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Stabilization and Environmental Sustainability of Swelling Clays Soils: A Review

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Received: 21:05:2025 Accepted: 14:08:2025 Published: 14:08:2025

***Abstract*:**
Water movement in swelling soils conforms with material continuity. This invariably justifies the differences in the gravitational potential energy during expansion and the anisotropic stresses that press the soil but allow for vertical movement. Under fluid conditions, vane efficiency exhibited by macropores is lowered by swelling of the clay, and a poorly drained soil results in surface saturation. The type of water applied to soil material tends to have an impact on the positioning of cracks in swelling clays, and thus, cracks can remain pathways for preferential flow much after they are covered at the soil surface. Over time, chemicals and chemical compounds have been utilized to further enhance the engineering properties of such soils. However, environmentally friendly biodegradable biological stabilizers are taking the place of conventional stabilizers, most especially lime and cement. Additionally, biochar amendment, which is ecofriendly, has also been found to lower the swelling index capability of expansive clay soil. Despite the dangers associated with swelling clay, it has found extensive use as adsorbents, carriers in drug delivery systems, and the building of a storage tank for the disposal of radioactive materials. In addition, swelling clays have found significant usage in the production of controlled-release fertilizers (CRFs) formulations. Hence this paper emphasizes the environmental impact of building large structures and road construction on swelling clay soils, highlights recent progress in the inhibition and stabilization of swelling soils to sustain the environment, and enumerates the economic importance associated with swelling clay soils.

***Keywords*: Biological stabilizers, Biochar amendment, Controlled-release fertilizers, Drug delivery**

1.0 Introduction

Swelling clays are a widespread form of geological material that typically has > 50% of its mineral particles less than 2 microns in size [1]. The expanding clay consists primarily of the smectite group clay minerals and vermiculite clay minerals, which are recognized for their interlayer expansion [1]. Clay soil shrinkage and swelling stem from its mineral composition, suction, and microstructure, influenced by climatic factors (e.g., drought, rainfall, temperature, humidity, and wind) and biological interactions [2, 3]. The continuous and seasonal influence of these factors affects the shrinkage and swelling in clay soil, with both beneficial and destructive effects on the landscape and the ecosystem. The amount of water present (i.e., wetness) and dryness of the expanding soil affect its swelling and shrinkage. Hence, slopes comprising expansive soil show dehydrated cracks/openings on the slope for rainwater infiltration [4]. The term 'clay fraction' in soil science (or simply 'clay') is used to describe a class of materials in which the particle size is < 2 µm [5, 6]. The phrase "clay mineral" denotes sheet silicate minerals and other minerals that enhance clay's plasticity and harden upon drying or firing [5].

The criteria that define both clay and clay minerals are presented in Table 1. The clay fraction in soils comprises both crystalline and non-crystalline minerals [7]. Table 2 presents a straightforward classification of clay minerals into kaolinite, smectite, illite, and chlorite. Swelling clay soil has been found to constitute a significant hazard to infrastructure such as buildings and roads [8-10]. Several clay soils experience a volume change, such as expansion when wetted and contraction when they dry out [11 - 13]. Two categories of swelling have been reported in swelling clays; the first is the inner crystalline swelling that has been traced to the absorption of water by interchangeable cations in dry clay [14 - 16], while the other is osmotic expansion [17 - 19]. This is a sequel to large variability in the ion clusters in contact with the clay facets and in water contained within the pores [20]. Several artificial factors and some natural factors could combine to initiate fundamental mineral features of swelling soil, which triggers the expansion or reduction in soil's volume [21]. The outcome of substantial volume changes in soils is immeasurable damage to superstructures, which is often a reflection of gradual and continuous failures. These kinds of soils exhibit their properties due to the existence of swelling clay minerals such as smectite. The expandability of soil is impacted by the category and proportion of clay present [22, 23]. The most consistent measures of potential swell in clay soils are Atterberg limits (liquid limit and plasticity index), Bar linear shrinkage, and natural soil suction [24].

Expansive clays, including smectites, constitute some of the most prevalent nanomaterials of inorganic compounds in the lithosphere [25] and play an essential role in determining the movement as well as retention of fluids (water and pollutants), CO_2, and nutrients in both natural and designed settings, due to their exceedingly large surface areas [26, 27]. Montmorillonite and allophane clay minerals constitute the most significant types of nanomaterials found in the clay portion of soil [7]. Nanoparticles have wide distribution in a natural environment [28]. Research work on nanomaterials has shown the adsorbing properties of allophones [7]. Despite serious damages to infrastructure resulting from the expansion of swelling clays, nevertheless, this ability of clay to swell has found favourable applications in barrier materials [29] and in nanocomposites [30]. Most clays, especially smectite, exhibit crystalline swelling because of the hydration of cations that are present between the layers of clay, thus resulting in the increase in the interlayer distance of clay [31, 32]. These volume changes result in ground movements, which in turn cause extensive destruction to infrastructures built on them. Research work has shown that the swell-shrink reaction of expansive clay soil is influenced by an increase in suction pressure resulting from transpiration by plants [33, 34]. Models have been presented to appraise the behavior pattern of soil influenced by transpiration by vegetation [35, 36]. Consistent seasonal changes in climatic conditions cause the swelling and shrinking of clays and thus negatively affect underground infrastructure [37] and railway embankments [38, 39]. The effects of swelling clay soils cause varying destruction and disorders in different aspects in several regions that cut across the entire world [40 - 43]. Clay and clay minerals exhibit plasticity and harden upon drying (Table 1) [44].

Factors that are external in nature, such as initial wetness and dry density, the presence of moisture, climate, and plants, determine the extent of shrinkage in swelling soils [23, 45]. Researchers in recent times have investigated volume change resulting from expansive clayey soils, hence predicting movements associated with such soils [46, 47]. Interlayer responses exhibited by clay when compressed are crucial in the development of models of expansive clays and estimation of compressive behavior, which is important to the design of structures in clay-rich soils, which are prone to shrinkage or swelling and in the densification of clays in the production of ceramics [30, 48, 49].

The chance of damage to structures resulting from the swelling of clays is compounded by deficiency in proper evaluation of soil swelling capability and general soil characterization [50, 51]. Smectite an expansive clay is one of the four groups of clay minerals [52]. This review enumerates the knowledge gaps in dynamics and application of expansive clay soil over recent time.

Table 1: Criteria that characterizes clay and clay minerals [44]

Criteria	Clay	Clay mineral
Origin	Natural	Natural & Synthetic
Main constituent	Phyllosilicate	Not restricted to Phyllosilicate Non-phyllosilicate can be included
Size	Fine grained	Any
Plasticity	Yes	Yes
Hardens upon drying or firing	Yes	Yes

2.0 Mineralogy of Swelling Clays

Clay, as a mineral, is group of silicates that have a layered structure and are usually by-products of the weathering (i.e., chemical) of some silicate minerals, such as feldspars, in the surficial environment. Clay minerals could be of residual [53, 54], sedimentary [55, 56], and hydrothermal [57, 58] origin. Clay minerals are flaking, crystallized platelets composed of numerous units of tetrahedral or octahedral sheets (T- O), joined by mineral fragments such as silicon (Si), oxygen (O), and aluminum (Al) atoms [59]. Structurally, clay is comprised of both the tetrahedral and octahedral sheets (Fig. 1). The way newly formed clay, such as kaolinite, appears in size and is stacked strongly hangs on the structure as well as the properties of the parent (original) minerals from which the clay is derived [60]. Montmorillonite (smectite) has been established as the principal clay mineral found to occur in several highly swelling soils [61].

