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Source: Air, Soil and Water Research, 18(1)

Published By: SAGE Publishing

URL: https://doi.org/10.1177/11786221241311725

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Air, Soil and Water Research
Volume 18: 1–13

DOI: 10.1177/11786221241311725
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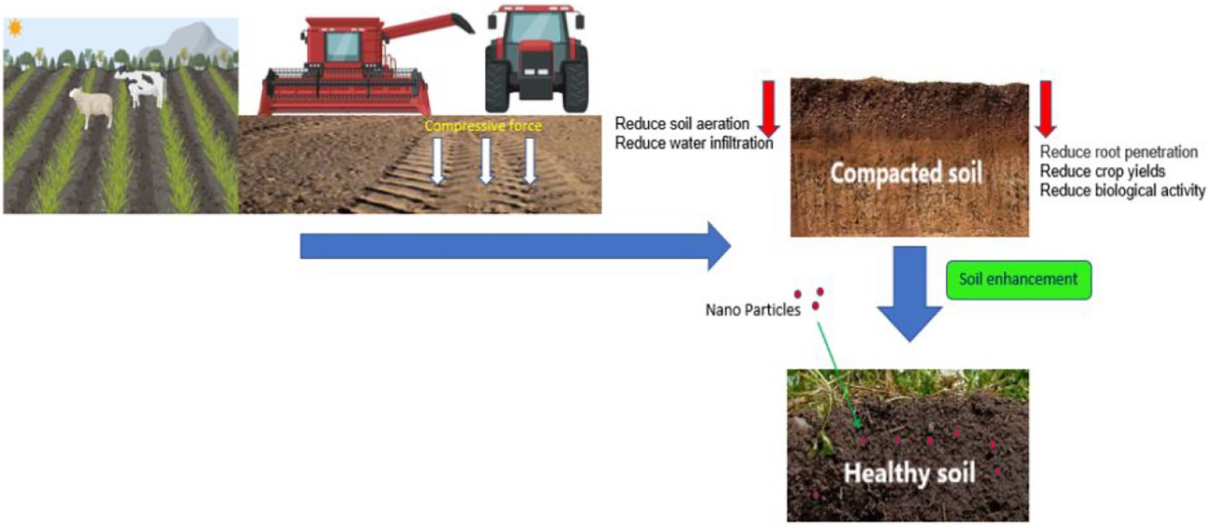
ABSTRACT: Rapid population growth and increased use of agricultural technology have exacerbated agrarian problems. While mechanization has improved agricultural production, the use of heavy machinery for planting, irrigation, and harvesting has resulted in soil compaction. Soil compaction reduces pore space and increases soil bulk density, which hinders plant growth. Globally, automated agriculture has reduced crop production by more than 50%. In developing countries, grazing animals in crop fields increases soil compaction. Soil compaction hinders root penetration, nutrient absorption, and water infiltration, increasing the risk of soil erosion and runoff. The study investigates novel ways to reduce soil compaction, namely the utilization of nanoparticles (NPs) and nanotechnology (NT). NPs have unique qualities that can improve the mechanical properties of soil, increase its strength, and minimize compaction. Some of the NPs such as Carbon nanotubes, nanolites, nanosilica, and nanoclay have been demonstrated to increase soil fertility, water retention, and structural stability. NPs can reduce environmental pollutants while improving soil quality. However, questions about their long-term biodegradability, ecological toxicity, and health effects require further investigation. The study also addressed how NPs affect the environment and human health. Their small size raises concerns about potential exposure and toxicity to individuals and ecosystems. The paper also briefly discusses the economic and regulatory considerations related to the production, use, and disposal of NPs, emphasizing the need for comprehensive legislation, environmental impact studies, and stakeholder involvement in decision-making. Although NPs offer promise for sustainable agriculture practices, more research is necessary to optimize their use and ensure long-term safety, as well as to gain a better understanding of their unique interactions with soil physics.

KEYWORDS: Soil compaction, nanoparticles, nanotechnology, soil fertility, sustainability

Graphical abstract



(Some icons created in BioRender. Alkhaza'leh, H. (2024) https://BioRender.com/b61r626)

RECEIVED: August 15, 2024. **ACCEPTED:** December 17, 2024.

TYPE: Review Article

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Introduction

The rapid growth of the world's population, combined with climate change and changes in land use, has placed significant pressure on soil, water, and agricultural systems (Food and Agriculture Organization of the United Nations, 2017; Youssef et al., 2024; Weiberg et al., 2021). Soil compaction has emerged as a major concern affecting agricultural production and sustainability. This issue, largely attributed to increased mechanization in agricultural practices, has been shown to lead to significant loss of arable land. A recent study found that severe soil compaction can result in crop yield losses of 50% or more, depending on the level of compaction (Shaheb et al., 2021).

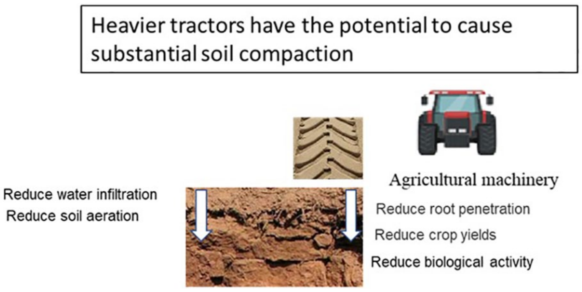

Figure 1. Soil compaction due to agricultural machinery impact (Some icons created in BioRender. Alkhaza'leh, H. (2024) https://BioRender.com/b61r626).

