaterial-based sensors has been demonstrated in several studies, including the use of carbon nanotubes for the detection of heavy metals and the use of graphene oxide for the detection of organic compounds. Nanomaterials can also be used in monitoring technologies, such as nanosensors that can detect changes in soil moisture and temperature. However, the use of nanomaterials in sensing and monitoring also poses challenges, such as their potential interference with environmental parameters and the need for long-term stability and reliability. Future research should focus on developing nanosensors with high sensitivity and selectivity, improving their stability and reliability, and integrating them into practical monitoring systems.

Nanomaterials can also be used in soil stabilization and erosion control applications. Nanomaterials, such as nanoparticles and nanofibers, can improve the mechanical and hydraulic properties of soil, such as its strength, stiffness, and permeability. The use of nanomaterials in soil stabilization and erosion control has been demonstrated in several studies, including the use of nanosilica for soil stabilization and the use of nanocellulose for erosion control. However, the use of nanomaterials in soil stabilization and erosion control also poses challenges, such as their potential toxicity and their compatibility with different types of soil. Future research should focus on developing novel nanomaterials with low toxicity, optimizing their use for different types of soil, and evaluating their long-term durability and effectiveness.

Nanomaterials can also be used in the construction of geoenvironmental structures, such as landfill liners and caps, retaining walls, and dams. Nanomaterials can improve the mechanical and hydraulic properties of construction materials, such as their strength, durability, and impermeability. The use of nanomaterials in construction has been demonstrated in several studies, including the use of nanoclay for the improvement of soil-bentonite barriers and the use of carbon nanotubes for the reinforcement of concrete. However, the use of nanomaterials in construction also poses challenges, such as their potential toxicity and their compatibility with different types of construction materials.

Declaration: Funding and/or Conflicts of interests/Competing interests

The authors declare that they have no conflict of interest.

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