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Authors: Alkhaza'leh, Hasan, Rahbeh, Michel, Hamadneh, Imad, AL-Mashakbeh, Habes, and Albalawna, Zohair

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Nanoparticles in Soil Reclamation: A Review of Their Role in Reducing Soil Compaction

Hasan Alkhaza'leh¹, Michel Rahbeh², Imad Hamadneh²,
Habes AL-Mashakbeh¹ and Zohair Albalawna³

¹Al al-Bayt University, Mafrq, Jordan. ²The University of Jordan, Amman, Jordan. ³Jordan Valley Authority, Amman, Jordan.

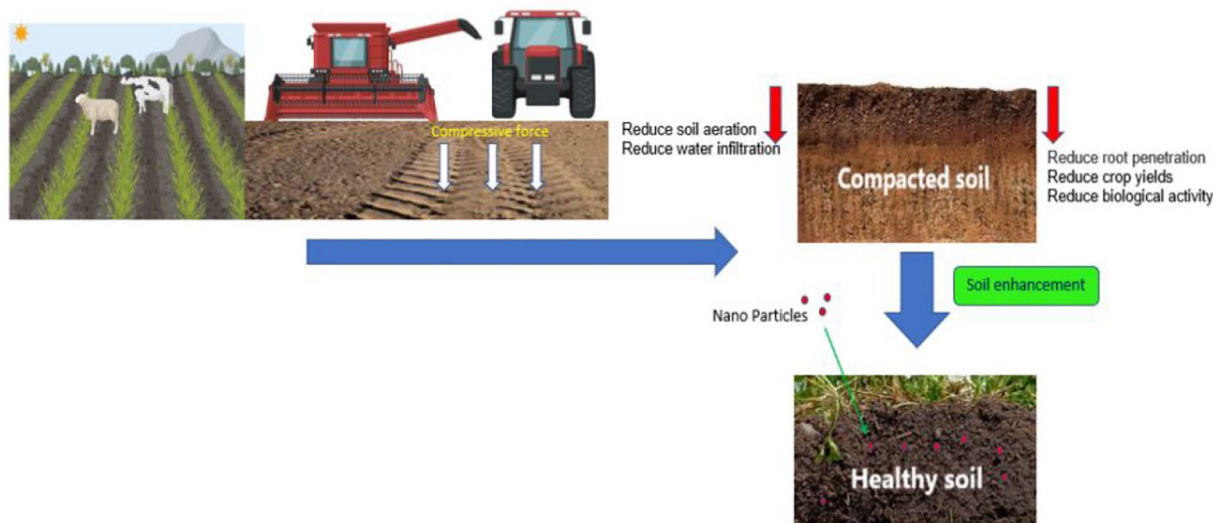
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ABSTRACT: Rapid population growth and increased use of agricultural technology have exacerbated agrarian problems. While mechanization has improved agricultural production, the use of heavy machinery for planting, irrigation, and harvesting has resulted 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>)

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CORRESPONDING AUTHOR: Hasan Alkhaza'leh, Al al-Bayt University, Mafrq 25113, Jordan. Emails: hasan-khazaleh@aabu.edu.jo; hasan_khazaleh@yahoo.com

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).



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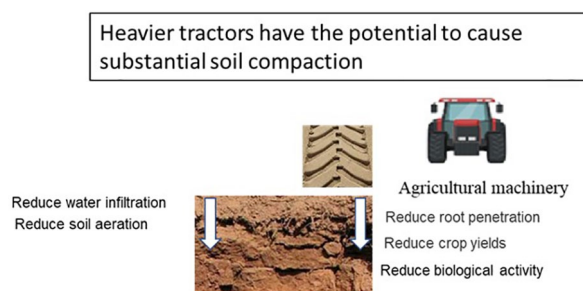


Figure 1. Soil compaction due to agricultural machinery impact (Some icons created in BioRender. Alkhaza'leh, H. (2024) <https://BioRender.com/b61r626>).

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 (Alsharif 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

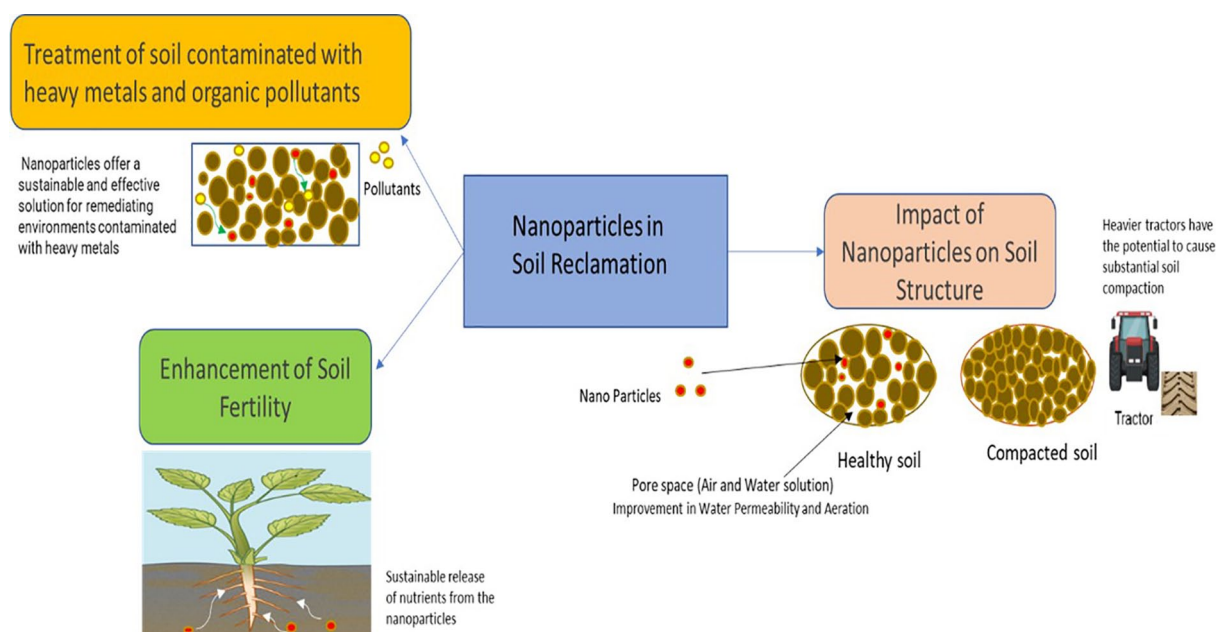


Figure 2. Nanotechnology approaches in soil reclamation (Some icons created in BioRender. Alkhaza'leh, H. (2024) <https://BioRender.com/b61r626>).

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_2O_3 " (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/cm³ 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)

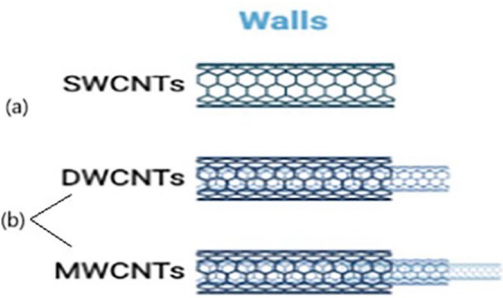


Figure 3. The chemical structure of (a) single-walled and (b) multi-walled carbon nanotube (Created in BioRender. Alkhaza'leh, H. (2024) <https://BioRender.com/c02s558>).