Table 2: Major group of clay minerals [52]

S/N	Group name	Member Mineral	General formula	Remarks
1	Kaolinite	Kaolinite	$Al_2Si_2O_5\,(OH)_4$	members are polymorphs (composed of the same formula and different structure)
2	Smectite	montmorillonite, pyrophyllite, talc, vermiculite, sauconite, saponite, nontronite	$(Ca,Na,H)(Al,Mg,Fe,Zn)_2\,(Si,Al)_4O_{10}(OH)_2\text{-}XH_2O$	X indicates varying level of water in mineral type
3	Illite	Illite	$(K,H)Al_2\,(Si,Al)_4\,O_{10}(OH)_2\text{-}XH_2O$	X indicates varying level of water in mineral type
4	Chlorite	(i) amesite, (ii) chamosite, (iii) cookeite, (iv) nimite etc	(i) $(Mg,Fe)_4Al_4Si_2O_{10}(OH)_8$ (ii) $(Fe,Mg)_3\,Fe_3\,AlSi_3O_{10}(OH)_8$ (iii) $LiAl_5\,Si_3O_{10}\,(OH)_8$ (iv) $(Ni,Mg,Fe,Al)_6AlSi_3O_{10}(OH)_8$	each member of mineral has separate formula; this group has relatively larger member minerals and is sometimes considered as a separate group, not as part of clay

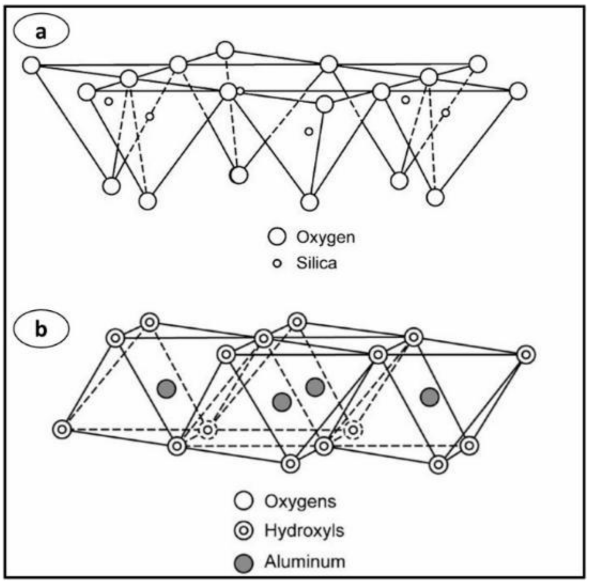

Fig. 1. Diagrammatic structure of clay; (a) Tetrahedral sheet comprising of oxygen and silica (b)Octahedral sheet comprising of oxygen, hydroxyls and aluminum [62]

Smectites belong to the 2:1 type of swelling clay minerals that have a wide distribution in the earth's crust [1]. The name smectite refers to a group of Na, Ca, Mg, Fe, and Li-Al silicates. The names that are commonly used under the smectite group are: Ca-montmorillonite, Na-montmorillonite, saponite, nontronite, and hectorite [63].

The difference between smectite (2:1-layer silicate) and kaolinite (1:1-layer silicate) lies within the structure of clays (Fig. 2). The layers of aluminosilicate present in the expansive clay, such as montmorillonite, and the saturated pores they mark have a significant control on the mechanical properties, which can be linked with the movement of solutes in both natural and engineered (man-made) environments; pore networks contained in water-saturated montmorillonite, which are usually on a nanoscale, indicate possible broad characteristics of colloidal interconnection in wetted clay minerals [64, 65].

Table 3 summarizes the physical and chemical features of montmorillonite. Studies reveal that the anisotropy in water diffusion may be anticipated based on the regular alignment of particles, notwithstanding the aggregate or the distribution of the various porosity types [66, 67]. Data pertaining to conditions of mineral reactions can serve as a tool to alter the physicochemical parameters associated with clays, which have the tendency to swell [68, 69].

3.0 Hydrology of Swelling Clays

When wet, hydraulic capability exhibited by macropores is lowered by the expansion of clay [70, 71]. As a result, surface saturation increases on the undrained (e.g., waterlogged) soil, resulting in higher peak flows than on the drained soil. Wetting also causes most of the clay macropores to close [72, 73]. Recession discharges and total water yields have been found to be higher from the drained soil [70].

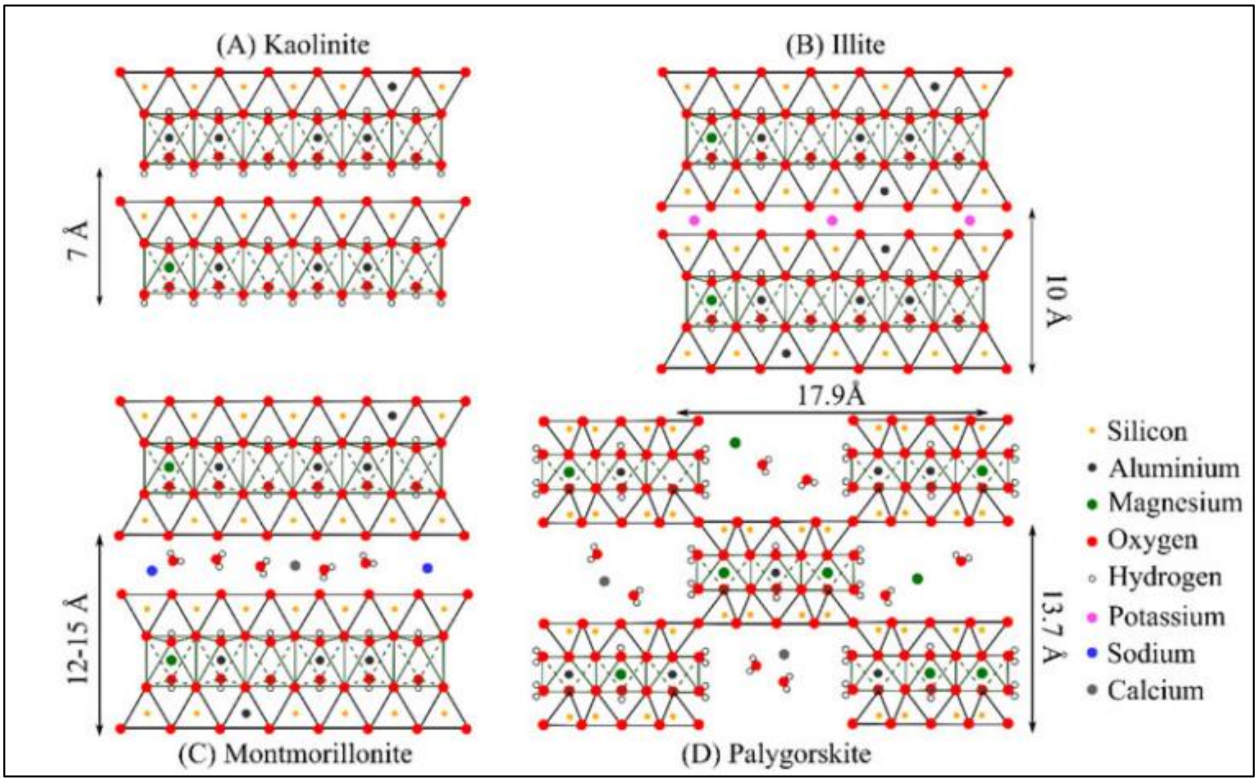

Fig. 2. Different layered structures of clay minerals, Adapted from [74].