To address the challenges in the agricultural sector and ensure food security, it is crucial to employ innovative measures to enhance soil health and reduce the negative impacts of soil compaction. The use of soil amendments has been identified as an effective method for improving soil porosity and reducing compaction (Gupta et al., 2023; Rashmi et al., 2024). Additionally, soil amendments play a significant role in enhancing irrigation water use efficiency (Ferretti et al., 2024) and increasing overall soil productivity (Mali et al., 2020; Shukla et al., 2024). The mechanisms of amendments work by increasing the pore space and reducing the bulk density of the soil. However, this issue is worsened by the frequent use of agricultural machinery during tillage, irrigation, and harvesting (Pitla et al., 2016; Figure 1), ultimately leading to reduced crop yields (Yu et al., 2024). Additionally, in many developing countries, soil compaction is intensified by the weight of grazing animals rather than mechanization (Bertonha et al., 2015). Soil compaction hinders root penetration and nutrient uptake, resulting in poor crop growth and loss of yield (de Moraes et al., 2020; Yu et al., 2024).

Soil compaction has effects beyond reducing agricultural production. It reduces infiltration rates, increasing the risk of runoff and soil erosion (Alam et al., 2017). Traditional soil amendments such as organic farm wastes, lime, and gypsum have contributed to improving soil health and agricultural production. However, recent developments in nanotechnology (NT) offer a promising path to overcome the challenges facing the agricultural sector and soil by increasing soil fertility and pest control. It also has the potential to improve soil mechanical properties, increase soil strength, and reduce compaction (Alsharef et al., 2020; El-Sharkawy et al., 2022; Rajabi et al., 2021).

Nanoparticles, which are particles with diameters less than 100 nm, are essential to NT components. Their unique size-dependent physicochemical properties differentiate them from bulk or micron-sized particles (Dasgupta et al., 2017; Verleysen et al., 2019). NPs can be formed through natural processes such as dust storms, volcanic ash, and artificial synthesis methods (Buzea et al., 2007; Chimbekujwo et al., 2024). The metal-based nanoparticles (NPs) have a long persistence (Ameen et al., 2021; Li et al., 2012). Therefore, the introduction of NPs into ecosystems raises significant environmental concerns for both human health and ecological integrity (Adhikari, 2021). Historically, the unique characteristics of NPs have made them useful in various industries such as agriculture, food production, environmental management, pollution control, and energy. These qualities make NPs valuable for addressing climate change and sustainability goals (Chausali et al., 2023; Choudhary et al., 2023; Mohammed et al., 2023).

Recent research has primarily focused on demonstrating the effects of NPs on the physical and hydrological properties of soil for construction purposes. At the agricultural level, studies have addressed their effects on plant nutrition (Iqbal et al., 2024; Komendova et al., 2019; Sharifnasab et al., 2016; Sharma et al., 2024; Younis et al., 2021;). Several studies have explored the role of NPs in influencing soil water dynamics, revealing that the materials used and the properties of the parent soil had a reciprocal effect on the mechanism and behavior of the medium (Elahe et al., 2024; Gill et al., 2024; Komendova et al., 2019). Additionally, physical and chemical variables such as soil texture, moisture content, pH levels, and nutrients affect the interaction and behavior of NPs in soil (X. Gao et al., 2019; Figure 2).

The use of NPs to enhance agricultural soil strength is an exciting possibility for future research (Sonderegger & Pfister, 2021; Stolte et al., 2016). However, current research indicates that NP exposure has various effects on plants, such as differences in crop production and potential cytotoxicity, with many studies still in their early stages. Therefore, a review of recent studies on the role of NPs in improving physical properties is necessary, especially given the ongoing advancements in NT, to enhance our understanding of their potential in reclaiming agricultural soil. In this paper, a comprehensive analysis of certain NPs is presented, with a focus on their role in enhancing the physical and microstructural properties of soil. The paper also examines the interaction mechanisms that influence soil behavior and compaction. Additionally, it briefly discusses the potential toxic effects of NPs on human health and ecosystems. The final section assesses the economic viability and sustainability of NP applications, as well as the regulatory frameworks governing their use and waste management.

Nanoparticles Used in Soil Reclamation and Protection

Nanoparticles show promise in improving compacted soil in agriculture. However, it is important to thoroughly document the effects of NPs on the physical characteristics of soil, especially in geotechnical and geological engineering and construction. Nanotechnology (NT), which involves manipulating and utilizing materials at the nanoscale (generally below 100 nm), has been developed and used for environmentally sustainable and cost-efficient soil improvement in geotechnical, geological, and engineering applications. NPs promote flocculation, increasing soil porosity, and reducing bulk density, thereby mitigating the effects of soil compaction (Harsh

