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REVIEW ARTICLE

Insights of nanoclay as a soil conditioner: Enhancing soil physical properties for sustainable soil health

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Abstract

Nanoclays are clay minerals of extremely small particle sizes, typically in the nanometer range, that have emerged as a versatile tool in agriculture due to their unique properties such as high aspect ratio with layered structure, adsorption and ion-exchange capacity. Moreover, Nanoclays are identified as a potential nanocarrier for controlled release of nutrients, while they can also be used as a soil amendment to improve soil properties. This review examines the potential of nanoclay application to improve the physical properties of various soil types. The paper explores how nanoclay additions influence dispersive soils, soft soils, clay and silt soils and coarse-grained soils. Studies on the impact of nanoclay on key physical properties like shear strength, water retention, consistency limits, density, plasticity limit, stability and susceptibility to wind erosion are addressed. The underlying mechanisms by which nanoclay modifies soil behaviour are discussed, focusing on factors like particle interaction, pore space reduction and improved aggregation. Additionally, the review underscores the potential of nanoclay as a sustainable strategy for geotechnical engineering applications and soil erosion control. However, the application of nanoclay in agricultural soils is still in its early stages, with limited large-scale field validation. Understanding its interactions with different soil types and environmental conditions is critical for optimizing its use to bridge knowledge gaps and support the development of nanoclay-based soil management practices.

Keywords: clay; nanoclay; physical properties; soil amendment

Introduction

Conventional agriculture has been largely dependent on intensive chemical inputs that play a major role in increasing food productivity to meet human demands. In recent years, farmers use an excess amount of fertilizers and pesticides, which results in decreased soil quality (1). Soil serves as the fundamental base for crop cultivation and is essential for maintaining sustainable agricultural practices (2). The chemical and mechanical processes, such as weathering and erosion, have altered the soil over a period of time (3). Sand, silt and clay are important fractions that determine several physical and chemical properties in the soil. Among these, clay has a huge impact on texture, water retention, fertility and consistency, playing a significant role in maintaining the soil health and productivity (4). Conventional practices, namely reduced tillage, cover cropping, crop rotation and the incorporation of organic and inorganic amendments such as compost and gypsum, are commonly used to improve soil properties. While these practices are effective in enhancing soil health over time, they are often slow-acting and may not produce immediate results. Additionally, their effectiveness can vary significantly depending on soil type, climate and management conditions. Some practices, like heavy organic amendment, may lead to nutrient imbalances or leaching if not carefully managed. Moreover, long-term application of certain amendments may contribute to salinity or heavy metal accumulation. As such, these traditional approaches, though valuable, may not always provide a timely or universally suitable solution for degraded or problematic soils. (5). Furthermore, the continued reliance on chemical-intensive methods has contributed to serious environmental degradation, including contamination of soil and water resources and biodiversity loss. Addressing these challenges calls for the adoption of sustainable agricultural practices that prioritize soil regeneration, environmental conservation and long-term productivity. Hence, alternate strategies are the need of the hour for effective soil management. Nanotechnology is gaining traction in agriculture for its role in controlled nutrient release and enhancing nutrient use efficiency through modifying the functional properties of materials for effective plant growth (6).

Significant advancements have been made in the field of nanotechnology to improve soil quality (7). The nano perspective of soil deals with particles with sizes ranging from as small as 1 nm to as large as 75 mm (8). Nanomaterials that exist in the soil environment interact very actively with other soil constituents including the liquid phase, cations and organic matter, having a greater influence on the microstructure and the physical, chemical properties of soils, due to their high surface area and reactivity (9). The presence of nanoporosity in some nanoparticles significantly influences soil properties by increasing the specific surface area, water retention, absorption and reducing bulk density even in a smaller fraction (9). Nanoclay is found to be a potential alternative to conventional soil management practices due to its unique properties at the nanoscale, such as high surface area and particle size, which result in enhanced nutrient delivery and water retention (10). This has led scientists to investigate its potential benefits for soil health by investigating how nanoclay might impact some key physical properties of soil. The addition of nanoclay increases the strength and stability of soil, making it more resistant to erosion and contamination (10). This paper critically examines how nanoclay influences the physical properties of various soil types and discusses its role in promoting sustainable soil health.

Properties of soil

Soil is a complex and vital mixture made up of minerals, organic matter, air, water and tiny organisms. Soil properties significantly affect plant health, water movement and nutrient availability. Soil properties are commonly classified as physical, chemical and biological (11). Physical properties like texture, structure and porosity are determined by the size and arrangement of mineral particles. The texture of soil, determined by the proportions of sand, silt and clay, plays a crucial role in its water retention and drainage abilities. Sandy soils drain quickly but struggle to retain moisture, while clay soils hold water effectively but can become waterlogged. Loam, a balanced mix of sand, silt and clay, is considered the ideal soil texture for most plants. Soil structure, which refers to how particles are organized into aggregates, impacts air circulation and root penetration. Well-structured soil allows for healthy root systems, while compacted soil can hinder growth. Porosity or the amount of space between soil particles, influences water retention and air movement. Chemical properties, such as pH, indicate its acidity or alkalinity and affect nutrient availability for plants, with most preferring slightly acidic to neutral soil. The cation exchange capacity (CEC) determines how well soil can hold essential nutrients like calcium and potassium. Biological properties depend on the types and numbers of organisms living in the soil and organic matter, which play a crucial role in keeping the soil healthy by breaking down organic matter, cycling nutrients and maintaining its structure (12). All these properties are interconnected and influence how well soil functions, making it an important natural resource.

Physical properties

Soil is a complex and dynamic system characterized by a range of properties that critically influence its ability to support plant growth and maintain ecosystem functions. A thorough understanding of these physical attributes is essential for the effective management and conservation of soil health. Though often perceived as mere dirt, soil encompasses a complex array of physical properties that determine its ability to sustain life (13). These properties are determined by the size, shape and arrangement of tiny mineral particles within the soil (14). Soil texture is considered one of the key properties referring to the relative proportions of sand, silt and clay particles. Sandy soils drain well but hold less water, while clay soils retain water but can become waterlogged (15). Another critical property is structure, which describes how these particles clump together. Good structure allows for air pockets, providing oxygen to plant roots and beneficial microbes. Poor structure restricts air and water flow, hindering plant growth (16). Porosity, the space between soil particles, is crucial for air and water movement, vital for healthy plants. Sandy soils have large pores that drain quickly, while clay soils have smaller pores that hold more water. Density, the weight of soil per unit volume, also plays a role. Soils with more organic matter like decomposed plant material, are less dense and have more pore space, allowing for better air and water movement. Among the soil particles clay has a greater influence on soil physical properties (17).