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.

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).

nanostillbene (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 nanobentonite 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.

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ORCID iDs

Hasan Alkhaza'leh  <https://orcid.org/0009-0009-3057-5650>

Michel Rahbeh  <https://orcid.org/0000-0003-1270-5035>

REFERENCES

- Abbas, Q., Yousaf, B., Ullah, H., Ali, M. U., Ok, Y. S., & Rinklebe, J. (2020). Environmental transformation and nano-toxicity of engineered nano-particles (ENPs) in aquatic and terrestrial organisms. *Critical Reviews in Environmental Science and Technology*, 50(23), 2523–2581.
- Abbasi, N., Farjad, A., & Sepehri, S. (2018). The use of nanoclay particles for stabilization of dispersive clayey soils. *Geotechnical and Geological Engineering*, 36(1), 327–335.
- Abd-El Salam, K. A. (Ed.). (2019). *Carbon nanomaterials for agri-food and environmental applications*. Elsevier.
- Abd-El Salam, K. A., Mehmood, M. A., Ashfaq, M., Abdelkhalek, T. E., Hassan, R. K., & Ravichandran, M. (2024). Liquid nanoclay: Synthesis and applications to transform an arid desert into fertile land. *Soil Systems*, 8(3), Article 73.
- Abed, M. S., & Jawad, Z. A. (2022). Nanotechnology for defence applications. In N. M. Mubarak, S. Gopi, & P. Balakrishnan (Eds.), *Nanotechnology for electronic applications. Materials horizons: From nature to nanomaterials* (pp.187–205). Springer.
- Acharya, A., & Pal, P. K. (2020). Agriculture nanotechnology: Translating research outcomes to field applications by influencing environmental sustainability. *Nano-Impact*, 19, Article 100232.
- Adamcakova-Dodd, A., Stebounova, L. V., Kim, J. S., Vorrink, S. U., Ault, A. P., O'Shaughnessy, P. T., Grassian, V. H., & Thorne, P. S. (2014). Toxicity assessment of zinc oxide nanoparticles using sub-acute and sub-chronic murine inhalation models. *Particle and Fibre Toxicology*, 11, Article 15.
- Adhikari, T. (2021). Nanotechnology in environmental soil science. In A. Rakshit, S. Singh, P. Abhilash, & A. Biswas (Eds.), *Soil science: Fundamentals to recent advances* (pp. 297–309). Springer.
- Ahmadi, H., & Shafiee, O. (2019). Experimental comparative study on the performance of nano-SiO₂ and microsilica in stabilization of clay. *The European Physical Journal Plus*, 134(9), Article 459.
- Alam, M. K., Salihin, N., Islam, S., Begum, R. A., Hasanuzzaman, M., Islam, M. S., & Rahman, M. M. (2017). Patterns of change in soil organic matter, physical properties, and crop productivity under tillage practices and cropping systems in Bangladesh. *The Journal of Agricultural Science*, 155(2), 216–238.
- Alazaiza, M. Y., Albahnasawi, A. M., Ali, G. A., Bashir, M. J., Copt, N. K., Amr, S. S., Abushammala, M. F., & Al Maskari, T. (2021). Recent advances of nanoremediation technologies for soil and groundwater remediation: A review. *Water*, 13(16), Article 2186.
- Al-Mansob, R. A., Wong, W. F., Alsharef, J., Jassam, T. M., Ng, J. L., Ali, S. I. A., & Yusof, Z. B. M. (2021, October). Unconfined compressive strength characteristic of soft soil mixed with lime and nano alumina. In AIP conference proceedings (Vol. 2401, No. 1). AIP Publishing.
- Alobaid, A., Rehman, K. U., Andleeb, S., Erinle, K. O., & Mahmood, A. (2022). Capacity assessment of carbon-based nanoparticles in stabilizing degraded soils. *Journal of King Saud University-Science*, 34(1), Article 101716.
- Alsharef, J. M. A., Taha, M. R., Govindasamy, P., Firoozi, A. A., & Al-Mansob, R. A. (2020). Effect of nanocarbons on physical and mechanical properties of soils. In K. A. Abd-El Salam (Ed.), *Micro and nano technologies: Carbon nanomaterials for agri-food and environmental applications* (pp. 459–485). Elsevier.
- Ameen, F., Alsamhary, K., Alabdullatif, J. A., & AlNadhari, S. (2021). A review on metal-based nanoparticles and their toxicity to beneficial soil bacteria and fungi. *Ecotoxicology and Environmental Safety*, 213, Article 112027.
- Amin, M., Juita, N., & Asnawi. (2023). Application of nano silica fertilizer in agricultural sustainability (a review). IOP Conference Series: Earth and Environmental Science, 1230, Article 012012.
- Arabani, M., Shalchian, M. M., & Rahimabadi, M. M. (2023). The influence of rice fiber and nanoclay on mechanical properties and mechanisms of clayey soil stabilization. *Construction and Building Materials*, 407, Article 133542.
- Arabania, M., Haghib, A. K., & Moradic, Y. (2012, March). Evaluation of mechanical properties improvement of clayey sand by using carbon nanotubes. In *Proceedings of the 4th International Conference on Nanostructures (ICNS4)* (pp. 12–14), Kish Island, Iran.
- Arvidsson, R. (2018). Risk assessments show engineered nanomaterials to be of low environmental concern. *Environmental Science & Technology*, 52(5), 2436–2437.
- Arulmurugan, S., & Venkateshwaran, N. (2021). Wear study of jute fiber polymer composite—Influence of montmorillonite nanoparticles. *Surface Review and Letters*, 28(1), Article 2050040.
- Asgar Pour, Z., Alassmy, Y. A., & Sebakhy, K. O. (2023). A survey on zeolite synthesis and the crystallization process: Mechanism of nucleation and growth steps. *Crystals*, 13(6), Article 959.
- Awad-Allah, E. F. A. (2023). Effectiveness of silica nanoparticle application as plant nano-nutrition: A review. *Journal of Plant Nutrition*, 46(11), 2763–2776.
- Balkaya, M. (2015). Evaluation of the geotechnical properties of alum sludge, zeolite, and their mixtures for beneficial usage. *Environmental Progress and Sustainable Energy*, 34(4), 1028–1037.
- Bertonha, R. S., Furlani, C. E. A., Silva, V. F. A., & Wright, D. L. (2015). Tractor performance and corn crop development as a function of furrow opener and working depth in a Red Latosol. *Australian Journal of Crop Science*, 9(9), 812–818.
- Bisinoti, M. C., Moreira, A. B., Melo, C. A., Fregolente, L. G., Bento, L. R., dos Santos, J. V., & Ferreira, O. P. (2019). Application of carbon-based nanomaterials as fertilizers in soils. In R. F. do Nascimento, O. P. Ferreira, A. J. De Paula, & V. de O. Sousa Neto (Eds.), *Advanced nanomaterials: Nanomaterials applications for environmental matrices* (pp. 305–333). Elsevier.
- Boros, B. V., & Ostafe, V. (2020). Evaluation of ecotoxicology assessment methods of nanomaterials and their effects. *Nanomaterials*, 10(4), Article 610.
- Brock, S. L. (2004). Nanostructures and nanomaterials: Synthesis, properties and applications by Guozhang Cao (University of Washington). *Journal of the American Chemical Society*, 126, Article 14679.
- Brunelli, A., Calgaro, L., Semenzin, E., Cazzagon, V., Giubilato, E., Marcomini, A., & Badetti, E. (2021). Leaching of nanoparticles from nano-enabled products for the protection of cultural heritage surfaces: A review. *Environmental Sciences Europe*, 33, 1–19.
- Buzea, C., Pacheco, I. I., & Robbie, K. (2007). Nanomaterials and nanoparticles: Sources and toxicity. *Biointerphases*, 2(4), MR17–MR71.
- Changizi, F., & Haddad, A. (2016). Effect of nano-SiO₂ on the geotechnical properties of cohesive soil. *Geotechnical and Geological Engineering*, 34(3), 725–733.
- Chausali, N., Saxena, J., & Prasad, R. (2023). Nanotechnology as a sustainable approach for combating the environmental effects of climate change. *Journal of Agriculture and Food Research*, 12, Article 100541.
- Cheng, G., Zhu, H. H., Wen, Y. N., Shi, B., & Gao, L. (2020). Experimental investigation of consolidation properties of nano-bentonite mixed clayey soil. *Sustainability*, 12(2), Article 459.
- Chifriuc, M. C., Ratiu, A. C., Popa, M., & Ecovoiu, A. A. (2016). Drosophosphotoxicology: An emerging research area for assessing nanoparticles interaction with living organisms. *International Journal of Molecular Sciences*, 17(2), Article 36.
- Chimbekujwo, K. I., Sani, A. R., Oyewole, O. A., & Isibor, P. O. (2024). Sources of nanoparticles. In P. O. Isibor, G. Devi, & A. A. Enuneku (Eds.), *Environmental nanotoxicology* (pp. 41–58). Springer.
- Choi, Y., Kim, J., Yu, S., & Hong, S. (2020). PH- and temperature-responsive radially porous silica nanoparticles with high-capacity drug loading for controlled drug delivery. *Nanotechnology*, 31(33), Article 335103.
- Choudhary, S. K., Mali, P. C., Jangir, R. N., Meena, S., & Tiwari, R. (2023). Applications of nanoparticles in agriculture improvement: A review. *SSR Institute of International Journal of Life Sciences*, 9(3), 3223–3228.
- Chowdhury, A. T., Rafa, N., Kabir, A., Selvakumar, P. M. (2022). Consumer nano-products for environment. In *Handbook of consumer nanoproducts* (pp. 1169–1200). Springer, Singapore.
- Darlington, T. K., Neigh, A. M., Spencer, M. T., Guyen, O. T., & Oldenburg, S. J. (2009). Nanoparticle characteristics affecting environmental fate and transport through soil. *Environmental Toxicology and Chemistry: An International Journal*, 28(6), 1191–1199.
- Das, S., Yadav, A., & Debnath, N. (2019). Entomotoxic efficacy of aluminium oxide, titanium dioxide, and zinc oxide nanoparticles against *Sitophilus oryzae* (L.): A comparative analysis. *Journal of Stored Products Research*, 83, 92–96.
- Dasgupta, N., Ranjan, S., & Ramalingam, C. (2017). Applications of nanotechnology in agriculture and water quality management. *Environmental Chemistry Letters*, 15, 591–605.
- Dave, P. N., & Chaturvedi, S. (2021). The economic contributions of nanotechnology to green and sustainable growth. In C. Hussain & V. Kumar (Eds.), *Handbook of functionalized nanomaterials* (pp. 365–380). Elsevier.
- De Matteis, V. (2017). Exposure to inorganic nanoparticles: Routes of entry, immune response, biodistribution, and in vitro/in vivo toxicity evaluation. *Toxics*, 5(4), Article 29.
- de Moraes, M. T., Debiasi, H., Franchini, J. C., Mastroberti, A. A., Levien, R., Leitner, D., & Schnepf, A. (2020). Soil compaction impacts soybean root growth in an Oxisol from subtropical Brazil. *Soil and Tillage Research*, 200, Article 104611.