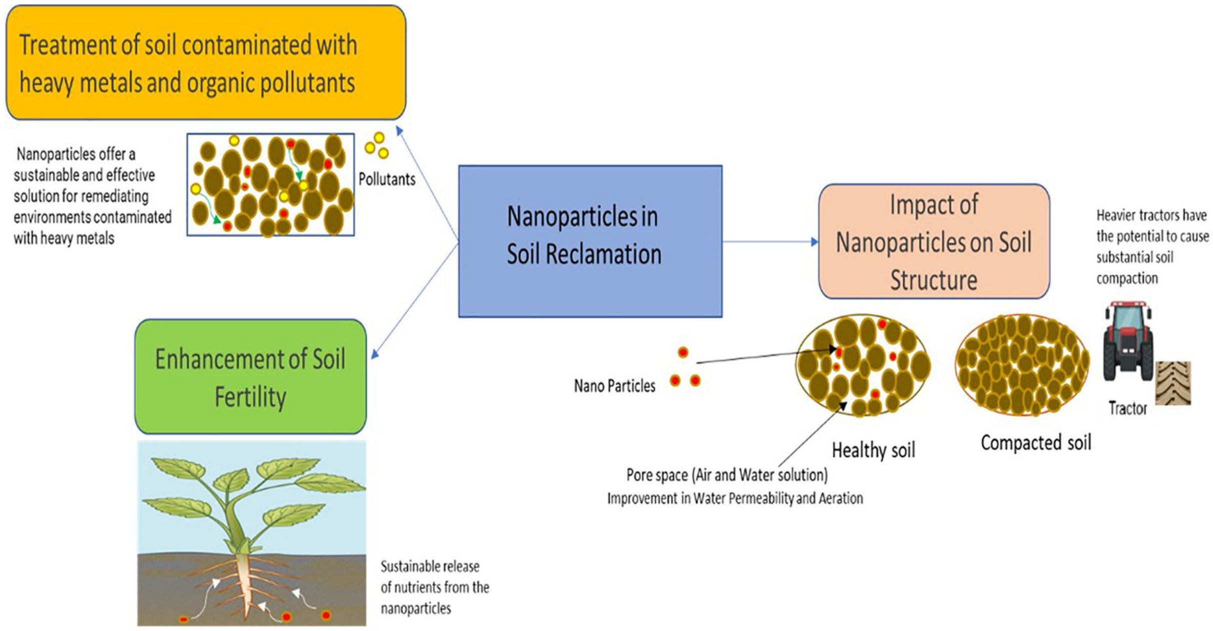

Figure 2. Nanotechnology approaches in soil reclamation (Some icons created in BioRender. Alkhaza'leh, H. (2024) https://BioRender.com/b61r626).

et al., 2023; Krishnan & Shukla, 2019; Taha & Taha, 2012; Zhang, 2007). In agriculture, nanotechnology (NT) has been used for plant nutrition, protection, and increased productivity (see Table 1). In 2006, the US National Research Council (NRC, 2006) highlighted the introduction of NT in geotechnical materials, creating clay-sized particles of 0.002 mm. Over time, NT applications for soil enhancement have evolved to align with the principles of sustainable development (Liu et al., 2020). This paper explores various environmentally friendly NPs and their potential for soil treatment, especially in reducing soil compaction and for agricultural use. These NPs include Carbon nanotube (CNT), nanozeolites (NZ), nanosilica (NS), Nano-Clays (NCs), Nano-Calcium Carbonate "$CaCO_3$" (NCC), and Nano-Aluminum Oxide "Al$_2$O3" (NAO).

Carbon nanotubes

Carbon nanotubes (CNTs) are formed from extremely thin, concentric graphene sheets. CNT atoms are arranged in a hexagonal "honeycomb" pattern to create multi-walled carbon nanotubes (MWCNT) and single-walled carbon nanotubes (SWCNTs; see Figure 3). CNTs vary in length and size, ranging from a few hundred nanometers to several micrometers (Brock, 2004; Herrero-Latorre et al., 2015). CNTs have diverse applications in industries, agriculture, and the environment, including use in sports materials, battery electrodes, LCDs, transparent films, and supercapacitors (De Volder et al., 2013; Wieland et al., 2021). CNTs have a large specific surface area and can effectively absorb chemicals and biological toxins, especially in aquatic environments, making them a promising and environmentally friendly option in the field of environmental science (Alobaid et al., 2022; Hsu et al., 2023; Li et al., 2013). Over the past two decades, CNTs have consistently demonstrated reliability in agricultural applications, particularly in the controlled release of fertilizers and herbicides, which contributes to their stability and effectiveness (Abd-Elsalam, 2019; Bisinoti et al., 2019; Giraldo et al., 2014; Tiwari et al., 2014).

The exceptional flexibility and unique physical properties of CNTs are due to their high-dimensional structure and extremely high flexibility (Fakhim et al., 2012; Sathurusinghe et al., 2012; Terrones, 2004; Xu & Jiang, 2023). The use of CNTs in soils results in significantly stronger and stiffer matrices, which enhances their physical and geotechnical potential as reinforcing fillers to improve soil strength and stability (Liu et al., 2020; Taha, Alsharef, Al-Mansob, & Khan, 2018; Taha, Alsharef, Khan, et al., 2018). While the mechanisms governing the interaction of CNTs with soil are not fully understood, CNTs have the potential to enhance soil behavior and reduce compaction. This underscores the need for further research on their impacts (Morais et al., 2024).

Most of the reviewed studies focused on improving the physical structure and soil stability for non-agricultural purposes. Morais et al. (2024) enhanced the compressive strength of clay soil by using CNTs. The liquidity and flexibility tests showed a decrease of 10% and 13% respectively. Zhao and Xu investigated the effect of adding 2% CNT to sand, and the results showed a 36% increase in the sand's modulus of elasticity with a hydrostatic pressure increase from 100 to 300 kPa. According to Alobaid et al. (2022), CNTs show great potential for soil reclamation. The treatments resulted in a decrease in soil specific gravity from 2.6 to 2.53 and an increase in soil dry density from 1.48 to 1.49 g/cm^3 using 0.05% of CNTs. Additionally, CNTs improved the hydraulic retention time by

Table 1. Summary of Nanoparticles Used in Soil Reclamation.