Clays and Clay Minerals

Clays are mainly inorganic materials having a diameter less than 0.005 mm. They undergo hydrolysis, resulting in the formation of minerals such as kaolinite and smectite (18). Clays exhibit the property of plasticity due to water absorption, which allows clay to mould into any form when they retain water (19). Further, mixing of one or more clay minerals is possible even in the presence of minimal quantities of SiO_2 and metal oxides, Al_2O_3 and MgO (18). Clay minerals are naturally occurring, fine-grained materials formed during the weathering process and belong to the phyllosilicate group. They are characterized by a layered structure composed of sheets of silicate tetrahedra (SiO_4) and aluminate octahedra (AlO_6) arranged in various configurations (20). The crystalline units of clay minerals can be classified into two categories based on the arrangement of ions. Silicon oxygen tetrahedron (silicon surrounded by four oxygen atoms) forms a silica sheet and aluminium or magnesium octahedron. Fig. 1 shows the results in the formation of gibbsite or brucite sheet (21). Based on the arrangement of sheets, the clay minerals are classified into 1:1, 2:1 and 2:1:1 clay minerals (22). The properties such as high surface area, cation exchange capacity, plasticity, shrinking and swelling behaviour with respect to water absorption are exhibited by clay and clay minerals (23).

Nanoclays

Nanoclays are processed form of clay minerals that belongs to phyllosilicates of about 1 nm thickness and have surfaces about 50 -150 nm in any one of the dimensions, which are stratified aluminosilicate sheets composed of aluminium and silicon oxides stacked on each other (22, 24, 25). These sheets are the basic structural unit, joined together by Van der Waals forces, electrostatic forces or hydrogen bridges that protect active molecules against environmental disintegration and ensure sustained release of active ingredient (26). The unique physical properties of nanoclay make them highly valuable in a wide range of applications over bulk clay minerals. They can be effectively used as a carrier for the controlled delivery of fertilizers, phytohormones and pesticides with more effective biological action due to low volume to high surface ratio (23). Nano clay is composed of 98 % of the montmorillonite constituent of smectite (27). They are widely used in industries such as ceramics, construction, agriculture, environmental remediation and pharmaceuticals (28). However, the application of nanoclay in agriculture as a soil amendment is limited and not much explored, which would enhance the soil quality.

Importance of nanoclay

Nanoclay has emerged as a promising nanomaterial in sustainable agriculture due to its multifaceted role in enhancing soil quality and crop productivity. Its high surface area and layered structure enable it to significantly reduce nutrient loss and increase the CEC of soils, thereby improving the retention and availability of

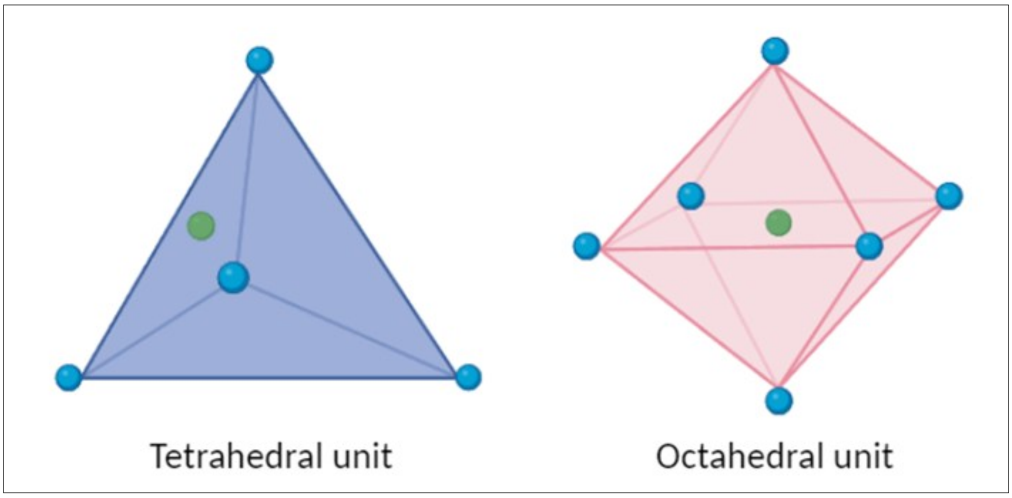

Fig. 1. Tetrahedral and octahedral sheet of clay minerals.

essential nutrients. Furthermore, nanoclay contributes to enhancing the water-holding capacity of soils, which is particularly beneficial under drought-prone conditions, ensuring better water availability to plants (29). Nanoclay enhances soil buffering capacity, helping stabilize pH and protect plants from sudden pH shifts. Application of nanoclay also significantly increases nutrient use efficiency, reducing the need for frequent or high-dosage fertilizers, thereby lowering environmental pollution such as nutrient runoff into water bodies, nitrate leaching into groundwater, soil contamination and greenhouse gas emissions. Nitrogen-loaded nanoclay-polymer composites have been shown to match or exceed crop yields using just 60 %-75 % of conventional fertilizer dosages. This improved efficiency also reduced N_2O emissions by about 15 %-18 % and buffered soil pH during crop growth, indicating enhanced soil health and resilience to pH fluctuations (30) (Fig. 2 & 3).

Classification of Nanoclays

Nanoclays can be classified based on their chemical composition and the shape of the clay mineral. Based on the arrangement of sheets, the clay minerals are classified into 1:1, 2:1 and 2:1:1 clay mineral (Fig. 4). The 1:1 Clay mineral structure consists of the association of a tetrahedral oxygen sheet with an octahedral hydroxyl sheet, establishing a hydrogen bond providing stability to the structure (31). In general, kaolinite and halloysite are less utilized as carriers for active components since kaolinite is nonexpendable in nature and halloysite has a hollow tubular shape (32). However, halloysite, when immersed in water with a pH between 3 and 8, its internal and external surfaces exhibit contrasting electrical charges during ionization due to the difference in dielectric properties of aluminum and silicon oxides. This unique property has been utilized as a carrier for bioactive compounds (32, 33). While the layered structure of 2:1 phyllosilicate is formed by two silicon (Si) tetrahedral sheets surrounded by an oxygen (O) octahedral sheet (31). Clay minerals such as vermiculite, pyrophyllite, mica and smectite are mostly used as a carrier for active molecules (22, 25). Chlorite mineral example of a 2:2 clay mineral, is mainly composed of a 2:1 layer, such as in vermiculite clay mineral. The main alternative with tri-octahedral magnesium sheet (also known as brucite) gives rise to a 2:1:1 ratio (34).