- De Volder, M., Tawfick, S. H., Baughman, R. H., & Hart, A. J. (2013). Carbon nanotubes: Present and future commercial applications. *Science*, 339, 535–539.
- Dhanapal, A. R., Thiruvengadam, M., Vairavanathan, J., Venkidasamy, B., Easwaran, M., & Ghorbanpour, M. (2024). Nanotechnology approaches for the remediation of agricultural polluted soils. *ACS Omega*, 9, 13522–13533.
- Diab, R., Canilho, N., Pavel, I. A., Haffner, F. B., Girardon, M., & Pasc, A. (2017). Silica-based systems for oral delivery of drugs, macromolecules, and cells. *Advances in Colloid and Interface Science*, 249, 346–362.
- Elahe, D., Hossein, B., & Pouya, Z. (2024). Effect of oxide nanoparticles on soil water retention curve and soil tensile strength. *Pedosphere*, 34(6), 1136–1145.
- Elmi, C. (2023). Physical-chemical properties of nano-sized phyllosilicates: Recent environmental and industrial advancements. *Encyclopedia*, 3(4), 1439–1460.
- El-Sharkawy, M., Mahmoud, E., Abd El-Aziz, M., & Khalifa, T. (2022). Effect of zinc oxide nanoparticles and soil amendments on wheat yield, physiological attributes, and soil properties grown in saline-sodic soil. *Communications in Soil Science and Plant Analysis*, 53(17), 2170–2186.
- Faizan, M., Bhat, J. A., El-Serehy, H. A., Moustakas, M., & Ahmad, P. (2022). Magnesium oxide nanoparticles (MgO-NPs) alleviate arsenic toxicity in soybean by modulating photosynthetic function, nutrient uptake, and antioxidant potential. *Metals*, 12(12), Article 2030.
- Fakhim, B., Hassani, A., Rashidi, A., & Ghodousi, P. (2012). Predicting the impact of multiwalled carbon nanotubes on the cement hydration products and durability of cementitious matrix using artificial neural network modeling technique. *The Scientific World Journal*, 2013(1), Article 103713.
- Feng, S., Zhang, P., Hu, Y., Jin, F., Liu, Y., Cai, S., & Dang, X. (2022). Combined application of biochar and nano-zeolite enhanced cadmium immobilization and promoted the growth of Pak Choi in cadmium contaminated soil. *NanoImpact*, 28, Article 100421.
- Ferretti, G., Rosinger, C., Diaz-Pines, E., Faccini, B., Coltorti, M., & Keiblinger, K. M. (2024). Soil quality increases with long-term chabazite-zeolite tuff amendments in arable and perennial cropping systems. *Journal of Environmental Management*, 354, Article 120303.
- Florek, J., Caillard, R., & Kleitz, F. (2017). Evaluation of mesoporous silica nanoparticles for oral drug delivery—current status and perspective of MSNs drug carriers. *Nanoscale*, 9(40), 15252–15277.
- Food and Agriculture Organization of the United Nations. (2017). *The future of food and agriculture—Trends and challenges*.
- Fu, P. P., Xia, Q., Hwang, H. M., Ray, P. C., & Yu, H. (2014). Mechanisms of nanotoxicity: Generation of reactive oxygen species. *Journal of Food and Drug Analysis*, 22(1), 64–75.
- Gao, X., Rodrigues, S. M., Spielman-Sun, E., Lopes, S. P., Rodrigues, S., Zhang, Y., Avellan, A., Duarte, R. M., Duarte, A. C., Casman, E. A., & Lowry, G. V. (2019). Effect of soil organic matter, soil pH, and moisture content on solubility and dissolution rate of CuO NPs in soil. *Environmental Science & Technology*, 53(9), 4959–4967.
- Gao, Y., Chen, S., Yang, M., Hao, Z., Wang, X., & Shi, Y. (2024). Nano calcium carbonate improves wheat nitrogen accumulation and grain yield by enhancing soil nitrogen supply and flag leaf photosynthetic characteristics. *Field Crops Research*, 310, Article 109341.
- Gao, Y., Dong, C., Chen, S., Li, Y., & Shi, Y. (2023). Effect of nano carbon and nano calcium carbonate application on soil nutrient dynamics in winter wheat (*Triticum aestivum* L.). *Communications in Soil Science and Plant Analysis*, 54(20), 2800–2812.
- García, S., Trejo, P., Ramírez, O., López-Molina, J., & Hernández, N. (2017, September). Influence of nanosilica on compressive strength of lacustrine soft clays. In *Proceedings of the 19th international conference on soil mechanics and geotechnical engineering* (pp. 369–372).
- Gill, S., Ramzan, M., Naz, G., Ali, L., Danish, S., Ansari, M. J., & Salmen, S. H. (2024). Effect of silicon nanoparticle-based biochar on wheat growth, antioxidants, and nutrients concentration under salinity stress. *Scientific Reports*, 14(1), Article 6380.
- Giraldo, J. P., Landry, M. P., Faltermeier, S. M., McNicholas, T. P., Iverson, N. M., Boghossian, A. A., Reuel, N. F., Hilmer, A. J., Sen, F. G., Brew, J. A., & Strano, M. S. (2014). Plant nanobionics approach to augment photosynthesis and biochemical sensing. *Nature Materials*, 13(4), 400–408.
- Goodarzi, A., Ghasemipana, A., Moayed, R. Z., & Niroumand, H. (2020). Influence of nanosilica particles on improvement of clayey soil. *International Journal of Geotechnical and Geological Engineering*, 14(1), 40–48.
- Gupta, A., Rayeen, F., Mishra, R., Tripathi, M., & Pathak, N. (2023). Nanotechnology applications in sustainable agriculture: An emerging ecofriendly approach. *Plant Nano Biology*, 4, Article 100033.
- Gupta, S., & Bharti, M. K. (2022). Nanowaste disposal and recycling. In M. Rai & T. A. Nguyen (Eds.), *Micro and nano technologies: Nanomaterials recycling* (pp. 109–123). Elsevier.
- Haeri, S. M., & Valishzadeh, A. (2021). Evaluation of using different nanomaterials to stabilize the collapsible loessial soil. *International Journal of Civil Engineering*, 19(5), 583–594.
- Hamad, H. T., Al-Sharify, Z., Al-Najjar, S. Z., & Gadooa, Z. A. (2020). A review on nanotechnology and its applications on fluid flow in agriculture and water resources. *IOP Conference Series: Materials Science and Engineering*, 870, Article 012038.