NANOPARTICLE TYPE	FUNCTION IN SOIL RECLAMATION	REFERENCES
Nano Iron Oxide (Fe_2O_3, Fe_3O_4)	It removes heavy metals, such as arsenic and lead, by adsorption and reduction, which enhances soil quality. Detection and tracking of pollutants as sensors because of their sensitivity to environmental changes.	Rizwan et al. (2019) Konate et al. (2017), and Mohamed and Awad, 2022
Nano-Zero Valent Iron (nZVI)	Used for soil remediation of toxic metals and organic pollutants by reducing their bioavailability.	Dhanapal et al. (2024), Jiang et al. (2018), and O'Carroll et al. (2013)
Nano-Titanium Dioxide (TiO_2)	Remediation of contaminated soils and the enhancement of sustainable crop production in polluted environments.	Ogunkunle et al. (2020)
Nano-Silica (SiO_2)	Enhances soil structure, improves water retention, effective nutrient delivery system and pest control, and supports pollutant immobilization in soil.	Dhanapal et al. (2024), Haeri and Valishzadeh (2021), and Singh and Endley (2020)
Nano-Clays	Enhances soil structure; increase aeration, and improve nutrient availability; Stabilizes contaminants and prevents them from leaching into groundwater; development of sensors for detecting environmental pollutants and changes in soil conditions. improves soil stability.	Johari et al. (2021), Abd-Elsalam et al. (2024), and Seif et al. (2019)
Nanozeolites (NZ)	Enhances soil structure; Improve soil fertility; Enhanced fertilizer efficiency; increase nutrient and water holding capacity.	Feng et al. (2022), Manjunatha (2019), Tsintskaladze (2017), and Öncü and Bilsel (2017)
Nano-Calcium Carbonate ($CaCO_3$)	Amends acidic soils (Soil pH Regulation), enhance soil stability, immobilizes heavy metals, improving soil fertility, and productivity.	Thomas et al. (2023), Mohammadi et al. (2022), and Y. Gao et al. (2023)
Carbon Nanotubes (CNTs)	Enhance soil strength and stability; release of fertilizers and herbicides; Assists in adsorbing organic pollutants and enhancing microbial degradation processes in contaminated soils.	Liu et al. (2020), Taha, Alsharef, Khan, et al. (2018), Hsu et al. (2023), Abd-Elsalam (2019), and Bisinoti et al. (2019)
Nano-Zinc Oxide (ZnO)	Enhances nutrient availability and supports soil fertility, while also helping in heavy metal detoxification.	Mahdavi et al. (2022) and Kareem et al. (2023)
Nano-Aluminum Oxide (Al_2O_3)	Enhances soil stability; supports soil fertility; reduces phytotoxic aluminum ions by reducing their mobility and contamination potential in soils.	Parsaei et al. (2023) and Hayes et al. (2020)
Nano-Silver (Ag)	Has antimicrobial properties that reduce pathogens in soil; used for bioremediation support.	Kulikova (2021)
Nano-Magnesium Oxide (MgO)	Improving soil fertility, enhancing nutrient absorption, combating pests, regulating soil pH, and contribute to plant tolerance of heavy metal/ metalloid toxicity	Faizan et al. (2022)

causing a slight decrease in hydraulic conductivity, which helped reduce soil cracking. Arabania et al. (2012) also studied the blending of clayey sand with CNTs (0.05%–3% by weight of the soil). The soil's compressive strength increased by about 120% when it contained 3% CNTs compared to the reference clay soil. These studies suggest that even a small amount of CNTs can significantly improve soil compressive strength. Additionally, CNTs reduce the friction angle while increasing the cohesiveness between soil grains. These findings suggest that CNTs may have the potential for agricultural soil reclamation. Further experiments going to help clarify the capabilities of CNTs in this field.

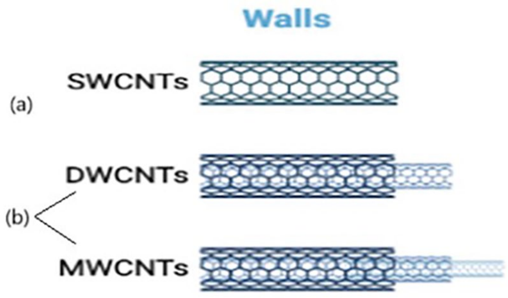

Figure 3. The chemical structure of (a) single-walled and (b) multi-walled carbon nanotube (Created in BioRender. Alkhaza'leh, H. (2024) https://BioRender.com/c02s558).

Nanozeolites

Nanozeolites (NZ) are porous crystals composed mostly of Si, Al, and O atoms. Their most important current application is in sustainable, green chemical processes. Synthetic NZ is preferred over natural zeolites due to its superior purity (Asgar Pour et al., 2023; Figure 4). Zeolites come in various forms and are used in many industrial applications. They are commonly found in volcanic and sedimentary materials (Holmberg et al., 2003; Niwa et al., 2010). When in their nano form, zeolites are used as catalysts in the chemical industry, providing high surface areas and shape/size selectivity (Yilmaz, 2009). NZ have been successfully produced and utilized in various petroleum chemical processes, such as catalytic cracking, hydrocracking, and hydroisomerization. NZ are efficient catalysts in methanol conversion processes, where crystal size impacts activity, product distribution, and coke production (Palčić, 2021). Furthermore, New Zealand-generated thermoelectric waste is beneficial for treating wastewater, particularly in nano-adsorption and Fenton-like processes (Oviedo, 2021).