Properties of nanoclay

Despite its size, nanoclay possesses a unique set of properties that make it valuable in various applications. One key feature of nanoclay is its high aspect ratio. Nanoclay particles are similar, incredibly thin and flat, resulting in a much larger surface area for their size. The extensive surface area provides numerous sites for chemical reactions to occur and for molecules to be adsorbed. The high aspect ratio allows them to interact strongly with other materials at the molecular level, influencing their properties (35). Similarly, nanoclay exhibits a property called CEC, attracting and

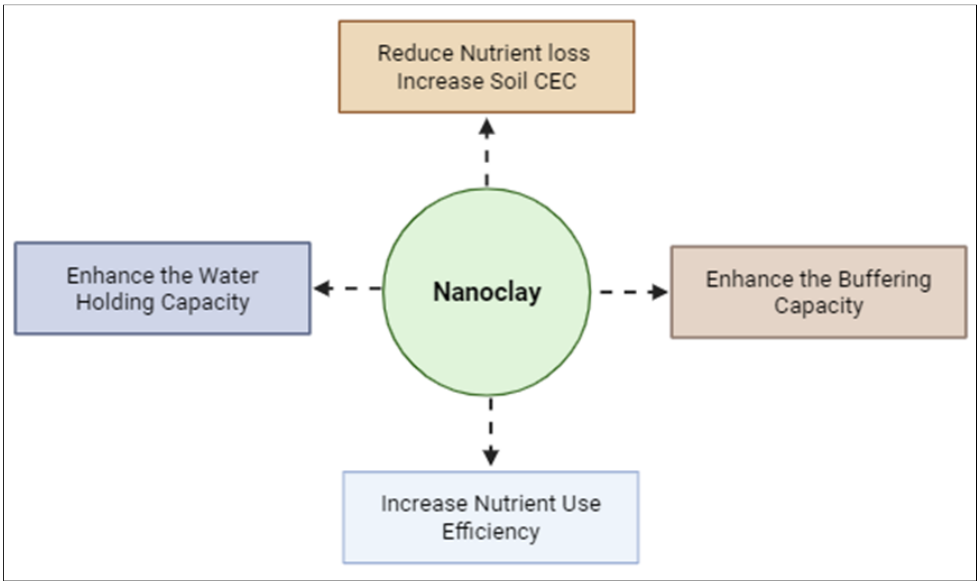

Fig. 2. Importance of nanoclay minerals.

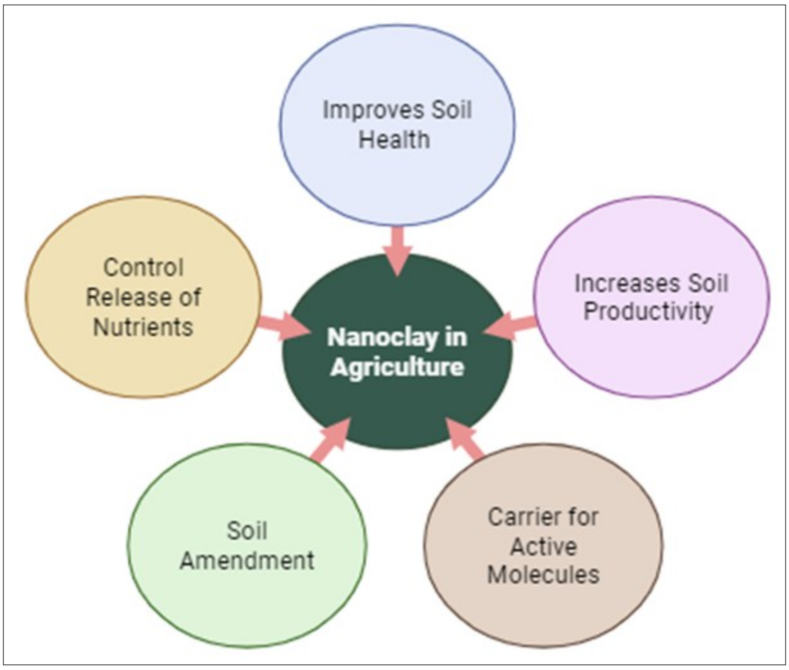

Fig. 3. Nanoclays in agriculture.

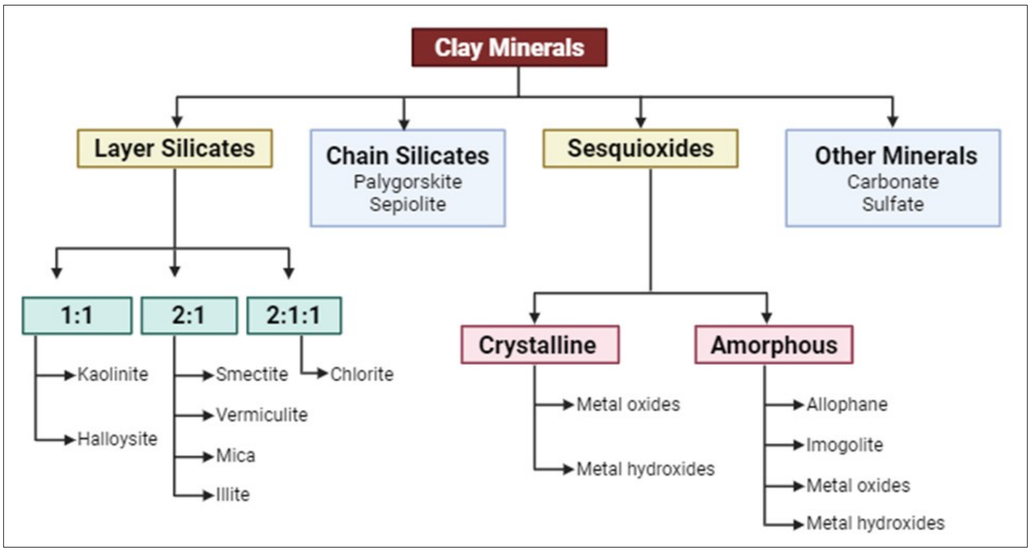

Fig. 4. Classification of clays.

holding onto positively charged ions (cations) and essential plant nutrients (potassium, calcium, magnesium) or even contaminants. This property makes nanoclay a potential tool for cleaning up polluted soil (remediation) and for controlled release of nutrients in agricultural applications. The layered structure of these microscopic particles can act as a barrier against various gases by creating a complex path that restricts the diffusion of gases, liquids and other substances (36). They can potentially restrict fire, making them additives for creating fire-retardant materials, ensuring products stay fresh and protected (37). Furthermore, nanoclay can act as a reinforcing agent when incorporated into other materials like polymers or composites. Nanoclay's strong interactions with the surrounding material can improve the overall strength, stiffness and dimensional stability of the composite material (38). For the environmentally conscious applications, some types of nanoclay are even biodegradable. This biodegradability makes them more suitable for certain applications where traditional, non-degradable materials might pose environmental concerns.