- Harsh, H., Moghal, A. A. B., Rasheed, R. M., & Almajed, A. (2023). State-of-the-art review on the role and applicability of select nano-compounds in geotechnical and geoenvironmental applications. *Arabian Journal for Science and Engineering*, 48(4), 4149–4173.
- Hayes, K. L., Mui, J., Song, B., Sani, E. S., Eisenman, S. W., Sheffield, J. B., & Kim, B. (2020). Effects, uptake, and translocation of aluminum oxide nanoparticles in lettuce: A comparison study to phytotoxic aluminum ions. *Science of the Total Environment*, 719, Article 137393.
- Herrero-Latorre, C., Alvarez-Méndez, J. C., Barciela-García, J., García-Martín, S., & Peña-Creciente, R. M. (2015). Characterization of carbon nanotubes and analytical methods for their determination in environmental and biological samples: A review. *Analytica Chimica Acta*, 853, Article 77–94.
- Holmberg, B. A., Wang, H., Norbeck, J. M., & Yan, Y. (2003). Controlling size and yield of zeolite Y nanocrystals using tetramethylammonium bromide. *Microporous and Mesoporous Materials*, 59(1), 13–28.
- Hsu, C., Rheima, A. M., Mohammed, M. S., Kadhim, M. M., Mohammed, S. H., Abbas, F. H., Abed, Z. T., Mahdi, Z. M., Abbas, Z. S., Hachim, S. K., Ali, F. K., Mahmoud, Z. H., & Kianfar, E. (2023). Application of carbon nanotubes and graphene-based nanoadsorbents in water treatment. *BioNanoScience*, 13, 1418–1436.
- Hu, F., Li, S., Xu, C., Gao, X., Miao, S., Ding, W., Liu, X., & Li, H. (2019). Effect of soil particle interaction forces in a clay-rich soil on aggregate breakdown and particle aggregation. *European Journal of Soil Science*, 70(2), 268–277.
- Huang, Y., Li, P., Zhao, R., Zhao, L., Liu, J., Peng, S., Fu, X., Wang, X., Luo, R., Wang, R., & Zhang, Z. (2022). Silica nanoparticles: Biomedical applications and toxicity. *Biomedicine and Pharmacotherapy*, 151, Article 113053.
- Iqbal, A., Khan, T. F., & Iqbal, Y. (2024). Nanobiotechnology. In M. I. Malik, D. Hussain, M. R. Shah, & D.-S. Guo (Eds.), *Micro and nano technologies: Handbook of nanomaterials*, Volume 2 (pp. 685–713). Elsevier.
- Iravani, R., An, C., Adamian, Y., & Mohammadi, M. (2022). A review on the use of nanoclay adsorbents in environmental pollution control. *Water, Air, & Soil Pollution*, 233(4), Article 109.
- Jain, A., Wadhawan, S., & Mehta, S. K. (2022). Nanoparticles-based adsorbents for water pollutants removal. In R. Das & B. B. Saha (Eds.), *Rapid refrigeration and water protection* (pp. 237–265). Springer Water. Springer, Cham.
- Jiang, D., Zeng, G., Huang, D., Chen, M., Zhang, C., Huang, C., & Wan, J. (2018). Remediation of contaminated soils by enhanced nanoscale zero valent iron. *Environmental Research*, 163, 217–227.
- Johari, A., Golkarfard, H., Davoudi, F., & Fazeli, A. (2021). A predictive model based on the experimental investigation of collapsible soil treatment using nano-clay in the Sivand Dam region, Iran. *Bulletin of Engineering Geology and the Environment*, 80, 6725–6748.
- Joudeh, N., & Linke, D. (2022). Nanoparticle classification, physicochemical properties, characterization, and applications: A comprehensive review for biologists. *Journal of Nanobiotechnology*, 20(1), Article 262.
- Kang, S., Mauter, M. S., & Elimelech, M. (2008). Physicochemical determinants of multiwalled carbon nanotube bacterial cytotoxicity. *Environmental Science and Technology*, 42(19), 7528–7534.
- Kanjana, D. (2017). Advancement of nanotechnology applications on plant nutrients management and soil improvement. In R. Prasad, V. Kumar, & M. Kumar (Eds.), *Nanotechnology* (pp. 209–234). Springer.
- Kannan, G., O'Kelly, B. C., & Sujatha, E. R. (2023). Geotechnical investigation of low-plasticity organic soil treated with nano-calcium carbonate. *Journal of Rock Mechanics and Geotechnical Engineering*, 15(2), 500–509.
- Kantesaria, N., & Sharma, S. (2020). Exfoliation and extraction of nanoclay from montmorillonite mineral rich bentonite soil. In A. Prashant, A. Sachan, & C. S. Desai (Eds.), *Advances in computer methods and geomechanics: IACMAG symposium 2019* (Vol. 56, pp. 1–12). Springer.
- Kareem, H. A., Adeel, M., Azeem, M., Ahmad, M. A., Shakoar, N., Hassan, M. U., Saleem, S., Irshad, A., Niu, J., Guo, Z., Branko, C., Holubowicz, R., & Wang, Q. (2023). Antagonistic impact on cadmium stress in alfalfa supplemented with nano-zinc oxide and biochar via upregulating metal detoxification. *Journal of Hazardous Materials*, 443, Article 130309.
- Kataki, M. S., Kakoti, B. B., Deka, K., & Rajkumari, A. (2022). Nanotechnology applications in natural nanoclays production and application for better sustainability. In *Nanotechnology in the agriculture sector* (pp. 159–171). Wiley.
- Kleandrova, V. V., Luan, F., González-Díaz, H., Ruso, J. M., Speck-Planche, A., & Cordeiro, M. N. (2014). Computational tool for risk assessment of nanomaterials: Novel QSTR-perturbation model for simultaneous prediction of ecotoxicity and cytotoxicity of uncoated and coated nanoparticles under multiple experimental conditions. *Environmental Science & Technology*, 48(24), 14686–14694.
- Komendova, R., Židek, J., Berka, M., Jemelková, M., Řezáčová, V., Conte, P., & Kučerík, J. (2019). Small-sized platinum nanoparticles in soil organic matter: Influence on water holding capacity, evaporation, and structural rigidity. *The Science of the Total Environment*, 694, Article 133822.