Nanozeolites have shown significant potential in agriculture, especially in the development of nanofertilizers. These nanofertilizers can slowly release nitrates into the soil (Tsintskaladze, 2017), thereby reducing groundwater contamination and soil toxicity, minimizing fertilization losses, and increasing the soil's capacity for holding nutrients and water. This can help mitigate the negative effects of overdosing (Feng et al., 2022; Manjunatha, 2019). In addition to improving nutrient delivery in precision farming and restoring soil health and fertility (Pimsen et al., 2021; Hamad, 2020), NZ substantially enhance the geotechnical properties of clayey soil and increase the compression strength of fine-grained soil (Goodarzian, 2020).

The interaction mechanism between soil and NZ particles is a balance of attractive and repulsive forces, with electrostatic forces playing a crucial role in forming or separating aggregates by promoting soil particle binding (Hu et al., 2019). NZ, when combined with other NPs, may effectively solve soil cracking and compaction (Taha & Taha, 2012). Öncü and Bilsel (2017) assessed the effectiveness of combining zeolite with clay soil in a semi-arid climate. The results showed that using a soil/zeolite ratio of 0.5 reduced observed swelling potential by 85%, and shrinkage and compression by 30% to 34%.

A study by Balkaya (2015) observed that zeolite exhibits physical stability and has potential applications in geotechnical and environmental engineering. The samples showed low compressibility, with cohesion (c) values ranging from 0 to 25 kPa and an internal friction angle (φ, shear strength coefficient) ranging from 44° to 37°. Yukselen-Aksoy (2010) found that loamy clay soil supported with zeolite has moderately high internal friction angles (34° to 36.5°), making zeolites mechanically stable. The zeolite samples' free swelling index (FSI) was estimated to be about 2.0, indicating low swelling potential. While most studies focus on geotechnical applications, zeolites, especially NZ, combined with other nanomaterials, can effectively address agricultural soil cracking and compaction.

Nanosilica

Silica is the most abundant chemical on Earth and is the most prevalent silicate mineral in the Earth's crust, as well as in plants and grains (Diab et al., 2017). Nanosilica (NS) and Colloidal nanosilica (CNS) are types of silica with easily modifiable surfaces, high surface area, uniform pore size, and customizable particle size due to the presence of silanol groups (Si-OH; Choi et al., 2020; Figure 4). The water-based CNS is a better alternative to NS powder in certain applications because it eliminates the possibility of agglomeration (Huang et al., 2022; Kong et al., 2015). The unique properties of silica at the nanoscale level make it more stable under temperature fluctuations, organic solvents, and acidic environments, which expands its applications in medicine. Importantly, silica nanoparticles are significantly less expensive than other types of nanoparticles, making them practical and cost-effective (Florek et al., 2017; Singh et al., 2019). In agriculture, NS can be utilized as a nano-fertilizer to improve plant growth and productivity. Its small size and high surface area make it an effective nutrient delivery system and pest control (Amin et al., 2023; Awad-Allah, 2023; Singh & Endley, 2020). In addition, Salami et al. (2022) studied the importance of NS in water purification and wastewater treatment. Kotresha et al. (2021) explored the use of NS to enhance the binding of heavy metals in polluted soil. Their studies demonstrated that NS significantly enhanced the retention of heavy metals compared to untreated soil, potentially reducing groundwater contamination and associated health risks.

Nanosilica improves the mechanical and geotechnical properties of various soils. Previous studies have demonstrated that NS enhances soil strength and behavior. Its mechanism is based on increasing hydration, enhancing the surface bonding between soil particles and binding materials, and increasing the production of calcium silicate hydrate gel (C-S-H; Patro & Sahoo, 2022; Zhang et al., 2020). Haeri and Valishzadeh (2021) investigated the impact of adding NS at three different percentages (0.1%, 0.2%, and 0.4% by weight of the loess soil). The findings showed that even a small amount of NS (less than 1%) could significantly enhance the soil's mechanical properties. According to Ahmadi and Shafiee (2019), around 1% of NS provides the best soil strength and stiffness performance. In a study by García et al. (2017), clay cohesion was examined using the compressive test after adding 0.5% to 3% NS. The study found that samples containing 3% NS increased strength by 60% to 90%. In a study by Changizi and Haddad (2016), the effect of adding NS at three different percentages (0.5%, 0.7%, and 1.0% by weight of the parent soil) was reported. It was observed that an increase in NS content led to a higher angle of internal friction, cohesion, and compression strength. The study also identified that the optimal NS content was at 0.7%. Overall, the findings indicate that even small amounts of

Figure 4. Micrography of zeolite, silica, and clay. Images from “Selvam et al., 2020, and Arulmurugan and Venkateshwaran, 2021” (used according to the Creative Commons Attribution 3.0 Unported License and STM permission guidelines, respectively), and “Richard et al., 2022” (used with permission from the Copyright Clearance Center’s RightsLink® service; Order Number: 5881860570738, Order Date: Oct 4, 2024).

nanostilbene (NS) can significantly enhance the compressive strength of soil by improving its physical and mechanical properties. As a result, NS may play a vital role in agricultural soil reclamation by reducing soil compaction.