Table 3: Physical and chemical characteristics of Montmorillonite [75]

Properties	Description
Physical properties	
Colour	White, grey, beige to buff
Surface area (m^2/g)	240
Bulk density (g/L)	370
Diameter of particles (µm)	1
Length of particles (nm)	100–150
Surface dimensions (nm)	300–600
Crystal system	Monoclinic
Transparency	Translucent
Fracture	Irregular
Aspect ratio	High
Nature	Hydrophilic
Chemical properties	
Chemical composition (%)	Values
SiO_2	73.0
Al_2O_3	14.0
Fe_2O_3	2.7
K_2O	1.9
MgO	1.1
Na_2O	0.6
CaO	0.2

Material continuity has been found to enhance the theory of water flow, which in turn explain the changes in gravitational potential energy of the system associated with expansion as well as anisotropic forces that tend to confine the soil horizontally and yet allow vertical movement [76]. Differences as pertaining to hydrological characteristics, which are temporal, could be seen due to the expansion of the clay soil as it takes up water during the periods of autumn and winter [77]. The progressive swelling in smectite was caused by the assimilation of one to three layers of interlayer water molecules (Fig. 3). The spaces between lattices contain hydrated cations that can be exchanged (Fig. 4). In Fig. 5, you can see what would happen if the layer distance went from 0.96 nm to 1.52 nm because of the polarity of the water molecules when they were absorbed by other molecules of water [78]. The swelling behavior in smectite is basically dictated by the hydrated interlayer cation [79]. The permeability of the clay has been reported to be enhanced more when the infiltrating fluid in the Na-montmorillonite clay is converted from polar fluid water to low-polar fluid [80]. A combination of both vibrational and gravimetric measurements shows that water molecules on the surface of montmorillonite are substantially controlled by the sort of interchangeable metallic cations present on the clay mineral and the total water content [81]. Modeling, coupled with experimental research, has shown that basal spacing has been enhanced by the non-uniformity form of hydration of swelling clays [82]. Swelling clay minerals, due to their natural physicochemical capabilities, have a net negative electrical charge imbalance that captures the positive pole of dipolar molecules of water and cations [83].

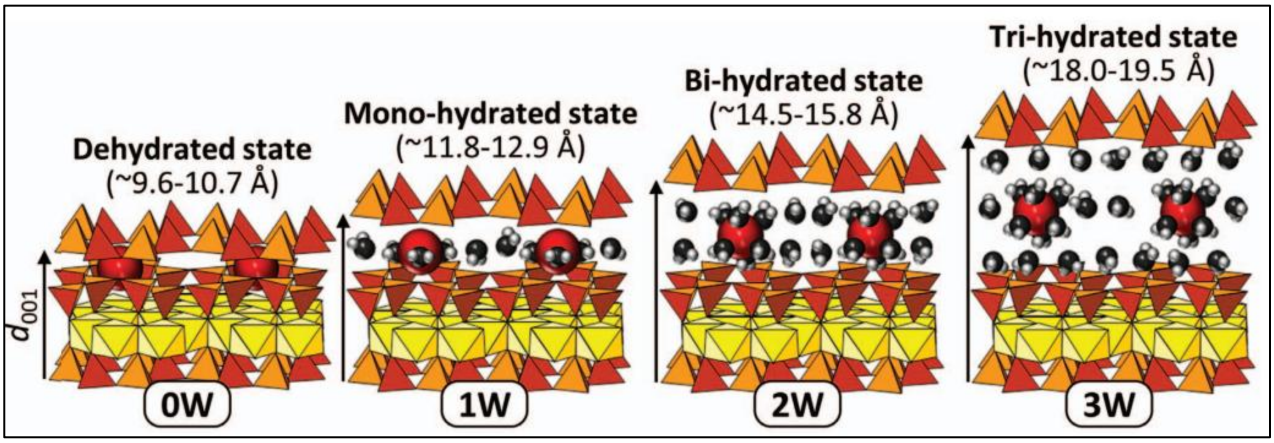

Fig. 3. Diagrammatic depiction of the crystal structure for the various smectite hydration stages and the layer-to-layer variations following water molecule absorption; Adapted from [84]

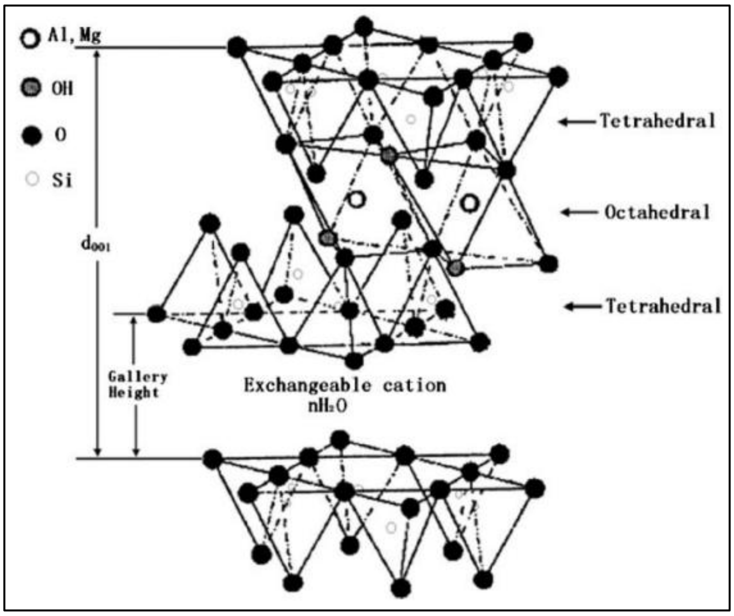

Fig. 4. The T-O-T (2: 1) structure in smectite; d_{001} refers to basal plane spacing Adapted from [85]

3.1 Tortuosity of Crack Systems in Expanding Clay Soils

The configuration and arrangement of the crack network present in expansive clays have significant control over their hydraulic properties [86, 87]. Networks have been reported to emanate from the several cracks of varying magnitudes in swelling soils [88]. Crack tortuosity system in expansive clay soils influences the actual mean length of flow in the cracks and is a significant characteristic that enhances the soil's hydraulic characteristics [89]. Furthermore, investigations have demonstrated that horizontally produced cracks in the network of cracked, swelling soils improve the transport of water and solute [89]. Providing protection for swelling clay against cracks and intense damage to structures, several stabilization techniques are used to mitigate these effects.

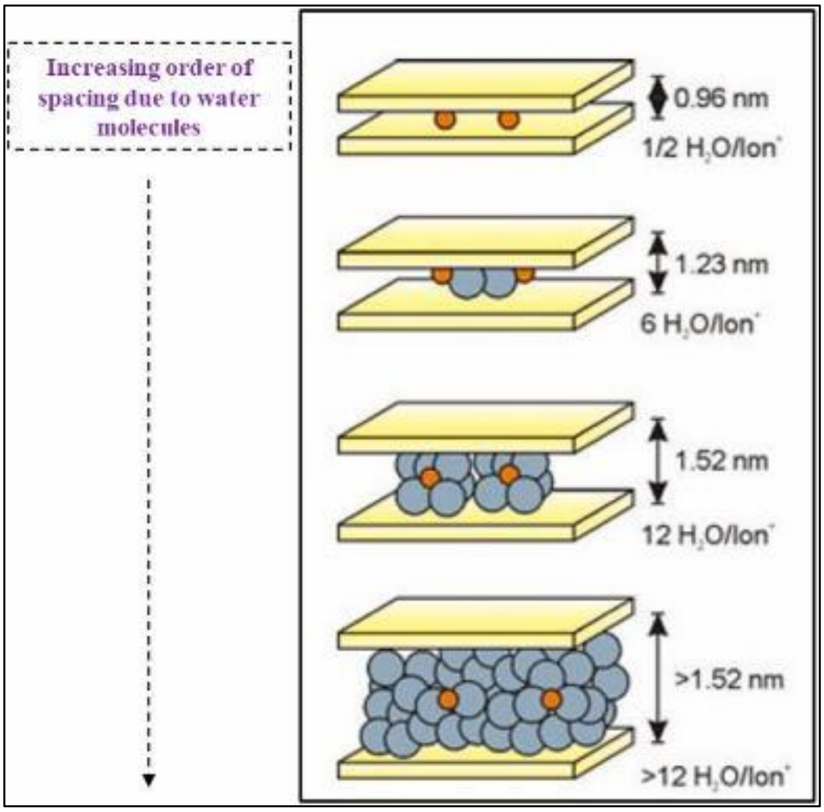

Fig. 5. Crystalline swelling mechanism [78]

4.0 Stabilization of Swelling Clays

Swelling clay soil causes significant damage to soil and structures. The damage is caused by the chemical and physical characteristics of the expansive clay minerals, i.e., montmorillonite. Montmorillonites are minerals in expansive soils that allow absorption of moisture within their sheets and volume alterations [90]. Thus, it leads to cracks that usually result in structural and reservoir channel damage. The more the proportion of montmorillonite in the clay soil, the higher its swelling capability. Although the swelling and shrinking of the expansive soil is more common in the surface layer than the deep layer of the soil [51]. However, continuous damage caused by swelling clays is usually cost-effective considering the preventive and remedial measures applied.