- Konate, A., He, X., Zhang, Z., Ma, Y., Zhang, P., Alugongo, G. M., & Rui, Y. (2017). Magnetic (Fe_3O_4) nanoparticles reduce heavy metals uptake and mitigate their toxicity in wheat seedling. *Sustainability*, 9(5), Article 790.
- Kong, D., Corr, D. J., Hou, P., Yang, Y., & Shah, S. P. (2015). Influence of colloidal silica sol on fresh properties of cement paste as compared to nano-silica powder with agglomerates in micron-scale. *Cement and Concrete Composites*, 63, 30–41.
- Kotresha, K., Mohammed, S. A. S., Sanaulla, P. F., Moghal, A. A. B., & Moghal, A. A. B. (2021). Evaluation of sequential extraction procedure (SEP) to validate binding mechanisms in soils and soil-nano-calcium silicate (SNCS) mixtures. *Indian Geotech Journal*, 51(4), 1069–1077.
- Krishnan, J., & Shukla, S. (2019). The behaviour of soil stabilised with nanoparticles: An extensive review of the present status and its applications. *Arabian Journal of Geosciences*, 12(14), Article 436.
- Krug, H. F. (2014). Nanosafety research—Are we on the right track? *Angewandte Chemie International Edition*, 53(46), 12304–12319.
- Kulikova, N. A. (2021). Silver nanoparticles in soil: Input, transformation, and toxicity. *Eurasian Soil Science*, 54, 352–365.
- Kumar, A., Gupta, K., Dixit, S., Mishra, K., & Srivastava, S. (2019). A review on positive and negative impacts of nanotechnology in agriculture. *International Journal of Environmental Science and Technology*, 16, 2175–2184.
- Lead, J. R., Batley, G. E., Alvarez, P. J., Croteau, M. N., Handy, R. D., McLaughlin, M. J., Judy, J. D., & Schirmer, K. (2018). Nanomaterials in the environment: Behavior, fate, bioavailability, and effects—An updated review. *Environmental Toxicology and Chemistry*, 37(8), 2029–2063.
- Li, S., Anderson, T. A., Green, M. J., Maul, J. D., & Cañas-Carrell, J. E. (2013). Polyaromatic hydrocarbons (PAHs) sorption behavior unaffected by the presence of multi-walled carbon nanotubes (MWNTs) in a natural soil system. *Environmental Science: Processes and Impacts*, 15(6), 1130–1136.
- Li, W., He, Y., Wu, J., & Xu, J. (2012). Extraction and characterization of natural soil nanoparticles from Chinese soils. *European Journal of Soil Science*, 63(5), 754–761.
- Li, X., He, F., Wang, Z., & Xing, B. (2022). Roadmap of environmental health research on emerging contaminants: Inspiration from the studies on engineered nanomaterials. *Eco-Environment and Health*, 1(3), 181–197.
- Liu, G., Zhang, C., Zhao, M., Guo, W., & Luo, Q. (2020). Comparison of nanomaterials with other unconventional materials used as additives for soil improvement in the context of sustainable development: A review. *Nanomaterials*, 11(1), Article 15.
- Mahdavi, S., Karimi, R., & Valipouri Goudarzi, A. (2022). Effect of nano zinc oxide, nano zinc chelate, and zinc sulfate on vineyard soil Zn-availability and grapevines (*Vitis vinifera* L.) Yield and quality. *Journal of Plant Nutrition*, 45(13), 1961–1976.
- Mali, S. C., Raj, S., & Trivedi, R. (2020). Nanotechnology: A novel approach to enhance crop productivity. *Biochemistry and Biophysics Reports*, 24, Article 100821.
- Manjunatha, R. L., Naik, D., & Usharani, K. V. (2019). Nanotechnology application in agriculture: A review. *Journal of Pharmacognosy and Phytochemistry*, 8(3), 1073–1083.
- Martínez, G., Merinero, M., Pérez-Aranda, M., Pérez-Soriano, E. M., Ortiz, T., Villamor, E., Begines, B., & Alcudia, A. (2020). Environmental impact of nanoparticles' application as an emerging technology: A review. *Materials*, 14(1), Article 166.
- Mir, B. A., & Reddy, S. H. (2021). Mechanical behaviour of nano-material (Al_2O_3) stabilized soft soil. *International Journal of Engineering*, 34(3), 636–643.
- Moghal, A. A. B., Sanaulla, P. F., Mohammed, S. A. S., & Rasheed, R. M. (2023). Leaching test protocols to evaluate contaminant response of nano-calcium silicate-treated tropical soils. *Journal of Hazardous, Toxic, and Radioactive Waste*, 27(2), Article 04023002.
- Mohamed, E. F., & Awad, G. (2022). Development of nano-sensor and biosensor as an air pollution detection technique for the foreseeable future. *Comprehensive Analytical Chemistry*, 99, 163–188. <https://doi.org/10.1016/B978-0-12-820849-0.00009-4>
- Mohammadi, M., Khodaparast, M., & Rajabi, A. M. (2022). Effect of nano calcium carbonate (nano CaCO_3) on the strength and consolidation properties of clayey sand soil. *Road Materials and Pavement Design*, 23(10), 2394–2415.
- Mohammed, S., Abu, S., Sanaulla, P. F., & Kishore, S. R. (2023). Nano-based soil amendments for heavy metal retention in brown fields. *Journal of Mines, Metals & Fuels*, 71(8), 1099–1104.
- Morais, M. V. D. A., Nunes, M. R. D. S., Morais, C. D. D. N., Nascimento, R. R. D., & Rodriguez, A. F. R. (2024). Influence of the addition of carbon nanotube on the physical behavior of a lateritic soil from the southwest Amazon. *Soils and Rocks*, 47(4), Article e2024007523.
- Musee, N. (2011). Nanowastes and the environment: Potential new waste management paradigm. *Environment International*, 37(1), 112–128.
- Nath, H., Subhranshu, S. S., & Manohara, S. R. (2021). Current guidelines and regulatory challenges: Insight into the legal, societal, and ethical issues of nanomaterials. In H. K. Daima, S. L. Kothari, & B. S. Kumar (Eds.), *Nanotoxicology: Toxicity evaluation of nanomedicine applications* (1st ed., p. 19). CRC Press.
- National Research Council. (2006). *Geological and geotechnical engineering in the new millennium: Opportunities for research and technological innovation*. The National Academies Press.