Nanoclays

Nanoclays (NCs) are clay minerals with dimensions of at least 1 nm, primarily found in the clay fraction of soil (Kantesaria & Sharma, 2020). The main forms of nanoclays are montmorillonite and allophane, which have various applications in agriculture, industry, and medicine (Kataki et al., 2022). In agriculture, NCs promote soil health, water retention, and nutrient release (Rao et al., 2024). Additionally, NCs have a significant impact on pollution control and water treatment (Iravani et al., 2022). These functions stem from their distinct chemical and physical properties. The high cation exchange capacity (CEC) of NCs has increased their nutrient and water retention. This mechanism led to higher crop yields and reduced the need for chemical fertilizers (Elmi, 2023; Kanjana, 2017). NCs enhance soil structure by promoting particle aggregation, increasing porosity, and improving air and water circulation, all essential for root growth and microbial activity (Zewdu et al., 2024). Nanoclay acts filling the spaces between soil particles. This increases soil moisture by enhancing the absorption of moisture from the surrounding environment due to the high surface area of NC and the formation of hydrogen bonds with clay minerals. This mechanism enhances the cohesion of particles and the stability of their overall structure (Arabani et al., 2023). Additionally, NCs’ high adsorption capacity enables the efficient removal of heavy metals and organic pollutants from water (Iravani et al., 2022).

Research has shown that NC plays an important role in enhancing soil stability and reducing erosion. This is because NC improves the mechanical properties of soil, such as compressive and shear strength. A study showed that adding 0.9% rice fiber with NCs significantly improved the shear and compressive strength of soil, as well as its elasticity (Arabani et al., 2023). Abbasi et al. (2018) found that incorporating NC at concentrations ranging from 0% to 4% by dry weight significantly enhanced soil stability and decreased dispersivity in both low- and high-plasticity clay soils. Similarly, Tabarsa et al. (2018) investigated the use of NCs for stabilizing loess soils. They discovered that NC concentrations between 0.2% and 3% resulted in increased plasticity, strength, and stiffness, while also reducing dispersivity and collapse associated with wetness. Cheng et al. (2020) investigated the effects of blending nano-bentonite with clay soil at concentrations of 0.5% to 2%. They found the most notable improvements at a 0.5% concentration of nano-bentonite, which enhanced water drainage and decreased soil compaction. Similarly, Nohani and Alimakan (2015) evaluated the impact of NC on the engineering properties of clay by adding various NC concentrations (0.5%, 1%, 1.5%, and 2% by dry weight). Their findings showed that increasing NC concentration led to higher liquid and plastic limits, as well as significant increases in soil resistivity at 1.5% NC content during uniaxial compression and California Bearing Ratio (CBR) testing. Overall, low levels of NC improved soil characteristics.

A review of the literature indicates that similar to other NPs, most studies emphasize the importance of NCs in enhancing the mechanics of soil for non-agricultural applications. This highlights the need for further research into the potential of NCs to improve compacted agricultural soils by enhancing soil structure, increasing water retention, and promoting root growth, ultimately leading to higher agricultural productivity.

Nano-calcium carbonate

Nano-calcium carbonate (NCC) is a highly versatile material with a wide range of applications across various industries, including agriculture, construction, coatings, and catching heavy metals . Its nanoscale size enhances surface area, dispersion, and mechanical properties (Y. Gao et al., 2023; Kotresha et al., 2021; Qiu et al., 2024). In agriculture, NCC improves soil fertility, supplies essential nutrients to plants, and helps prevent insect infestations. It delivers nitrogen to the soil, which increases microbial activity and supports plant development. As a result, NCC is a more effective solution for sustainable agriculture compared to traditional fertilizers, as it can significantly enhance agricultural productivity (Y. Gao et al., 2024). Additionally, NCC has considerable potential to improve the physical properties of soil and boost agricultural production. It enhances soil stability and compressive strength while reducing compressibility, making it an effective tool for decreasing soil compaction (Kannan et al., 2023; Mohammadi et al., 2022).

The mechanism of NCC is rooted in its capacity to aggregate particles, which over time results in the formation of calcium silicate hydrate (CSH) gel (Kannan et al., 2023; Mohammadi et al., 2022). Research by Kannan et al. (2023) demonstrated that incorporating 0.4% NCC into fine-grained soils with low plasticity significantly increased compressive strength compared to untreated soils. Similarly, Haeri and Valishzadeh (2021) discovered that the use of NCC significantly increased the compressive strength of collapsible loess soils, with optimal results achieved at a concentration of 0.2% NCC. Similarly, Mohammadi et al. (2022) examined the effects of NCC on sandy loam soils and found that samples containing 10% and 20% clay with 0.7% NCC exhibited the best compressive strength and cohesiveness. In contrast, soils with 30% clay required 1.1% NCC to achieve similar effects. These findings strongly suggest that NCC could be a promising method for reducing soil compaction in agriculture. Further specific research is needed to clarify its functions in agricultural soil.

Nano-aluminum oxide

Nano-aluminum oxide (NAO) is a versatile nanomaterial known for its unique properties, which make it valuable in various applications, including coatings, abrasives, military fuels, and agriculture (Abed & Jawad, 2022; Stanley et al., 2010). Its large surface area, thermal stability, and high mechanical strength enhance performance across multiple industries. Recent studies have shown that NAO can improve soil structure, fertility, and agricultural yields. It aids in soil aeration, water retention, root development, and overall plant health. By incorporating NAO into the soil, farmers can enhance nutrient absorption efficiency, leading to higher crop yields (Hayes et al., 2020). NAO serves as an effective tool for agricultural pest control by delivering pesticides at a high level of efficiency. This approach results in effective pest management while minimizing environmental impact. It also reduces the risk of pesticides being transported by rainwater runoff or irrigation into water sources or food supplies (Das et al., 2019). In addition to pest control, NAO can remove pollutants by acting as an adsorbent for contaminants such as dyes, antibiotics, and heavy metals (Jain et al., 2022). Furthermore, NAO has shown the potential to improve soil stability and structure by reducing compaction and erosion.