Owing to the damage caused by swelling clay soils. Adequate improvement of the soil's characteristics to gain construction stability and, at the same time, sustain the environment is paramount. In essence, stabilization strengthens and enhances durability in affected clay soil [91, 92]. Numerous studies have explored stabilizing swelling clays through various stabilization techniques [93 - 97]. This clay soil can be stabilized or inhibited using organic and inorganic materials to adjust the characteristics of the soil mineral. Although some of the studies were carried out in the laboratory [98] without any field experiment and by not considering the cost and the environmental implications. Also, the use of different stabilization techniques or combinations of techniques has provided understanding on the sustainability of the techniques in the environment. Consequently, it results in effective and environmentally friendly swelling clay stabilizers. Aside from sustainability, the extent of stabilization depends on various factors: soil type, composition and mineralogy, stabilizer type and content, soil pH, and moisture content [99]. The soil stabilization techniques are categorized into three: biological, chemical, and mechanical.

4.1 Biological Stabilization

This involves the direct use of a biological entity (such as vegetation and microorganisms) or any substance from a biological source (e.g., enzymes and other bio-additives; waste products from plants and agricultural produce) to modify the soil structure [100]. Additionally, these biological stabilizers increase soil strength and reduce its permeability [101]. Stabilizers from biological sources are easily and usually available, less toxic, and cost-effective. Besides the advantages of biological stabilization in construction and engineering, it also improves ecological and environmental stability [102]

4.1.1 Biological Stabilization: Vegetation

In urban settings, vegetation is often considered a cause of infrastructure issues, stemming from deep subsurface soil movements in areas where tree roots extract water from the soil. The effect on root growth varies depending on various plant species, root barriers (tarred roadways, concretized footpaths, buried pipes, weather conditions, forms of irrigation, etc.), root clustering and competition, and condensation degree [103 - 105]. A study on soil-water retention indicated that vetiver grass could be used to gain stability on moderately sloppy soil due to the root structure and arrangement [106]. Also, vegetation prevents erosion as a bigger leaf area, and deeper roots reduce water content in the soil [4].

A recent study carried out suggested that plant species with higher root lengths support and improve soil physical properties, especially in compacted soil [107]. The planting of native trees adjacent to rail lines has provided a form of stability on the clay soils [108]. On the other hand, vegetation was considered to remove moisture from clay soils, resulting in the sinking of buildings [105].

Furthermore, the intensity and duration of rainfall, as well as slope height and inclination, influence swelling clay vegetation [4, 109]. Heavy downpours of rain with larger intensity within a little period apparently increase the depth of infiltration of the vegetated expansive soil slope. Although the impact of heavy downpour is of little or no significance on infiltration at greater depths except for a longer duration. An excessive downpour is more harmful to the stability of vegetated swelling soil [4]. Furthermore, an increase in the steepness of a slope reduces the magnitude of rainfall percolating into the ground, while a gentle slope enhances evaporation. Also, higher angles of inclination of slope and reduction in slope height reduce the evaporation rate, thereby lowering possible cracking [4, 110, 111]. Similarly, soil structure significantly influences the swelling and shrinking of clay soil [112].

4.1.1.1 Significance of Vegetation on Swelling Clays for a Sustainable Environment

Vegetation propels environmental and soil physicochemical characteristics variations, as soil and plant interact, although plant type mostly depends on its adaptability and survival in the environment [113, 114]. The structure of swelling soil without vegetation can be extensively affected, resulting in soil instability [115 - 117]. Nevertheless, the resultant effects of vegetation in soil properties lay emphasis on biological and geological changes on the soil environment [118].

Studies have shown that vegetation has made a significant contribution to movements in swelling soils, which in turn causes damage to engineering structures. The main effect of vegetation on swelling clay is desiccation of the soil leading to localized settlement [119, 120]. A study shows that British clays possess large potential for volume change with large deficits created by large trees, even though it was very difficult to detect desiccations in the clays [121]. Surface evaporation, coupled with evapotranspiration through the demand of water by the roots of plants, results in soil desiccation [122, 123]. Mature trees, with deeper root systems than grasses, herbs, and smaller plants, can extract greater amounts of water from expansive clay soils, potentially causing slab distress in certain conditions [124 - 126].

Water molecules attach to the clay structure, and their removal by vegetation reduces clay volume, forming a localized negative pressure zone that leads to desiccation. The continuous influence of trees on water movement near embankment and cutting slopes has been observed to have both positive and negative effects on earthwork performance [39, 127]. Vegetal fibers added to soils have shown a reduction in swelling capacity of soils due to increased soil cohesion and soil ductility [128, 129]. Certain native vegetation has been shown to enhance soil shear strength by increasing matric suction and restricting soil movement [130].

In clay soils, vegetation can cause stabilizing and/or destabilizing effects on the soil profiles. This could be because of the absorption and redistribution of moisture within the soil by the tree roots. The interaction and distribution of roots in different expansive clay soils vary in specific environments, such as rail tracks, roads, buildings, and slope elevations [105].

4.1.2 Biological Stabilization: Microorganisms

The microbial community in the soil environment is influenced by several factors. This includes nutrient content, substrate availability, water activity, growth factors, ionic composition, organic and inorganic particulates, pH, temperature, radiation, pressure, presence or absence of oxygen, oxidation-reduction potential, and space [131 - 134]. The interaction of these variations with the microbial community depicts the metabolic activities exhibited by the microorganisms [135 - 137].

In extreme situations like high temperature, limited activity of water, reduced pore size, and elevated pore pressure fluid, the metabolic activities of the indigenous microorganisms will be affected, resulting in spore formation [138 - 140]. However, changes in soil dynamics could change the microbial community and/or make the indigenous microorganisms adapt to new soil conditions [141].

Microbial interaction with clay minerals depends on the clay's complexity and structure; microbial interactions occur in the community and with other organisms [142]. Clay minerals serve as a source of nutrients and an enabling environment for effective growth and biosynthetic activities of the microbial community [143]. With these abilities, microorganisms play a significant role in clay mineral transformation and geochemical cycling [135, 144, 145]. Bacteria and fungi, along with other microbes, colonize the microenvironment of the clay soil. Bacteria influence the dynamic processes in soil water retention, mineral formation, cementation, and degradation, as well as the types and distribution of microbial communities in the soil [145]. The attachment of clay minerals to fungal cells influences fungal growth and metabolic and genetic activities [146, 147]. However, the interaction of bacteria with clay soil is more effective and functional than fungal interaction. For example, MAS NMR (magic angle spinning nuclear magnetic resonance) analyses of dithionite and microbially reduced montmorillonite reveal reversible changes in the structure of smectite due to reduction in structural Fe [148, 149]. Bacterial reduction of structural Fe (from Fe^{3+} to Fe^{2+}) in the octahedral site of smectite leads to: reduced specific surface area, increased cation exchange capacity, decreased water swelling, enhanced reactivity with organic chemicals and pesticides, and increased mineral stability [150, 151]. A study on microbe-clay interaction revealed that microorganisms have the capability to reduce clay minerals, with smectite showing the greatest reduction while illite is least reduced [152]. The process of smectite illitization by structural reduction of Fe^{3+} found in clay has been reported to be promoted by the action of *Desulfovibrio vulgaris* [153]. Also, mesophilic methanogen has the capability to reduce structural Fe(III) found in illite-smectite minerals, thus causing a number of structural alterations [154].