- Niwa, M., Katada, N., & Okumura, K. (2010). *Characterization and design of zeolite catalysts: Solid acidity, shape selectivity, and loading properties* (Vol. 141). Springer Science and Business Media.
- Nohani, E., & Alimakan, E. (2015). The effect of nanoparticles on geotechnical properties of clay. *International Journal of Life Sciences*, 9, 25–27.
- O'Carroll, D. M., Sleep, B. E., Krol, M. M., Boparai, H. K., & Kocur, C. M. (2013). Nanoscale zero valent iron and bimetallic particles for contaminated site remediation. *Advances in Water Resources*, 51, 104–122.
- Ogunkunle, C. O., Gambari, H., Agbaje, F., Okoro, H. K., Asogwa, N. T., Vishwakarma, V., & Fatoba, P. O. (2020). Effect of low-dose nano titanium dioxide intervention on Cd uptake and stress enzyme activity in Cd-stressed cowpea (*Vigna unguiculata* (L.) Walp) plants. *Bulletin of Environmental Contamination and Toxicology*, 104(5), 619–626.
- Öncü, Ş., & Bilsel, H. (2017). Effect of zeolite utilization on volume change and strength properties of expansive soil as landfill barrier. *Canadian Geotechnical Journal*, 54(10), 1320–1330.
- O'Shaughnessy, P. T. (2013). Occupational health risk to nanoparticulate exposure. *Environmental Science: Processes and Impacts*, 15(1), 49–62.
- Oviedo, L. R., Rhoden, C. R. B., & da Silva, W. L. (2021). Nanozeolites from thermoelectric waste for application to wastewater treatment. *Disciplinarum Scientia: Naturae e Tecnológicas*, 22(2), 1–23.
- Palčić, A., & Catizzzone, E. (2021). Application of nanosized zeolites in methanol conversion processes: A short review. *Current Opinion in Green and Sustainable Chemistry*, 27, Article 100393.
- Pallas, G., Peijnenburg, W. J., Guinée, J. B., Heijungs, R., & Vijver, M. G. (2018). Green and clean: Reviewing the justification of claims for nanomaterials from a sustainability point of view. *Sustainability*, 10(3), Article 689.
- Parsaei, M., Rojhani, M., & Seyedahmadian, S. (2023). Effect of the addition of nano alumina on the mechanical properties of clay. *Geotechnical and Geological Engineering*, 41(6), 3767–3779.
- Patro, A., & Sahoo, R. R. (2022). Strength and microstructure evolution of soft soils by using nano-silica. In C. N. V. Satyanarayana Reddy, K. Muthukumar, N. Satyam, & R. Vaidya (Eds.), *Ground characterization and foundations: Proceedings of Indian geotechnical conference 2020 volume 1* (pp. 315–325). Springer.
- Pérez-Hernández, H., Fernández-Luqueño, F., Huerta-Lwanga, E., Mendoza-Vega, J., & Álvarez-Solis, J. D. (2020). Effect of engineered nanoparticles on soil biota: Do they improve the soil quality and crop production or jeopardize them? *Land Degradation & Development*, 31, 2213–2230.
- Pérez-Hernández, H., Pérez-Moreno, A., Sarabia-Castillo, C. R., García-Mayagoitia, S., Medina-Pérez, G., López-Valdez, F., Campos-Montiel, R. G., Jayanta-Kumar, P., & Fernández-Luqueño, F. (2021). Ecological drawbacks of nanomaterials produced on an industrial scale: Collateral effect on human and environmental health. *Water, Air, & Soil Pollution*, 232, 1–33.
- Pimsen, R., Porrawatkul, P., Nuengmatcha, P., Ramasoot, S., & Chanthai, S. (2021). Efficiency enhancement of slow release of fertilizer using nanozeolite-chitosan/sago starch-based biopolymer composite. *Journal of Coatings Technology and Research*, 18, 1321–1332.
- Pitla, S. K., Luck, J. D., Werner, J., Lin, N., & Shearer, S. A. (2016). In-field fuel use and load states of agricultural field machinery. *Computers and Electronics in Agriculture*, 121, 290–300.
- Qiu, J., Lyu, J. W., Yang, J. L., Cui, K. B., Liu, H. Z., Wang, G. F., & Liu, X. (2024). Review on preparation, modification and application of nano-calcium carbonate. *Particle & Particle Systems Characterization*, 41, Article 2400097.
- Rajabi, A. M., Sadeh, M., Mohammadrezaei, M. H., & Behnia, B. (2021). A laboratory investigation of the geomechanical properties of graphite stabilized clayey sands. *Arabian Journal of Geosciences*, 14, 1–10.
- Rajan, C. S. (2011). Nanotechnology in groundwater remediation. *International Journal of Environmental Science and Development*, 2(3), Article 182.
- Ramanathan, A. (2019). Toxicity of nanoparticles: Challenges and opportunities. *Applied Microscopy*, 49(1), Article 2.
- Rao, P., Dzinamarira, I., Shahabudeen, F., Chikambwe, V., & Padil, V. V. T. (2024). Contribution of nanoclay toward sustainable agriculture. In V. V. T. Padil (Ed.), *Nanoclay-Based Sustainable Materials* (pp. 369–384). Elsevier.
- Rashmi, I., Meena, B. P., Rajendiran, S., Jayaraman, S., Joshy, C. G., Ali, S., Mina, B. L., Kumar, K., Kumar, A., Kumawat, A., & Kala, S. (2024). Can gypsum and organic amendments achieve sustainability, productivity, and maintain soil health under soybean-mustard cropping in sodic soils of western India? *Soil and Tillage Research*, 240, Article 106075. <https://doi.org/10.1016/j.still.2024.106075>
- Rathore, A., & Mahesh, G. (2021). Public perception of nanotechnology: A contrast between developed and developing countries. *Technology in Society*, 67, Article 101751.
- Richard, J., Phimpachan, A., Jamet-Fournier, A., Cacciaguerra, T., Dieudonné-George, P., Cot, D., & Gérardin, C. (2022). Dual control of external surface and internal pore structure of small ordered mesoporous silica particles directed by mixed polyion complex micelles. *Microporous and Mesoporous Materials*, 338, Article 111915.
- Rizwan, M., Ali, S., Ali, B., Adrees, M., Arshad, M., Hussain, A., Zia ur Rehman, M., & Waris, A. A. (2019). Zinc and iron oxide nanoparticles improved the plant