Synthesis of nanoclay minerals

The synthesis of nanoclay minerals can be achieved through both top-down and bottom-up approaches, depending on the desired particle size, structure and application. In top-down techniques, naturally occurring clay minerals such as montmorillonite or kaolinite are physically broken down to nanoscale dimensions using methods like ball milling and ultrasonication. Ball milling involves mechanical grinding under controlled conditions and is commonly used due to its scalability and cost-effectiveness, although prolonged milling can lead to structural damage or contamination (39). Ultrasonication, on the other hand, employs high-frequency sound waves to exfoliate layered clays into individual nanosheets and is particularly effective for achieving uniform dispersion (40). Conversely, bottom-up synthesis offers greater control over the morphology and purity of the final nanoclay product. The sol-gel method is a widely adopted chemical route in which metal alkoxides such as silicon and aluminium precursors undergo hydrolysis and condensation reactions to form nanostructured layered silicates. This method enables precise tuning of particle size, porosity and surface chemistry, making it suitable for advanced applications such as nano-fertilizers and smart delivery systems (41). Another prominent method is hydrothermal synthesis, where silicate and metal salts are treated under high-temperature and high-pressure conditions in autoclaves, leading to the crystallization of clay minerals with high structural order and purity (42). Additionally, co-precipitation techniques allow for the simultaneous formation of silicate and metal hydroxide layers in a controlled pH environment, facilitating the creation of synthetic clays with tailored properties (43).

Moreover, synthesized nanoclays are often subjected to surface modification such as organic functionalization with quaternary ammonium compounds or surfactants, to improve their compatibility in hydrophobic matrices or to enable controlled -release properties. These modifications enhance the performance of nanoclays in agricultural, environmental and material science applications by increasing stability, reactivity and dispersion (44). Overall, the synthesis and tailoring of nanoclay minerals open up versatile pathways for sustainable innovations in fields ranging from soil remediation to nano-enabled agrochemical delivery.

Conventional soil enhancement methods and shortcomings

Soil enhancement involves manipulation of soil properties, which results in a change in properties such as soil texture and water retention properties (45). Farmers have relied on various conventional methods such as organic manure application, crop rotation, cover cropping, balanced fertilizer use and efficient irrigation management to enhance soil health and promote optimal crop growth. These practices aim to improve the physical, chemical and biological properties of the soil. There are diverse and widely adopted management techniques for enhancing soil properties that include conventional tillage methods like ploughing, which disrupt soil structure and harm beneficial organisms. Reduced tillage practices like no-till or strip tillage minimize soil disturbance, which helps retain moisture, improve soil aeration and promote healthy microbial activity. Planting cover crops between main crops helps in loosening compacted soil and the decaying plant material adds organic matter, a crucial component for healthy soil. Cover crops also suppress weeds and help retain soil moisture (46). Adding organic materials like compost, manure or crop residue to the soil increases organic matter content. This improves soil structure, water retention and fertility and provides a food source for beneficial soil microbes. The addition of inorganic amendments like lime or gypsum helps in adjusting soil pH and improving drainage in certain soil types (5). However, conventional soil enhancement methods, while valuable, have some shortcomings. They often depend on external inputs like compost or amendments, which can be expensive and require transportation. Additionally, some methods may be slow to show results and might not be suitable for all soil types. The selection of a suitable soil enhancement technique depends upon the inherent characteristics of the soil, particularly its type (45, 47, 48). These limitations highlight the need for innovative approaches that address these challenges and promote sustainable soil health. In this context, the application of nanoclay and its impact on various physical properties of diverse soil types have been discussed.

Impact of Nanoclay and Its Role in Soil Remediation

The high surface area of nanoclay could attract and hold water molecules in the soil for longer durations. This could be particularly beneficial in sandy soils that drain excessively, which ultimately reduces the irrigation needs in drought-prone areas. Nanoclay serves as the carrier for essential plant nutrients like potassium, calcium and magnesium, which could then be slowly released to plants over time, improving nutrient availability in soils prone to leaching. Nanoclay reduces wind erosion and enhances nutrient retention through its high CEC and boosts microbial activity by acting as a carrier for beneficial bacteria. Its applications extend to soil remediation, where it can adsorb and immobilize pollutants and for controlled release of agrochemicals, improving their efficiency (23). Nanoclay significantly alters soil physical properties, particularly impacting bulk density and porosity. Primarily, nanoclay tends to decrease dry bulk density by promoting the flocculation and aggregation of soil particles. The newly formed aggregates create a more open, less compact soil structure with larger pore spaces, leading to a lighter overall volume. The improved aggregation fostered by nanoclay creates and stabilizes a more extensive network of both macro-pores, ensuring that the soil maintains or even gains crucial pore space, ultimately enhancing both water dynamics and gas exchange within the soil profile (49).

The use of nanoclay as a soil amendment for the improvement of soil physical properties is a relatively new area of research with some potential benefits. Studies suggest that nanoclay might improve soil aggregation, leading to better aeration and drainage. This could benefit plants by promoting healthy root development. The influence of nanoclay on the physical properties of clayey and silty soils was investigated (50). The study revealed that nanoclay incorporation resulted in significant improvements in soil strength and shear strength. Further, field observations from research indicate that amending loess soils with 2 % montmorillonite nanoclay significantly improved the erosion resistance (51). Additionally, the influence of nanoclay on various soil mechanical parameters was investigated using computational modelling. The results indicated that the introduction of nanoclay resulted in a modest increase in the soil's unconfined compressive strength and cohesion. However, research reported a diminishing trend in the effectiveness of nanoclay beyond a specific threshold concentration (52). The introduction of nanoclay particles exhibited a positive influence on the water retention characteristics of the sandy soil, increasing its capacity to store water. Conversely, the hydraulic conductivity of the soil was reduced, indicating a decrease in the ease with which water can flow through the pore spaces (53). The key soil properties improved by nanoclay application are summarized in Table 1, outlining its multifunctional benefits in soil systems and the varying impact of nanoclay on different soil types has been extensively studied and is summarized in Table 2.