Clay mineral particles significantly increase the transformation of the microbial cells with the chromosome and the plasmid because of the adsorption of the microbial cells on the surface of clay minerals [155, 156]. For the adsorption of the bacterial cell by clay minerals, an appropriate pH for bacterial growth is of great importance [157]. This was confirmed through the improvement in bacterial respiration when the culture medium pH was adjusted to 7 [158]. Similarly, the activities of *Pseudomonas fluorescens* were stimulated extensively at pH 5 and 9 by clay particles [157].

Bacterial interactions with clay minerals may lead to transformation, dissolution, reduction, and uptake of trace elements within the minerals, driven by chelators and siderophores, which can enhance or reduce trace element adsorption on clay particles [159]. Furthermore, clay minerals and bacteria have the capability to adsorb heavy metals in soil, as the availability of heavy metals is prompted by the clay mineral particle interactions and formation of complexes [145, 160].

Therefore, bacteria also influence the layer charge, exchangeable cations, cation exchange capacity, Brunauer-Emmett-Teller surface, the rheological properties, as well as the swelling of clay particles [159]. For instance, water retention increases in clay polysaccharide interactions, thereby modifying the expansion and contraction pattern of the clay soil. Some studies have reported the formation of clay-bacteria aggregates as free structures [161 - 163] associated within the biofilm [161, 164]. However, soil structure is highly affected by the shrinking and swelling of clay particles.

Fungi are a ubiquitous and highly biogeochemical functional group of eukaryotic microbes. Their competency in carrying out mineral dissolution is higher than that of bacteria in soils with an alkaline and extensive redox range [142, 144, 165]. Also, fungi establish a mutualistic symbiotic relationship with photosynthetic species such as plants, cyanobacteria, and algae to aid their biogeochemical ability [142]. Scleroglucan, the fungal polysaccharide, improves water stability in clay, which results in the shrinkage of clay [166]. Also, the growth of fungal hyphae and polysaccharides can influence clay aggregation [167 - 169].

4.1.2.1 Effect of Vegetation and Microorganisms in Soil Stabilization

Bacteria and fungi exist in colonies that surround the roots of trees [170]; because of this, it is therefore possible that the activities of bacteria in soils coupled with the symbiotic association between bacteria and specific plant roots could lead to soil stabilization. The symbiotic association of fungi with the plant root has been a channel by which plants obtain nutrients and alter soil minerals, resulting in the modification of soil pH and soil redox level [171, 172]. Consequently, the mineral-mycorrhizal interaction is very vital for soil shrinkage and swelling. The quantitative assessment of in situ soil mineral alteration at the nanometer scale by fungi symbiotic association (mycorrhiza) has been established [173]. Moreover, the interaction exhibited by the fungi association is of great advantage to improve soil fertility and preserve vegetation.

Ultimately, vegetation and microbe clay mineral interactions have implications for the expansion and contraction of the expansive soils. More studies on the interactions between the microorganisms and swelling soil will provide more relevant information on the diagenesis of the expansive soil.

4.1.3 Biological Stabilization: Bio-enzymes

Bio-enzymes are biological catalysts in living things. The main sources of these naturally occurring enzymes are microorganisms, plants, and animals. Bio-enzymes, employed as soil stabilizers, enhance soil's chemical bonding, forming a durable structure resistant to water infiltration, weathering, and cracking. [174, 175]. Several studies have exhibited the ability of bio-enzymes to improve soil physical properties by improving the soil strength and reducing the soil permeability [176 - 178]. Due to its sustainability and low cost as compared with chemical stabilizers, various products have emerged using bio-enzyme technology. This includes Eco enzyme, conaidsuper, terrazyme, permazyme, roadbond, and endurazyme. They are usually introduced into the soil in a dissolved state. Generally, each of these bio-enzymes is made of various enzymes with some other materials. For example, Eco-enzymes contain active components such as lipase, amylase, and protease, as well as water and proteins generated from the fermentation of plants [179]. The efficacy of these enzymes is dependent on dosage and soil characteristics [176, 180]. Certain authors recommend an enzyme concentration of 200 mL per 0.75 m^3 for effective stabilizing of the swelling soil. [181, 182]. Notwithstanding, soils with high plasticity may require higher dosages of bio-enzyme for effective soil stability [183]. Soils with higher clay content improve enzyme application effectiveness, and those with at least 10% clay are suitable for bio-enzyme treatment [181]. However, the specimen and the curing method used in soil stabilization treatment could be of disadvantage, resulting in negative stabilization results [184]. The combination of bio-enzyme with other materials to optimize soil's stability (i.e., strength, plasticity, and other geotechnical characteristics) has been recommended [175, 185]. Various bio-enzymes have been integrated with soil enhancement materials, like cement or lime, to improve soil plasticity, strength, and other geotechnical characteristics [186, 187]. Before applying a bio-enzyme in the field, it should undergo laboratory testing to confirm its effectiveness, whether with or without additives.

4.1.4 Biological Stabilization: Agricultural Waste Fibers

The use of agricultural waste fibers as bio-based stabilizers has gained significant interest in geo-technological engineering because of their strength, favourable environmental impact, affordability, and accessibility [188, 189]. Many agricultural fibers, such as coconut fiber, sisal, palm fiber, jute, flax, barley straw, bamboo powder, rice husk, sugarcane bagasse, and sawdust, have been used as soil stabilizers [190, 191]. Coconut fiber and sisal are the most-used fibers in concrete recently [192]. Moreover, using them as part of the constituent in building material production results in the sustainability of the product [193]. The utilization of natural fibers as strengthening elements is naturally distinct from other synthetic materials, resulting in improved soil as influenced by both physico-mechanical and biological characteristics of the agricultural fiber [194]. Cellulose, hemicellulose, and lignin are the basic chemical components of agricultural fiber, while the quantity of each of these components depends on the plant's part, species, age, as well as the effect of climate and topography [193]. Therefore, the biochemical composition of natural fiber is significant to its effectiveness. The limitation to the use of these agricultural fibers as soil stabilizers is their durability and hydrophobic nature [195] as well as expertise in the production and mixing for quality and standard soil stabilization [196]. Optimizing the mechanical characteristics of these fibers is necessary due to the limitations. Various techniques have yielded positive results; these include plasma treatment [197], sodium hydroxide treatment [198], and silane treatment [199]. These treatments tend to reduce the hydrophilic nature of the fiber and decrease the rate of biodegradation. Basically, agricultural waste fiber is an effective material for stabilizing expansive soil that encourages sustainable resource use.

4.1.5 Biological Stabilization: Biochar Amendment

Biochar is an amendment made from pyrolyzed agricultural waste biomass that has been discovered to be significant in soil stability [200 - 203]. It has also been reported to suppress expansive clay soils [204]. Equally, biochar as an amendment has been reported to mitigate the commencement, propagation, and reduction of desiccation cracks in expansive clay soils susceptible to series of wetting and drying [205, 206]. It is an eco-friendly and sustainable amendment that boosts soil strength and lowers the carbon footprint in stabilized soil for construction. [207, 208].