- growth and reduced the oxidative stress and cadmium concentration in wheat. *Chemosphere*, 214, 269–277.
- Salami, B. A., Oyeahan, T. A., Gambo, Y., Badmus, S. O., Tanimu, G., Adamu, S., & Saleh, T. A. (2022). Technological trends in nanosilica synthesis and utilization in advanced treatment of water and wastewater. *Environmental Science and Pollution Research*, 29(28), 42560–42600.
- Sathurusinghe, S. A. S. P., Herath, W. M. N. A. P. B., Subhashini, H., & Herath, K. (2012). Stress concentrations in single-walled carbon nanotube reinforced metal and polymer composites under uniaxial loading. *IJ Advanced Structural Geotechnical Engineering*, 1(2), 58–60.
- Seif, S., Marofi, S., & Mahdavi, S. (2019). Removal of Cr³⁺ ion from aqueous solutions using MgO and montmorillonite nanoparticles. *Environmental Earth Sciences*, 78, 1–10.
- Selvam, E., Parsapur, R. K., Hernandez-Tamargo, C. E., de Leeuw, N. H., & Selvam, P. (2020). Nanostructured zeolite with brain-coral morphology and tailored acidity: A self-organized hierarchical porous material with MFI topology. *CrysoEngComm*, 22(38), 6275–6286.
- Shaheb, M. R., Venkatesh, R., & Shearer, S. A. (2021). A review on the effect of soil compaction and its management for sustainable crop production. *Journal of Biosystems Engineering*, 46, 417–439.
- Sharifnasab, H., & Abbasi, N. (2016). Effect of nanoclay particles on some physical and mechanical properties of soils. *Journal of Agricultural Machinery*, 6(1), 250–258.
- Sharma, A., Banyal, A., Sirjohn, N., Kulshreshtha, S., & Kumar, P. (2024). Nano-bio-technology and its applications in maintaining soil health. In R. K. Bhatia & A. Walia (Eds.), *Advancements in microbial biotechnology for soil health* (Vol. 50, Microorganisms for sustainability). Springer.
- Shukla, K., Mishra, V., Singh, J., Varshney, V., Verma, R., & Srivastava, S. (2024). Nanotechnology in sustainable agriculture: A double-edged sword. *Journal of the Science of Food and Agriculture*, 104(10), 5675–5688.
- Singh, P., Srivastava, S., & Singh, S. (2019). Nanosilica: Recent progress in synthesis, functionalization, biocompatibility, and biomedical applications. *ACS Biomaterials Science & Engineering*, 5(10), 4882–4898.
- Singh, R. P., Handa, R., & Manchanda, G. (2021). Nanoparticles in sustainable agriculture: An emerging opportunity. *Journal of Controlled Release*, 329, 1234–1248.
- Singh, S. P., & Endley, N. (2020). Fabrication of nano-silica from agricultural residue and their application. In A. Husen & M. Jawaid (Eds.), *Nanomaterials for agriculture and forestry applications* (pp. 107–134). Elsevier.
- Sonderegger, T., & Pfister, S. (2021). Global assessment of agricultural productivity losses from soil compaction and water erosion. *Environmental Science & Technology*, 55(18), 12162–12171.
- Spinazze, A., Zellino, C., Borghi, F., Campagnolo, D., Rovelli, S., Keller, M., Fanti, G., Cattaneo, A., & Cavallo, D. M. (2021). Carbon nanotubes: Probabilistic approach for occupational risk assessment. *Nanomaterials*, 11(2), Article 409.
- Stanley, J. K., Coleman, J. G., Weiss, C. A. Jr., & Steevens, J. A. (2010). Sediment toxicity and bioaccumulation of nano and micron-sized aluminum oxide. *Environmental Toxicology and Chemistry*, 29(2), 422–429.
- Stolte, J., Tesfai, M., Oygarden, L., Kvaerno, S., Keizer, J., Verheijen, F., & Hessel, R. (2016). *Soil threats in Europe: Status, methods, drivers and effects on ecosystem services: Deliverable 2.1 RECARE project*.
- Suman, T. Y., & Pei, D.-S. (2022). Nanomaterial waste management. In M. Rai & T. A. Nguyen (Eds.), *Nanomaterials recycling* (pp. 21–36). Elsevier.
- Sun, H., Zhou, S., Jiang, Y., Xi, X., Tan, Y., Zhang, G., Jiang, N., Zhou, T., Yin, X., Wang, M., & Gao, B. (2022). Fate and transport of engineered nanoparticles in soils and groundwater. In B. Gao (Ed.), *Emerging contaminants in soil and groundwater systems* (pp. 205–251). Elsevier.
- Świdwińska-Gajewska, A. M. (2007). Nanoparticles (part 2): Advantages and health risk. *Medycyna Pracy*, 58(30), 253–263.
- Tabarsa, A., Latifi, N., Meehan, C. L., & Manahiloh, K. N. (2018). Laboratory investigation and field evaluation of loess improvement using nanoclay—A sustainable material for construction. *Construction and Building Materials*, 158, 454–463.
- Taha, M. R., & Taha, O. M. E. (2012). Influence of nano-material on the expansive and shrinkage soil behavior. *Journal of Nanoparticle Research*, 14, 1–13.
- Taha, M. R., Alsharif, J., Al-Mansob, R. A., & Khan, T. A. (2018). Effects of nano-carbon reinforcement on the swelling and shrinkage behaviour of soil. *Sains Malaysiana*, 47, 195–205.
- Taha, M. R., Alsharif, J., Khan, T. A., Aziz, M., & Gaber, M. (2018). Compressive and tensile strength enhancement of soft soils using nanocarbons. *Geomechanics and Engineering*, 16, 559–567.
- Taha, O. M. E., & Taha, M. R. (2016). Soil-water characteristic curves and hydraulic conductivity of nanomaterial-soil-bentonite mixtures. *Arabian Journal of Geosciences*, 9(1), Article 12.
- Tee, J. K., Ong, C. N., Bay, B. H., Ho, H. K., & Leong, D. T. (2016). Oxidative stress by inorganic nanoparticles. *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology*, 8(3), 414–438.
- Terrones, M. (2004). Carbon nanotubes: Synthesis and properties, electronic devices, and other emerging applications. *International Materials Reviews*, 49(5), 325–377.