Nanoclay Mitigation of Dispersive Soil Behaviour

Dispersive soils, primarily dispersive clays, are characterized by their unique physical properties that significantly impact their engineering behaviour. Dispersive soils are highly unstable due to their tendency to deflocculate in water, making them prone to erosion and structural failure. They typically have a bulk density ranging from 1.1-1.7 g/cm^3, with high porosity (35 %-50 %), which allows for rapid water infiltration and internal erosion. These soils are rich in fine particles, particularly silt and clay, with a clay content often exceeding 30 %, predominantly composed of sodium montmorillonite. Due to their expansive nature, dispersive soils exhibit a high plasticity index (10 %-40 %) and significant swelling and shrinkage behaviour, forming cracks upon drying. The CEC is relatively high, with a high sodium adsorption ratio (SAR) and exchangeable sodium percentage

Table 1. Physical and chemical properties enhanced by nanoclay application

S. No.	Property	Effect of nanoclay	Significance	References
1.	Water retention	Increases due to high surface area and adsorption capacity	Useful in drought-prone and sandy soils	(29)
2.	Cation exchange capacity	Improved due to layered structure and active sites	Better nutrient retention and slow-release fertilization	(23)
3.	Soil bulk density	Decreased by promoting aggregation and flocculation	Results in lighter, aerated soil with improved structure	(50)
4.	Porosity	Increased via formation of macro-aggregates and void spaces	Enhances gas exchange and water movement	(51)
5.	Plasticity index	Reduced in dispersive/clayey soils (though may increase at high dosage)	Improves handling and reduces swelling/ shrinkage behavior	(54, 55)
6.	Permeability	Decreased by void filling in sandy and silty soils	Limits contaminant flow and enhances soil barrier properties	(56)
7.	Shear strength	Increased by reinforcing soil structure	Improves load-bearing capacity in construction and root anchorage for crops	(38)

Table 2. Impact of nanoclay on various soil types

S. No.	Soil type	Observed effect of nanoclay	Key outcomes	References
1.	Sandy soil	Increases water-holding capacity, reduces leaching and wind erosion	Enhanced water retention, improved nutrient delivery, reduced irrigation requirement	(23)
2.	Clay & silt soil	Enhances compaction, reduces plasticity index, increases specific gravity, shear strength	Improved workability and strength; denser soil matrix	(57, 65)
3.	Dispersive soil	Reduces dispersity through flocculation; strengthens soil matrix	Erosion resistance, improved aggregate stability	(57, 59)
4.	Soft soil	Increases unconfined compressive strength and shear resistance	Enhanced mechanical properties, higher stability	(62, 63)
5.	Coarse-grained soil	Fills pores and modifies plasticity and permeability characteristics	Lower permeability, improved stability, increased shear strength	(56, 71)

(ESP) often exceeding 15 %, which weakens particle bonds and promotes dispersion. They can be treated with nanoclay additions to enhance their mechanical strength and overall stability (57). This enhancement can be attributed to a reduction in dispersivity, the tendency of these soils for clay particle detachment and dispersion in water. Consequently, the susceptibility of the soil to erosion is mitigated, promoting its stability (58). Nanoclay exhibits a potential to counteract the dispersive behaviour of soils through the inducement of flocculation. This phenomenon enhances the aggregation of individual soil particles into larger formations, technically termed agglomerates. The mechanism behind this process is attributed to the intercalation of nanoclay particles within the interparticle voids of the soil matrix. This ultimately results in the enhancement of the soil matrix stability (59, 60). Low dosage incorporation of nanoclay into the soil matrix may promote a favourable dispersion effect. However, exceeding the optimal nanoclay content might negate this beneficial influence on aggregate stability (61). Incorporation of nanoclay emerges as a viable strategy to enhance the stability of dispersive soils by improving their overall physical performance by mitigating dispersivity and promoting flocculation of soil particles and resistance to erosion (38).

Reinforcing soft soils by nanoclay

Soft soils are characterized by their susceptibility to deformation and by exhibiting low shear strength. This can be effectively improved through the addition of nanoclay particles that enhance the mechanical performance by increasing shear resistance (62, 63). The introduction of diverse nanomaterials, including nanoclay, has been shown to demonstrably enhance the geotechnical performance of soft soil samples (63). Numerous investigations have examined the effectiveness of nanoclay in soft soil stabilization. Research indicates that significant improvement in soil strength and shear strength parameters upon the addition of 3 % nanoclay content within the soft soil (62). Moreover, several studies also demonstrated that the application of nanoclay into soft soil enhanced their shear strength parameters (64). The presented findings provide evidence for the effectiveness of nanoclay incorporation in augmenting the physical properties of soft soils by improving the strength parameters, particularly shear resistance, leading to enhanced stability (38).

Clay and silt soils

Nanoclay particles emerge as a promising strategy for enhancing the overall physical properties of clay-rich and silt-rich soils by improving their mechanical behaviour, by influencing various key parameters (38). The integration of nanoclay particles offers a promising strategy to enhance the geotechnical performance of soil. Studies have shown that nanoclay treatment can address multiple aspects of soil behaviour. One key benefit is the reduction in plasticity index, which signifies a decrease in the range of water content where the soil exhibits plastic behaviour, making it easier to handle and less prone to problematic deformations. Additionally, nanoclay treatment can increase the specific gravity of the soil, essentially the particles become rigid and leading to a denser soil mass. Ultimately, the shear strength of the soil is enhanced. By incorporating nanoclay, the soil's resistance to deformation under shearing forces is increased and becomes more stable (57, 65). Adding more nanoclay to clay soil increases its unit weight and improves compaction of clay soil (50).

The significant benefit observed by adding nanoclay is the reduction in plasticity index. This decrease signifies a diminished range of water content at which the soil exhibits plastic behaviour. Consequently, the soil becomes less susceptible to deformations and exhibits improved stability, making it a more reliable material for geotechnical applications (50). Nanoclay particles enhance the compactive effect of clay-rich and silt-rich soils, leading to a denser soil matrix and consequently, improved resistance to deformation and enhanced stability (66). Research indicates that the influence of nanoclay incorporation on the plasticity characteristics of clayey soil by introducing 1, 2, 4 and 8 wt% nanoclay to the clay and subsequently comparing the results to those obtained for the unamended (nano-free) soil (54, 67, 68). The addition of nanoclay exhibited a negligible impact on the plastic limit and an increase in the liquid limit. Furthermore, the plasticity index exhibited a direct correlation with the nanoclay content, demonstrating a significant increase. Incorporating 8 wt% nanoclay resulted in a substantial enhancement of the plasticity index by 60 %. Research evaluates the influence of nanoclay on the compressive strength of clay. The investigation involved incorporating varying levels of nanoclay (2, 4 and 8 wt%) into the clay matrix (69). The results revealed a significant enhancement in compressive strength for the 8 wt% nanoclay addition. Compared to the untreated clay (389.01 kPa), the compressive strength rose to 521.99 kPa, representing a substantial increase of 34.2 %. However, this improvement in strength came at the expense of material behaviour, with a decrease in ductility and a corresponding increase in stiffness. Research indicates that the efficacy of nanoclay in reducing the permeability of clay, utilizing a case study from Kahrizak landfill (70). The study employed tests on samples prepared by mixing soil with varying nanoclay content (1, 2, 3, 4 and 5 wt%). Notably, the addition of nanoclay resulted in a decrease in the plasticity index of the clay and 4 wt% nanoclay addition was identified as the optimal level to achieve the desired permeability reduction. Overall application of nanoclay in clay and silt soils reduces the deformation of soil under stress, acting as a microscopic reinforcement, binding particles together, enhancing the soil overall strength. Nanoclay also reduces the plasticity index, making it less sticky in clayey soils. Nano clay makes the soil matrix dense by filling the pores between soil particles, making them more stable and compact.