4.2 Chemical Stabilization

Chemical stabilization employs traditional materials (e.g., salt, lime, cement), enzymes (e.g., PZ-22X), and polymeric resins such as polyvinyl acetate for the stabilization process. [128]. The abundance of lime and salt and the relatively low cost in many parts of the world have made their application as stabilizers very common [209]. A blend of lime and salt has been shown to effectively reduce the swelling pressures of clay soils [210]. Even though these materials are cheap, there is great concern about the effect of these materials on the ecosystem since most of them are non-biodegradable. In chemical stabilization, strength is provided to the soil either through the reaction of the additives (chemicals) with either water or with soil particles, i.e., minerals contained in the soil [211-213]. For example, in the addition of lime (CaO) to soil, there is the substitution of Ca^{2+} in clay, thus leading to the reduction in interlayer spaces that are present in swelling clays such as montmorillonite and in the process leading to a reduction in soil plasticity [214].

4.2.1 Additives used in Swelling Clay Stabilization

Swelling and consolidation of soils are usually linked to expansive clay minerals, which comprise smectite and illite [215]. Additives in stabilizing problematic soils, such as swelling clay soils, have been of paramount interest in the enhancement of engineering attributes [216]. According to research, the effective way of enhancing the physical and mechanical characteristics of swelling clay soils is to combine heavy clay with dust-filled sand and grade M400 cement to create a composite material [217].

Cement use in soil stabilization is of great importance based on the durability enhancement it provides [218, 219]. The addition of cement decreases the total pore volume and increases the strength of swelling clay soils. Additionally, lime has been successfully utilized to stabilize swelling clay soils [220 - 222]. Limestone powder has been found to be effective in the stabilization of swelling clayey soil [223, 224]. Limestone powder as an additive changes the Atterberg limits, free swell index, and the microstructure of the mixed soil. Similarly, expansive soils have been stabilized using marble dust, which is usually a waste material [225, 226].

Ionic additives have also been employed in soil stabilization [227]. Recent studies have shown that both compression and swell indices have decreased slightly and drastically by an additive that comprises a combination of lime and salt [96, 228]. Gypsum serves as an effective stabilizing agent for expansive clay soils, as evidenced by changes in clay properties, such as plasticity, strength, and swell, between treated and untreated clays [229 - 231]. Also, calcium chloride solutions have been used in the stabilization of expansive clay beds [232, 233]. Common salt (NaCl) has been found to be an effective additive in the stabilization of expansive soil [234 - 236].

Expansive clay soils treated with special polymers show enhanced California bearing ratio and maximum dry density (MDD) and a reduction in Atterberg limits, swelling pressure, and swelling potential [237 - 239]. Research shows that additives such as small amounts of calcium lignosulfonate (CLS) gave a satisfactory performance in reducing the natural clay's swelling ability [240].

4.2.2 Inhibition of Swelling Clays in Drilling Operations

In oil and gas drilling operations, wellbore instabilities present as one of the most serious issues connected with shale formations while drilling, particularly in areas with high levels of active clay minerals such as smectite and vermiculite [241]. Lubricating and cooling the drill bit while drilling is one of the drilling fluid's primary purposes [242]. Compressed clay components, which frequently arise during drilling operations, must be kept from absorbing water from the drilling fluids and subsequently expand by the fluid. To inhibit the swelling of such clays during drilling, inhibitors that contain cations such as K^+ that are capable of displacing Na^+ present in swelling clays are used [69]. Also, synthesized acylated inulins have also been reported to be successful as water-based drilling fluids, preventing wellbore instability due to swelling clays in oil and gas exploration [243]. It has been discovered that adding organic additives, including charged and uncharged polymers, can prevent clays from expanding [69].

Clay swelling has been prevented with the use of polyethers and polyhydroxyethers [244]. Polyalkylene glycols (polyethers) with moderate to high relative molecular mass have been shown in experiments to be efficient in inhibiting clay swelling [244]. To have the best inhibitory impact on swelling clays, these compounds have to be linear organic molecules with a moderately long chain that contains localized hydrophobic and hydrophilic areas. When polyethers are intercalated inside the clay layers, the hydrophobic portions create an efficient sealant against aqueous ingress, and the hydrophilic sections improve the adhesion of sodium ions to the clay surface, blocking hydration and the resulting clay swelling [244]. By combining the effects of adsorption, intercalation, and hydrophobic contact, piperazine-based polyether Gemini quaternary ammonium salts show intriguing suppression of montmorillonite in fluid [245]. A water-soluble organic molecule with a low molecular weight, distinct areas of moderately high hydrophobicity, and small hydrophobic domains are required for neutral inhibitors [246].

Researchers have found that adding surfactants can stop clay from swelling [247, 248]. Unlike conventional inhibitors like KCl-based, synthetic surfactants like gemini surfactants stopped clay swelling while leaving the other properties of the drilling fluids the same [247, 249]. Biosurfactants rich in non-ionic surfactants, which include ginsenosides, can form a hydrophobic shell over montmorillonite (Mt) active surfaces, lowering water adsorption and thereby greatly inhibiting swelling (Fig. 6) [250]. The strong hydrogen bonds resulting from the combination of amino acids and water in clays are their activity coefficients with base fluids, which triggers inhibition in clays [251 - 253]. Investigations have shown that real- produced formation water and artificially produced formation brine have justifiable free swelling indexes and sedimentation rates, which reduce the charge at clay facets and, as a result, the swelling capacity of Na-bentonite [254]. Solutions containing cationic polyacrylamide chloride with a quaternary ammonium group, when mixed with KCl brine and in contact with clay for a sufficient duration, have been shown to inhibit clay swelling, as reported in studies like [255]. A branched synthesized polyamine, which has a low molecular weight, has been appraised as an effective inhibitor in the swelling of clay [4].

The hydration of montmorillonite (MMT) was hindered by the adsorption of polyethyleneimine (PEI) on the MMT surface and intercalation in the MMT interlayer [256]. Fig. 7 shows the swelling mechanism utilizing PEI.

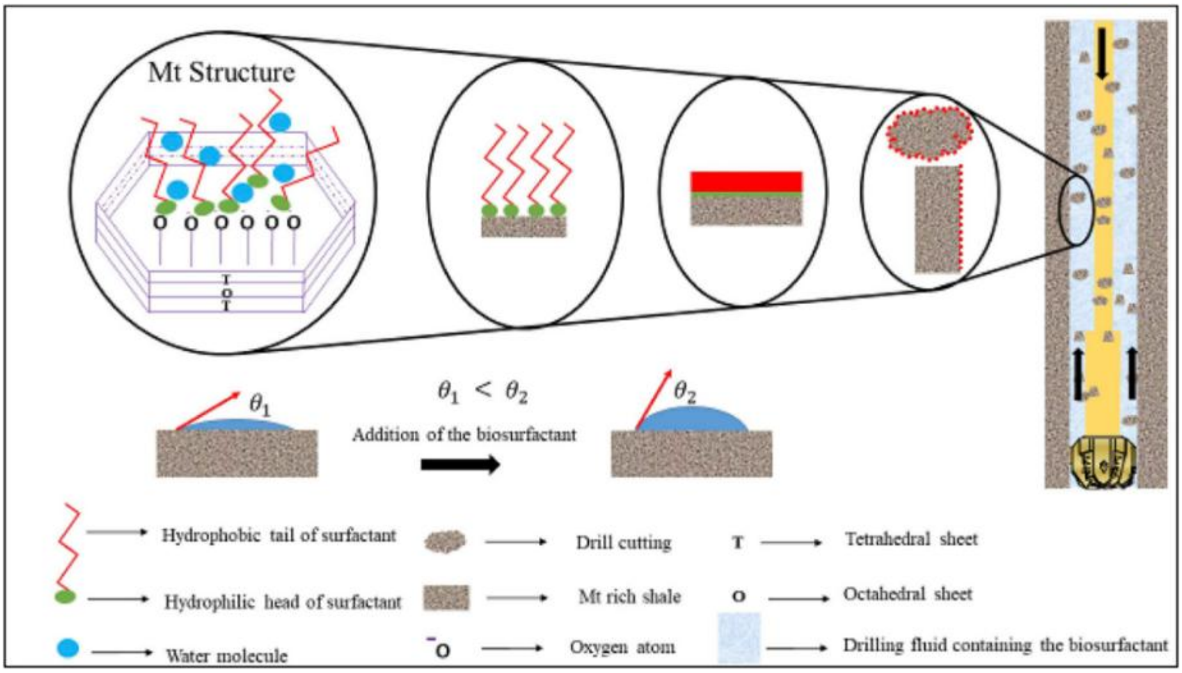

Fig. 6. An illustration depicting the reactions involving the biosurfactant and Mt-rich shale [250]