The improvements are attributed to the high surface area of NAO, which helps fill the pore spaces between soil particles, resulting in a denser and more compact soil structure (Mir & Reddy, 2021). Studies have shown that incorporating small percentages (0.2%–2%) of NAO into clay soils significantly enhances various engineering properties, such as unconfined compressive strength, California bearing ratio, and soil moisture content, while also reducing porosity and swell potential (Parsaei et al., 2023). Taha and Taha (2016) examined the impact of NAO on soil swelling and shrinkage, finding that adding 6% NAO led to a significant reduction of these effects, decreasing them by 17%. Al-Mansob et al. (2021) investigated how the addition of lime and NAO enhances the stability of native clay soils. Compression strength tests showed that mixing the soil with up to 5% lime and varying concentrations of NAO (0.05%, 0.1%, and 0.2%) significantly improved the soil's compressive strength. This demonstrates the potential of nanoparticles (NPs) in enhancing soil mechanics. These recent advancements underscore the growing importance of further research on NAO in agriculture, particularly in understanding soil dynamics and behavior. They also provide promising solutions for soil improvement, pest control, and contaminant removal, which are essential for meeting the increasing demands of global food production.

Environmental and Health Implications of Nanoparticle

Nanoparticles (NPs) have a complex dual impact, yielding both positive and negative effects on the environment and human health. Their unique physicochemical properties make them useful for applications in water treatment and pollution remediation (Kumar et al., 2019; Yamini et al., 2023). Despite their nano size and increased reactivity, these attributes pose significant eco-toxicity concerns that could result in major environmental challenges (Abbas et al., 2020; Ramanathan et al., 2019). Alongside environmental issues, health hazards linked to NPs are a major concern. Research by De Matteis (2017) and Świdwińska-Gajewska (2007) found that the nano size of NPs allows them to evade systemic barriers, particularly when inhaled, which is a significant route of exposure. NPs toxicity often manifests as inflammation, which can be triggered by oxidative stress (Świdwińska-Gajewska, 2007; Tee et al., 2016). Thus, robust methods for assessing occupational exposure and conducting toxicological studies are essential for understanding and mitigating health risks (Adamcakova-Dodd et al., 2014; O'Shaughnessy, 2013). Several factors influence the toxicity of NPs, including their surface properties, the generation of free radicals, and their specific characteristics (Fu et al., 2014; Warheit et al., 2008). Multiple factors influence the environmental impact of NPs, including their physicochemical properties, manufacturing processes, and ecological stability (Joudeh & Linke, 2022; Martínez et al., 2020). A key factor in assessing the environmental impact of NPs is their movement within soil and water systems, which can contaminate groundwater and disrupt ecosystems (Pérez-Hernández et al., 2020; Zheng et al., 2022). Migration is influenced by several factors, including particle size, surface charge, and organic content, all of which can hinder the mobility of NPs (Wang et al., 2016). Additionally, NPs experience changes that affect their movement, particularly during freeze-thaw cycles. The soil type and its moisture content also play significant roles in determining their mobility (Xu et al., 2021). The physical and chemical properties of NPs and their surrounding medium influence their retention and movement. The size of agglomerates is often more significant than the size of the primary particles (Darlington et al., 2009). A thorough understanding of these interactions is essential for addressing potential environmental concerns related to NPs and their long-term behavior in soil and groundwater systems (Sun et al., 2022).

Several studies have indicated that NPs are generally non-toxic to soil and groundwater systems (Alazaiza et al., 2021; Kang et al., 2008; Li et al., 2013; Rajan, 2011). However, some research suggests that NPs may pose minor to moderate environmental concerns (Lead et al., 2018; Pérez-Hernández et al., 2021). Krug (2014) explored the methodologies used in various nanotoxicology studies, critiqued certain research approaches, and suggested that improved study designs could yield more accurate and reliable outcomes. Most risk characterization ratios (RCRs) for NPs are below one. However, some NPs, such as CNTs, have RCRs that exceed one (Arvidsson, 2018; Spinazzè et al., 2021). While the environmental risks associated with the NPs reviewed are generally low, there are significant gaps in knowledge, particularly concerning ambient concentrations and dosimetry methods (Lead et al., 2018).

Several organisms are utilized to evaluate potential health risks. Such as the fruit fly (Drosophila melanogaster) serves as a valuable and cost-effective model organism due to its genetic similarities to humans. This makes it a reliable tool for accurately assessing toxicity (Chifiriuc et al., 2016; Vecchio et al., 2013). Traditional methods for eco-toxicity testing can also be applied to NPs, and research involving algae has demonstrated their high sensitivity to these substances (Boros and Ostafe, 2020). Additionally, leaching testing protocols are becoming an essential tool for examining the behavior of NPs in different environments and evaluating their environmental impact (Brunelli et al., 2021; Moghal et al., 2023). Leaching testing protocols offer an effective short-term alternative to traditional methods like using nano-calcium silicates in soil. They reduce metal extraction rates and enhance soil stability by encapsulating heavy metals, which helps prevent their migration into groundwater (Moghal et al., 2023).

Additionally, Computational methods, such as quantitative structure-activity relationship (QSAR) models, have enhanced our understanding of the toxicity of NPs and their associated health risks (Kleandrova et al., 2014). However, uncertainty still exists, particularly due to technological advancements that could alter the concerns regarding the increased release of particles into the environment (Lead et al., 2018). Therefore, further research is necessary to address these knowledge gaps and ensure the safe and sustainable use of NPs in various agricultural and industrial applications.