Coarse-grained soil

Coarse-grained soil is primarily composed of sand and gravel. Sand particles range in size from 0.075-4.75 mm, while gravel particles are larger, ranging from 4.75-60 mm (55). The influence of nanoclay on collapsible soil by converting natural bentonite particles to nanoscale dimensions through ball milling was investigated (71). The resulting nanoclay material was then incorporated into the soil and odometer testing was conducted to assess the impact on collapsibility. The findings suggest that the degree of soil collapsibility is primarily governed by particle size and plasticity associated with the clay fraction. The introduction of nanoscale clay particles alters the pore size distribution and plasticity in the soil, potentially affecting its susceptibility to collapse. Research indicates that the impact of incorporating montmorillonite-based colloidal nanoclay into clayey sand results in significant improvements in soil consistency and stability (71). The addition of 1 % nanoclay led to a 40 % reduction in the plasticity index, indicating a notable decrease in the soil's plastic behaviour, which contributes to improved workability and reduced deformation potential. Simultaneously, the liquid limit increased by 13 %, suggesting a slight enhancement in the soil's capacity to retain water before transforming into a liquid state. Moreover, the plastic limit increased by 38 %, indicating that the soil requires more moisture to begin exhibiting plastic characteristics. Together, these changes reflect enhanced consistency limits, improved structural integrity and better performance of the soil for agricultural and geotechnical applications. Shear strength also improved significantly with a small amount of nanoclay (0.5 %), but adding more didn't further improve strength. The findings suggest that adding nanoclay to clayey sand can improve its stability and reduce its plasticity, making clayey sand less sticky. Research indicates that the impact of nanoclay on the permeability of silty sand using falling head tests by incorporating varying weight percentages (0.25, 0.5 and 1 wt%) of nanoclay (56). The findings revealed a notable reduction in permeability due to an increase in fine content and void filling upon the introduction of nanoclay. The maximum reduction in permeability was observed with the addition of 0.25 wt% nanoclay.

Conclusion

The integration of nanoclay into soil systems presents a promising and innovative approach to address the limitations of conventional soil management practices. Nanoclay, with its high surface area, CEC and layered structure, offers significant advantages in enhancing key soil physical properties such as water retention, porosity, shear strength and bulk density across various soil types. Its ability to improve soil structure, mitigate erosion and provide controlled nutrient release contributes not only to soil health but also to sustainable agricultural productivity. Studies have demonstrated the effectiveness of nanoclay in stabilizing dispersive and soft soils, reducing permeability in coarse soils and improving compaction in clay-rich and silty soils. However, optimal application rates are essential as excessive usage may lead to diminished benefits. As the demand for climate-resilient and resource-efficient agricultural practices grows, nanoclay stands out as a versatile and eco-friendly soil amendment that bridges the gap between traditional soil enhancement methods and advanced nanotechnological interventions. While the potential benefits are promising, further research is needed to identify nanoclay as a promising soil conditioner. Future research should focus on long-term field trials and cost-effective synthesis techniques to fully harness the potential of nanoclay in sustainable soil management.

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Authors' contributions

SJ conceptualized the topic, performed an extensive literature review and drafted the manuscript. SM provided critical supervision, refined the structure of the manuscript and offered key technical inputs throughout the writing process. VG, KC and RS offered valuable suggestions in reviewing the draft critically and contributed to the improvement of the manuscript's scientific content and coherence. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest: All authors declare no conflict of interest.

Ethical issues: None

References

1. Narkhede S, Bhirud S, Patil N, Chaudhari R. Physico-chemical analysis of soil collected from Chorwad, Tehsil-Bhusawal, Dist. Jalgaon (MS). J Chem Pharm Res. 2011;9(4):1973-78
2. Tale KS, Ingole S. A review on role of physico-chemical properties in soil quality. Chem Sci Rev Lett. 2015;4(13):57-66.
3. Sumithra S, Ankalaiah C, Rao D, Yamuna R. A case study on physicochemical characteristics of soil around industrial and agricultural area of Yerraguntla, Kadapa district, AP, India. Int J Geo Earth Environ Sci. 2013;3(2):28-34.
4. Das D. Introduction to soil science. New Delhi: Kalyani Publication; 2011. p. 645.
5. Anderson GC, Barrett-Lennard EG. Management of soil

constraints to improve crop performance in water-limited environments. Agronomy. 2021;11(12):2558. https://doi.org/10.3390/agronomy11122558