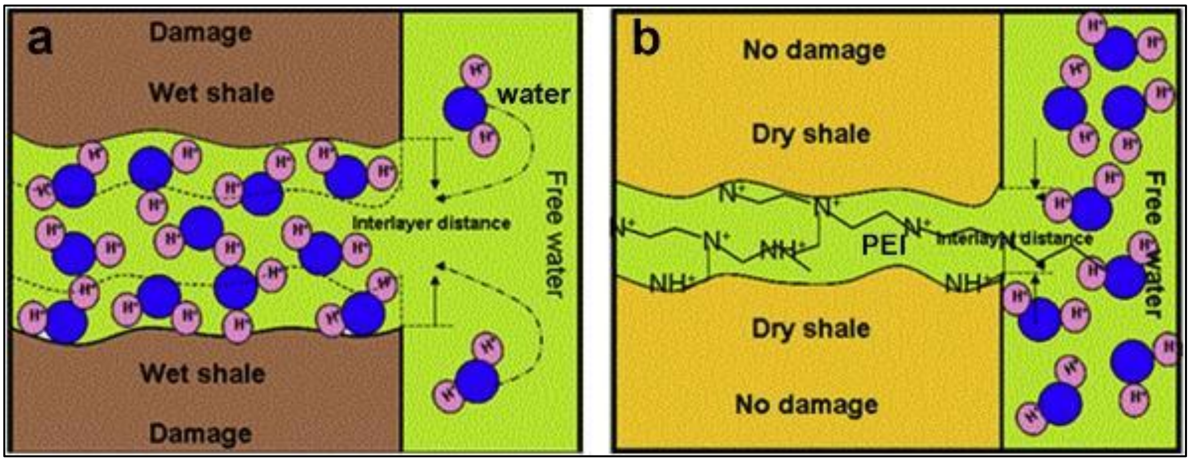

Fig. 7. Swelling mechanism utilizing polyethyleneimine [256]

4.3 Mechanical Stabilization

Mechanical stabilization is a fundamental soil stabilization technique commonly used to improve low-capacity subgrades with minimal environmental impact [257]. This method combines the engineering characteristics of the constituents of different soil mixtures by filling the spaces surrounding coarser granular soil particles with finer soil particles, which makes them compacted easily [257, 258]. Rollers and tampers are usually used for the compaction of soils with shallow depth, while dynamic compaction (e.g., heavy weight compaction, vibro-compaction, and blast densification) is used for deeper layer soils [259, 260]. The soil mixed in mechanical stabilization is grouped into two, i.e., aggregates and binders. Aggregate soil are soils with average particle size greater than 75 microns in size while binder has less than 75 microns particle size. Mainly, mechanical stabilization increases soil durability and strength of soil aggregate mixtures depending on the soil aggregate types (binder, coarse and fine aggregates) combination [261]. The influence of the compaction process on expanding soil is apparent more on a macroscopic scale than the microstructure. The importance of compaction management in swelling soil stabilization is clear since the variation in moisture drives the volume change behavior of the soil [262].

5.0 Economic Implications of Swelling Clays

Montmorillonite embedded with long-chain quaternary ammonium ions, often known as "organoclays," has long been utilized as an adsorbent of organic pollutants and in a number of sectors, including cosmetics, grease, paint, and paper [263 - 265]. Organoclays have recently been used extensively in the creation and fabrication of polymer-clay nanocomposites [7, 266].

During drilling, swelling clays such as bentonite are added to materials used to grout boreholes for thermal exchangers to control the suspension's stability and flowability [267, 268]. Swelling clays, such as montmorillonite, have outperformed cement and chemical grouts due to their geological stability at relatively low temperatures and their great capacity for radioactive adsorption [269 - 272]. Compressed expanding clays serve as structural barriers of considerable importance within multi-barrier systems [29, 273, 274]. In some countries, clays and argillaceous rock minerals are seen as potential deep confinement solutions for waste from nuclear power plants [275 - 277]. Expansive clays significantly enhance the waste separation capability of the designed near-field barriers [278, 279]. Restoration of disposal areas to their initial permeability has been enhanced using swelling clays [280]. Montmorillonite has great capacity to adsorb bacteria, mycotoxins, and heavy metals present in both animal feeds and the body [281 - 283]. These results highlight the significance of swelling, which is mainly dependent on the clay content, for seedbed consolidation [284].

In the tropical semi-arid regions, swelling clays have been found suitable for the cultivation of cotton, which is an important cash crop [285]. Montmorillonite clay provides better sorption characteristics due to its uneven and porous surface, which makes it suitable as a system for fertilizer delivery [286-288]. Hydrogels constructed of methylcellulose, polyacrylamide, and calcic montmorillonite have been discovered to be effective in the regulated dispersion of fertilizers in soils, where each component had a synergistic impact, giving very high fertilizer concentration in their physical makeup [289]. The montmorillonite component of the hydrogel facilitates a more regulated nutrient release compared to the pure hydrogel across various pH levels [289]. Nanoclay, such as multilayer clays (montmorillonite), is the most frequent nanoparticle (NP) utilized to create controlled-release fertilizers (CRFs) due to its high aspect ratio nanolayers [290]. Nanoclays are made using the smectite group of clays (2:1 phyllosilicates), the most common being montmorillonite, where the octahedral site is isomorphically substituted [1]. Clay nanoparticles (NPs) with large surface areas and nanolayer responsiveness can be used to create CRF formulations. Nanoclay is an important constituent in CRF production owing to the active surface it offers to various physicochemical and biological processes [291]. Nanofertilizers have the capability to reduce surface runoff and nutrient leakages into the environment during heavy rains, hence enhancing fertilizer usage efficiency, increasing environmental sustainability, and increasing crop output [292]. The process of regulated nutrient release of nanofertilizers in the field is shown in Fig. 8. The smectite–urea-formed nanocomposite fertilizer boosts both the quality and quantity of plant growth, thereby increasing yield [293].

Swelling clays have been utilized as carriers in drug delivery systems [294 - 297]. Planar nanoclay, such as montmorillonite, serves as effective drug carriers capable of delivering various medicines [298]. Montmorillonite can also load drugs through the interlayer, including paclitaxel, exemestane, curcumin, and aprepitant [298]. Fig. 9 shows the various types of drugs utilized in the drug delivery system.