Economics, Sustainability, and Regulatory of Nanoparticles

Nanotechnology has the potential to improve soil and plant nutrition in agriculture, offering more affordable and environmentally friendly alternatives to current methods (Singh et al., 2021). The economic feasibility of using NPs in agriculture depends on production and application costs. However, the long-term benefits, such as increased agricultural yields and improved soil health, far outweigh the initial costs (Yadav et al., 2023). Nevertheless, significant obstacles are present, including high manufacturing costs, limited availability, concerns about toxicity, and high energy requirements for synthesis, resulting in increased carbon emissions (Pallas et al., 2018).

The challenges mentioned above are important, particularly in developing countries. High initial costs, unclear regulations, and uncertainty in environmental risks make it difficult to adopt NT, despite its potential to address food insecurity (Acharya & Pal, 2020). Furthermore, potential benefits for rural populations in developing regions are greater than in developed countries (Rathore & Mahesh, 2021). On the other hand, the "green and clean" claims often associated with NPs are not universally applicable, especially in the energy sector, where life cycle assessments indicate high energy consumption and carbon emissions from production processes (Pallas et al., 2018).

Despite this, the emerging field of nanoeconomics combines nanoscience and economic theory, which can speed up technological advancements and encourage more sustainable economic growth. Some potential benefits include cost reductions, lower toxicity, improved efficiency, and increased reliability across various applications. However, it is important to thoroughly assess the full environmental costs of complex engineered nanomaterials to ensure they contribute to sustainable development sound (Dave & Chaturvedi, 2021).

It is crucial to establish regulatory guidelines for the use of NPs in agriculture. Current regulations may not fully address the unique properties and risks associated with NPs, highlighting the need for tailored policies. Conducting thorough risk assessments, implementing proper handling, storage, and disposal practices, and ensuring compliance with safety standards are essential steps to facilitate the safe development of NT (Nath et al., 2021). Additionally, collaboration among stakeholders, including researchers, policymakers, and industry leaders, is necessary to develop comprehensive regulations that consider both environmental and health impacts.

Concerns about nanowaste management and the need for adequate regulatory policies persist (Suman & Pei, 2022). Current waste management systems are often ill-equipped to handle nano-waste, necessitating new approaches and regulations (Musee, 2011). Effective nanowaste management requires proper detection, segregation, and treatment techniques, which depend on the specific class of engineered NPs involved (Gupta & Bharti, 2022). Further research is needed to understand the life cycle of NPs and their long-term effects on health and the environment (Li et al., 2022). To address these challenges, researchers propose tagging nanoproducts for easier separation and recovery. They emphasize the need for collaboration among all stakeholders to develop comprehensive regulations and conduct life cycle assessments of NPs, therefore, better understand their long-term environmental impacts (Chowdhury et al., 2022).

Conclusions and Prospects

Over the past century, extensive research on nanomaterials has highlighted their significant potential across various fields, including agriculture. Nanotechnology (NT) is emerging as a critical tool for enhancing agricultural productivity, with promising applications in pesticide delivery, biopesticides, fertilizers, and soil reclamation. The studies reviewed herein demonstrate the efficacy of these materials in improving soil structure and stability. Key factors such as the size and microstructure of NPs have been identified as essential contributors to enhancing soil strength. Moreover, the widespread availability of NPs—including clays, silica, calcium carbonate, and zeolite—coupled with their cost-effectiveness, positions them as economically viable options for large-scale agricultural use. Their eco-friendly characteristics further support their role in sustainable agricultural practices, striking a balance between technological advancement and environmental conservation.

However, despite these promising developments, research focusing on the application of NT to improve the physical properties of agricultural soils remains limited. Comprehensive investigations are needed to understand how NPs interact with natural ecosystems, including soil texture, moisture content, pH levels, and nutrients, to ensure that their application does not inadvertently lead to environmental degradation or demonstrate diminished effectiveness. Large-scale, long-term studies are crucial to identifying the specific properties of NPs that can enhance agricultural soils while assessing their potential health and environmental impacts. Although the reviewed studies reported no immediate toxic hazards, there remains a possibility that certain NPs could pose risks by entering biological systems, particularly through inhalation.

From an economic perspective, the scalability of NPs in agriculture will depend on production costs, market availability, and long-term benefits. While initial investments in NT can be substantial, the potential for increased crop yields, improved soil health, and reduced reliance on conventional agrochemicals may justify these costs over time. Sustainable practices in the development and deployment of NPs will be vital to ensuring that economic benefits are realized without compromising environmental integrity. The widespread adoption of NT in agriculture will require clear regulatory frameworks, robust economic models, and thorough sustainability assessments.

Ultimately, while NT holds great promise for transforming agricultural practices, long-term research is essential to fully understand its impacts. Future studies should prioritize not only the efficacy and safety of NPs but also their economic viability and environmental sustainability. Additionally, developing robust methods for assessing occupational exposure and potential toxicity is critical for minimizing health risks. By addressing these challenges, NT can play a pivotal role in advancing sustainable agriculture, providing solutions that are both economically feasible and environmentally responsible.

Acknowledgements

This study utilized [Grammarly, QuillBot, Microsoft Word Editor, and ChatGPT] for language refinement. These tools were used to correct grammatical errors and provide suggestions for improving the writing style, ensuring that the scientific integrity and content of the study remained intact. Additionally, some of the icons used were sourced from BioRender.com and Google.com.

Author Contributions

All authors were involved in manuscript writing and have approved the final version of the manuscript.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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