6. Nongbet A, Mishra AK, Mohanta YK, Mahanta S, Ray MK, Khan M et al. Nanofertilizers: a smart and sustainable attribute to modern agriculture. Plants. 2022;11(19):2587. https://doi.org/10.3390/plants11192587
7. Ghasabkolaei N, Choobbasti AJ, Roshan N, Ghasemi SE. Geotechnical properties of the soils modified with nanomaterials: A comprehensive review. Arch Civ Mech Eng. 2017;17(3):639-50. https://doi.org/10.1016/j.acme.2017.01.010
8. Lambe TW, Whitman RV. Soil mechanics. New York: John Wiley & Sons, Inc.; 1969. p. 553.
9. Zhang G. Soil nanoparticles and their influence on engineering properties of soils. In: DeGroot DJ, Vipulanandan C, Yamamuro JA, Kaliakin VN, Lade PV, Zeghal M et al., editors. Advances in measurement and modeling of soil behavior. Reston, VA: ASCE Press; 2007. p. 1-13.
10. Shahidi M, Asemi F, Farrokhi F. Improving the mechanical behavior of soil contaminated with Gas-Oil using organoclay and nanoclay. Arab J Sci Eng. 2023;48(4):4953-69. https://doi.org/10.1007/s13369-022-07239-w
11. Delgado A, Gomez JA. The soil: Physical, chemical and biological properties. In: Principles of agronomy for sustainable agriculture. Cham, Switzerland: Springer; 2017. p. 15-26. https://doi.org/10.1007/978-3-319-46116-8_2
12. Brady NC, Weil RR. The nature and properties of soils. Upper Saddle River, NJ: Prentice Hall; 2008.
13. Cleophas F, Isidore F, Musta B, Ali BM, Mahali M, Zahari N et al. Effect of soil physical properties on soil infiltration rates. J Phys Conf Ser. 2022;2314:012020. https://doi.org/10.1088/1742-6596/2314/1/012020
14. Sainju UM, Liptzin D, Jabro JD. Relating soil physical properties to other soil properties and crop yields. Sci Rep. 2022;12(1):22025. https://doi.org/10.1038/s41598-022-26619-8
15. Patnaik L, Raut D, Behera L, Nayak A, Misha S, Swain S. Physico-chemical and heavy metal characterization of soil from industrial belt of Cuttack, Orissa. Asian J Exp Biol Sci. 2013;4(2):219-25.
16. Kay BD, Angers DA. Soil Structure. In: Sumner ME, editor. Handbook of Soil Science. New York: CRC Press; 1999. p. 229-69.
17. Phogat V, Tomar V, Dahiya R. Soil physical properties. In: Soil science: An introduction. 2015. p. 135-71.
18. Al-saeedi AA. Clay basics and their physical and chemical properties. IAETS J Adv Res Appl Sci. 2022;10:13-8.
19. Guggenheim S, Martin RT. Definition of clay and clay mineral: joint report of the AIPEA nomenclature and CMS nomenclature committees. Clays Clay Miner. 1995;43(2):255-6. https://doi.org/10.1346/CCMN.1995.0430213
20. Brigatti MF, Galan E, Theng BKG. Structures and mineralogy of clay minerals. Developments in Clay Science. 2006;1:19-86. https://doi.org/10.1016/S1572-4352(05)01002-0
21. Guggenheim S, Brady J, Mogk D, Perkins D. Introduction to the properties of clay minerals. In: Brady JB, Mogk DW, Perkins D, editors. Teaching Mineralogy. Washington, DC: Mineralogical Society of America; 1997. p. 371-88.
22. Nazir MS, Mohamad Kassim MH, Mohapatra L, Gilani MA, Raza MR, Majeed K. Characteristic properties of nanoclays and characterization of nanoparticulates and nanocomposites. In: Jawaid M, Qaiss A, Bouhfid R, editors. Nanoclay Reinforced Polymer Composites. Singapore: Springer; 2016. p. 35-55. https://doi.org/10.1007/978-981-10-1953-1_2
23. Merino D, Tomadoni B, Salcedo MF, Mansilla AY, Casalongué CA, Alvarez VA. Nanoclay as carriers of bioactive molecules applied to agriculture. In: Kharissova OV, Torres-Martínez LM, Kharisov BI, editors. Handbook of nanomaterials and nanocomposites for energy and environmental applications. Cham, Switzerland: Springer; 2020. p. 1-22. https://doi.org/10.1007/978-3-030-11155-7_62-1
24. Pavlidou S, Papaspyrides C. A review on polymer-layered silicate nanocomposites. Prog Polym Sci. 2008;33(12):1119-98. https://doi.org/10.1016/j.progpolymsci.2008.07.008
25. Uddin F. Clays, nanoclays and montmorillonite minerals. Metall Mater Trans A. 2008;39(12):2804-14. https://doi.org/10.1007/s11661-008-9603-5
26. Bergaya F, Lagaly G. General introduction: clays, clay minerals and clay science. Developments in Clay Science. 2013;5:1-19. https://doi.org/10.1016/B978-0-08-098258-8.00001-8
27. Norkhairunnisa M, Farid B, Hua TC. Flame retardant nanofillers and its behavior in polymer nanocomposite. In: Hoque ME, Ramar K, Sharif A, editors. Advanced polymer nanocomposites. Woodhead Publishing; 2022. p. 483-511. https://doi.org/10.1016/B978-0-12-824492-0.00018-0
28. Carretero MI. Clay minerals and their beneficial effects upon human health: A review. Appl Clay Sci. 2002;21(3-4):155-63. https://doi.org/10.1016/S0169-1317(01)00085-0
29. Abd-Elsalam KA, Mehmood MA, Ashfaq M, Abdelkhalek TE, Hassan RK, Ravichandran M. Liquid nanoclay: Synthesis and applications to transform an arid desert into fertile land. Soil Syst. 2024;8(3):73. https://doi.org/10.3390/soilsystems8030073
30. Nayak BK, Chatterjee D, Paul R, Das SR, Adak T, Mandal N et al. Review of nano-clay polymer composites for controlled nitrogen release: prospects and limitations. Agric Res. 2025:1-22. https://doi.org/10.1007/s40003-025-00848-5
31. Belghazdis M, Hachem E-K. Clay and clay minerals: A detailed review. Int J Recent Technol Appl Sci. 2022;4(2):54-75. https://doi.org/10.36079/lamintang.ijortas-0402.367
32. Lazzara G, Massaro M, Riela S. Current status of nanoclay phytotoxicity. In: Phytotoxicity of nanoparticles. 2018. p. 151-74. https://doi.org/10.1007/978-3-319-76708-6_6
33. Massaro M, Lazzara G, Milioto S, Noto R, Riela S. Covalently modified halloysite clay nanotubes: Synthesis, properties, biological and medical applications. J Mater Chem B. 2017;5(16):2867-82. https://doi.org/10.1039/C7TB00316a
34. Kumari N, Mohan C. Basics of clay minerals and their characteristic properties. In: Do Nascimento GM, editor. Clay and clay minerals. London: IntechOpen; 2021. p. 1-24. https://doi.org/10.5772/intechopen.97672
35. Khatoon N, Chu MQ, Zhou CH. Nanoclay-based drug delivery systems and their therapeutic potentials. J Mater Chem B. 2020;8(33):7335-51. https://doi.org/10.1039/D0TB01031f
36. Kang H-Y. A review of the emerging nanotechnology industry: Materials, fabrications and applications. California: Department of Toxic Substances Control Pollution Prevention and Green Technology; 2010. p. 64.
37. Schartel B, Knoll U, Hartwig A, Pütz D. Phosphonium-modified layered silicate epoxy resins nanocomposites and their combinations with ATH and organo-phosphorus fire retardants. Polym Adv Technol. 2006;17(4):281-93. https://doi.org/10.1002/pat.686
38. Sedighi M, Farhadian H. The role of nanoclay in the soil stabilization: A short viewpoint. J Geomine. 2023;1(2):92-102.
39. Usman MS, Zowalaty MEE, Shameli K, Zainuddin N, Salama M, Ibrahim NA. Synthesis, characterization and antimicrobial properties of copper nanoparticles. Int J Nanomedicine. 2013;8:4467-79. https://doi.org/10.2147/IJN.S50837
40. Francucci G, Rodriguez E, Rodriguez ME. Ultrasound-assisted

extrusion compounding of nano clay/polypropylene nano compounds. Polymers. 2024;16(17):2426. https://doi.org/10.3390/polym16172426

41. Sanchez C, Julián B, Belleville P, Popall M. Applications of hybrid organic-inorganic nanocomposites. J Mater Chem. 2005;15(35-36):3559-92. https://doi.org/10.1039/b509097k

42. Ryu K-W, Jang Y-N, Chae S-C. Hydrothermal synthesis of kaolinite and its formation mechanism. Clays Clay Miner. 2010;58:44-51. https://doi.org/10.1346/CCMN.2010.0580104