- Thomas, S., Chandrakaran, S., & Sankar, N. (2023). Effect of nano-calcium carbonate on the geotechnical and microstructural characteristics of highly plastic paddy clay. *Arabian Journal for Science and Engineering*, 48(10), 12977–12989.
- Tiwari, D. K., Dasgupta-Schubert, N., Villaseñor Cendejas, L. M., Villegas, J., Carreto Montoya, L., & Borjas García, S. E. (2014). Interfacing carbon nanotubes (CNT) with plants: Enhancement of growth, water, and ionic nutrient uptake in maize (*Zea mays*) and implications for nanoagriculture. *Applied Nanoscience*, 4(6), 577–591.
- Tsintsikaladze, G., Eprikashvili, L., Mumladze, N., Gabunia, V., Sharashenidze, T., Zautashvili, M., Kordzakhia, T., & Shatakishvili, T. (2017). Nitrogenous zeolite nanomaterial and the possibility of its application in agriculture. *Annals of Agrarian Science*, 15(3), 365–369.
- Vecchio, G., Galeone, A., Malvindi, M. A., Cingolani, R., & Pompa, P. P. (2013). Ranking the in vivo toxicity of nanomaterials in *Drosophila melanogaster*. *Journal of Nanoparticle Research*, 15, 1–7.
- Verleyen, E., Wagner, T., Lipinski, H. G., Kägi, R., Koeber, R., Boix-Sanfeliciu, A., De Temmerman, P. J., & Mast, J. (2019). Evaluation of a TEM-based approach for size measurement of particulate (nano) materials. *Materials*, 12(14), Article 2274.
- Wang, M., Gao, B., & Tang, D. (2016). Review of key factors controlling engineered nanoparticle transport in porous media. *Journal of Hazardous Materials*, 318, 233–246.
- Warheit, D. B., Sayes, C. M., Reed, K. L., & Swain, K. A. (2008). Health effects related to nanoparticle exposures: Environmental, health and safety considerations for assessing hazards and risks. *Pharmacology and Therapeutics*, 120(1), 35–42.
- Weiberg, E., Bonnier, A., & Finné, M. (2021). Land use, climate change and 'boom-bust' sequences in agricultural landscapes: Interdisciplinary perspectives from the Peloponnese (Greece). *Journal of Anthropological Archaeology*, 63, Article 101319.
- Wieland, L., Li, H., Rust, C., Chen, J., & Flavel, B. S. (2021). Carbon nanotubes for photovoltaics: From lab to industry. *Advanced Energy Materials*, 11(3), Article 2002880.
- Xu, G., Zheng, Q., Yang, X., Yu, R., & Yu, Y. (2021). Freeze-thaw cycles promote vertical migration of metal oxide nanoparticles in soils. *Science of the Total Environment*, 795, Article 148894.
- Xu, T., & Jiang, J. (2023). On the configuration of the graphene/carbon nanotube/graphene van der Waals heterostructure. *Physical Chemistry Chemical Physics*, 25(6), 5066–5072.
- Yadav, A., Yadav, K., & Abd-El Salam, K. A. (2023). Exploring the potential of nanofertilizers for a sustainable agriculture. *Plant Nano Biology*, 5, Article 100044.
- Yamini, V., Shanmugam, V., Rameshpathy, M., Venkatraman, G., Ramanathan, G., Garalleh, H. A., Hashmi, A., Brindhadevi, K., & Rajeswari, V. D. (2023). Environmental effects and interaction of nanoparticles on beneficial soil and aquatic microorganisms. *Environmental Research*, 236, Article 116776.
- Yilmaz, B., & Müller, U. (2009). Catalytic applications of zeolites in the chemical industry. *Topics in Catalysis*, 52, 888–895.
- Younis, S. A., Kim, K. H., Shaheen, S. M., Antoniadis, V., Tsang, Y. F., Rinklebe, J., & Brown, R. J. (2021). Advancements of nanotechnologies in crop promotion and soil fertility: Benefits, life cycle assessment, and legislation policies. *Renewable and Sustainable Energy Reviews*, 152, Article 111686.
- Youssef, Y. M., Gemal, K. S., Atia, H. M., & Mahdy, M. (2024). Insight into land cover dynamics and water challenges under anthropogenic and climatic changes in the eastern Nile Delta: Inference from remote sensing and GIS data. *Science of the Total Environment*, 913, Article 169690.
- Yu, C., Mawodza, T., Atkinson, B. S., Atkinson, J. A., Sturrock, C. J., Whalley, R., Hawkesford, M. J., Cooper, H., Zhang, X., Zhou, H., & Mooney, S. J. (2024). The effects of soil compaction on wheat seedling root growth are specific to soil texture and soil moisture status. *Rhizosphere*, 29, Article 100838.
- Yukselen-Aksoy, Y. (2010). Characterization of two natural zeolites for geotechnical and geoenvironmental applications. *Applied Clay Science*, 50(1), 130–136.
- Zewdu, D., Krishnan, M. C., & Raj, P. P. N. (2024). Nanoclay for climate change adaptation and mitigation: A critical review. In V. V. T. Padil (Ed.), *Nanoclay-based sustainable materials* (pp. 151–166). Elsevier.
- Zhang, G. (2007). Soil nanoparticles and their influence on engineering properties of soils. In D. J. DeGroot, C. Vipulanandan, J. A. Yamamoto, V. N. Kaliakin, P. V. Lade, M. Zeghal, U. El Shamy, N. Lu, & C. R. Song (Eds.), *Advances in measurement and modeling of soil behavior* (pp. 1–13). American Society of Civil Engineers (ASCE).
- Zhang, X., Gao, J., Fan, H., Li, X., Gao, Z., Xue, L., & Sun, S. (2020). Study on the mechanism of nano-SiO₂ for improving the properties of cement-based soil stabilizer. *Nanomaterials*, 10(3), Article 405.
- Zheng, Y., Chen, X., Joseph, N. D., Zhang, Y., Chen, H., & Gao, B. (2022). Occurrences and impacts of engineered nanoparticles in soils and groundwater. In B. Gao (Ed.), *Emerging contaminants in soil and groundwater systems* (pp. 165–204). Elsevier.