43. Kielmann U, Jeschke G, García-Rubio I. Structural characterization of polymer-clay nanocomposites prepared by co-precipitation using EPR techniques. Materials. 2014;7(2):1384-408. https://doi.org/10.3390/ma7021384

44. He H, Zhou Q, Martens WN, Kloprogge TJ, Yuan P, Xi Y et al. Microstructure of HDTMA+-modified montmorillonite and its influence on sorption characteristics. Clays Clay Miner. 2006;54(6):689-96. https://doi.org/10.1346/CCMN.2006.0540604

45. Vincevica-Gaile Z, Teppand T, Kriipsalu M, Krievans M, Jani Y, Klavins M et al. Towards sustainable soil stabilization in peatlands: Secondary raw materials as an alternative. Sustainability. 2021;13(12):6726. https://doi.org/10.3390/su13126726

46. Ghorbani R, Wilcockson S, Koocheki A, Leifert C. Soil management for sustainable crop disease control: a review. Environ Chem Lett. 2008;6:149-62. https://doi.org/10.1007/s10311-008-0147-0

47. Thom N, Dawson A. Sustainable road design: Promoting recycling and non-conventional materials. Sustainability. 2019;11(21):6106. https://doi.org/10.3390/su11216106

48. Zahri AM, Zainorabidin A, editors. An overview of traditional and non traditional stabilizer for soft soil. IOP Conf Ser Mater Sci Eng. 2019. https://doi.org/10.1088/1757-899X/527/1/012015

49. Sharifnasab H, Abbasi N. Effect of nanoclay particles on some physical and mechanical properties of soils. J Agric Mach. 2016;6(1):250-8.

50. Bagherzadeh Khalkhali A, Safarzadeh I, Rahimi Manbar H. Investigating the effect of nanoclay additives on the geotechnical properties of clay and silt soil. J Civ Eng Mater Appl. 2019;3(2):65-77.

51. Padidar M, Jalalian A, Abdouss M, Najafi P, Honarjoo N, Fallahzade J. Effects of nanoclay on some physical properties of sandy soil and wind erosion. Int J Soil Sci. 2016;11(1):9-13. https://doi.org/10.3923/ijss.2016.9.13

52. Kamgar R, Salimi Naghani M, Heidarzadeh H, Nasiri Ardali F. Modeling nanoclay effects on different parameters of a clayey sand. Model Earth Syst Environ. 2021;7:795-808. https://doi.org/10.1007/s40808-020-00987-4

53. Padidar M, Jalalian A, Asgari K, Abdouss M, Najafi P, Honarjoo N et al. The impacts of nanoclay on sandy soil stability and atmospheric dust control. Agric Conspectus Sci. 2016;81(4):193-6.

54. Baziar M, Ghazi H, Mirkazemi S, editors. Effect of nanoclay additives on the properties of engineering-geotechnical soil. In: Proceedings of 4th International Conference on Geotechnical Engineering and Soil Mechanics; 2010. Tehran.

55. Michael OM, Hirpaya J. Influence of coarse-grained sand on shear strength of lateritic soil. Int J Pure Appl Sci. 2020;19(9):396-407.

56. Janalizadeh A, Nazarpoor H, Ebrahimi M. Effect of nanoclay on permeability of silty sand. In: Proceedings of the 8th National Congress on Civil Engineering; 2014 May 7-8; Babol, Iran. Babol Noshirvani University of Technology; 2014. (in Persian).

57. Abbasi N, Farjad A, Sepehri S. The use of nanoclay particles for stabilization of dispersive clayey soils. Geotech Geol Eng. 2018;36(1):327-35. https://doi.org/10.1007/s10706-017-0330-9

58. Majid MA, Ridzuan M, Lim K. Effect of nanoclay filler on mechanical and morphological properties of Napier/ epoxy composites. In: Goh KL, Aswathi MK, De Silva RT, Thomas S, editors. Interfaces in Particle and Fibre Reinforced Composites. Cambridge: Woodhead Publishing; 2020. p. 137-62. https://doi.org/10.1016/B978-0-08-102665-6.00006-6

59. Guan H, Zhao Y. Decontamination application of nanoclays. In: Cavallaro G, Fakhrullin R, Pasbakhsh P, editors. Clay nanoparticles. Elsevier; 2020. p. 203-24. https://doi.org/10.1016/B978-0-12-816783-0.00009-8

60. Katschnig M, Battisti M. Processing of polymer-nanoclay composites. In: Stephan L, editor. Polymer nanoclay composites. Amsterdam: Elsevier; 2015. p. 53-91. https://doi.org/10.1016/B978-0-323-29962-6.00003-0

61. Asakereh A, Avazeh A. The Effect of nano clay on dispersive soil behavior (Case Study of Minab City). Amirkabir J Civ Eng. 2017;49(3):503-12.

62. Khalid N, Arshad MF, Mukri M, Mohamad K. Influence of nano-soil particles in soft soil stabilization. Electron J Geotech Eng. 2015;20(20):731-8.

63. Subramani V, Sridevi S. Soil stabilization using nano materials. Int J Res Appl Sci Eng Technol. 2016;4:641-5.

64. Babu S, Joseph S. Effect of nano materials on properties of soft soil. Int J Sci Res. 2016;5(8):634-7.

65. Arora A, Singh B, Kaur P. Performance of Nano-particles in stabilization of soil: a comprehensive review. Mater Today Proc. 2019;17:124-30. https://doi.org/10.1016/j.matpr.2019.06.409

66. Arya A, Jain A. A review of geotechnical characteristics of nano-additives treated soils. Int J Adv Res Sci Eng. 2017;6(1):838-43.

67. George A, Kannan K. Investigation on the geotechnical properties of nano clay treated clayey soil. Int J Res Eng Sci Manag. 2020;3(2):453-5.

68. Nikookar M, Bahari M, Nikookar H, Arabani M. The strength characteristics of silty soil stabilized using nanoclay. In: Proceedings of the 7th Symposium on Advances in Science & Technology; 2013 Mar 7-8; Bandar-Abbas, Iran.

69. Ghazi H, Baziar M, Mirkazemi S. Assess of the improvement of the behavior of soil strength in the presence of nanoscale additive. Assas J Sci Technol. 2011:45-50.

70. Mohamadzadeh Sani A, Arabani M, Haghi AK, Chenari RJ. Effect of nanoclay additive on the geotechnical properties of silty sands. In: Proceedings of the 4th International Conference on Geotechnical Engineering and Soil Mechanics; 2010 Nov 2-3; Tehran. (in Persian).

71. Ouhadi VR, Bakhshalipour H. Impact of nano clays on the behavior properties of collapsible soils. In: Proceedings of the 9th International Congress on Advanced in Civil Engineering; 2010 Sep 27-30; Trabzon, Turkey, Karadeniz Technical University; 2010.

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