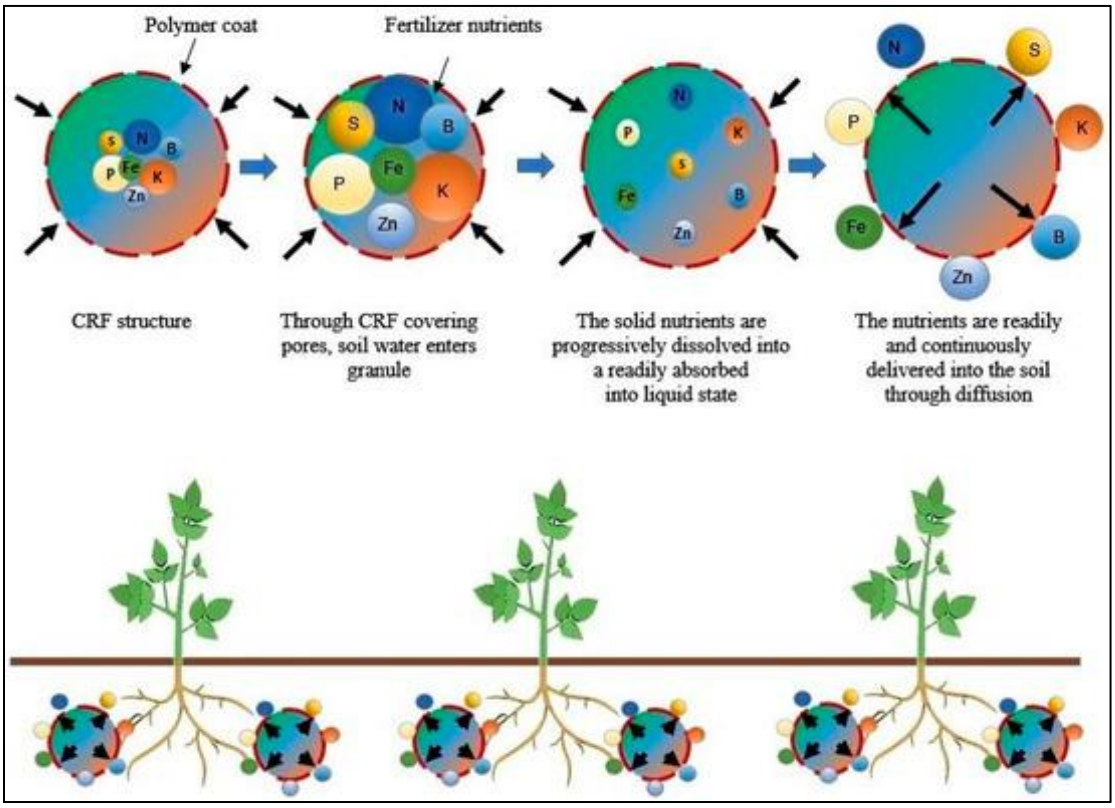

Fig. 8. In-field action process of regulated nutrient release of nanofertilizers [292]

Montmorillonite has been used in combination with other substances successfully in the incorporation of hydrophobic drugs into hydrophilic matrices [300] and has been applied to the preparation of reliable and effective biocompatible drug delivery for tanshinone IIA [301]. Properties such as exceptional plasma absorption capacity and strong adhesion due to its ultra-small particle size have made montmorillonite, a swelling type of clay, the most effective phyllosilicate for hemorrhaging control [302]. Nanoclay with a microporous structure can be utilized as drug carriers to make composites that are essential for suppressing bacterial development on wounds and encouraging vascular, muscular, and skin tissue regeneration [303]. Montmorillonite and vermiculite have been successfully used in antitumor therapy [304, 305]. Montmorillonite has been identified as an effective carrier polymer heterogonous adsorbent for physiologically active and anticancer heterocyclic compounds [306]. Chitosan and montmorillonite could be used together to make composite materials that are biocompatible and have hemostatic properties that can stop bleeding [307]. Incorporating montmorillonite-NH2 into CODM hydrogel improved its hemostatic performance, enhancing the hydrogel's capacity to promote erythrocyte coagulation and adhesion in tail vein and femoral artery bleeding models [308]. Montmorillonites can be used in the process of detoxification because of their capabilities of removing waste materials from the body [309]. Diosmectite, a natural silicate applied to treat contagious diarrhea, can absorb toxins and germs while also altering the rheological properties of gastrointestinal mucus [309 - 311]. A summary of the uses of swelling clays is presented in Table 4.

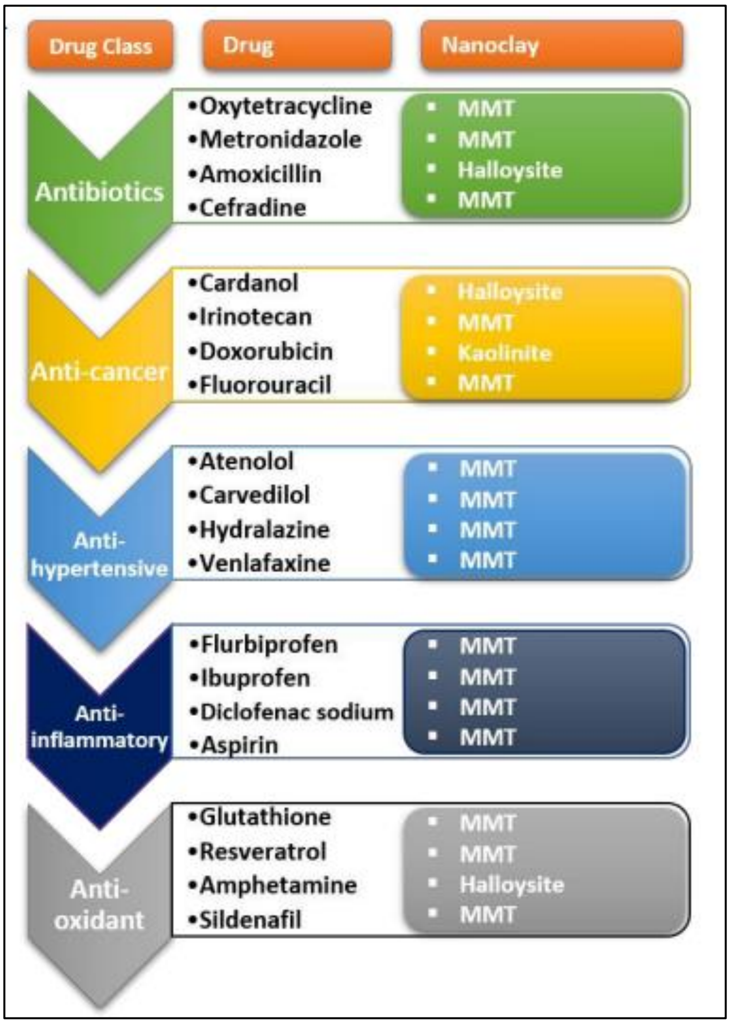

Fig. 9. Different types of medicines utilized in drug delivery systems [299]

6.0 Future Prospects

The studies reviewed so far show that there is need for the development of eco-friendlier forms of additives as stabilizers. Also, little or minimal studies have been done on the use of biochar amendments in the stabilization of swelling clay soils, as well as the use of swelling clays as nanomaterials. Optimization of the usefulness of montmorillonite and vermiculite in antitumor therapy and hemorrhage control should be further enhanced. Similarly, field studies should be carried out on the use of clay-based adsorbents such as smectite for the removal of organic contaminants from effluents.

Table 4: Economic uses of Swelling Clays

Uses	Swelling clay type
Industrial	
Adsorbents	Bentonite
Sealants	Bentonite, montmorillonite
Drilling muds	Bentonite
Environmental	
Landfills liners	Bentonite
Manufacture of nanocomposites	Bentonite, montmorillonite
Engineered barriers	Bentonite
Radioactive waste disposal	Bentonite
Industrial oil absorbents	Montmorillonite
Agricultural	
Soil carriers	Montmorillonite
Soil conditioners	Montmorillonite
Animal feeds bonds	Bentonite, Montmorillonite
Medical	
Drug carriers	Montmorillonite
Antioxidants	Bentonite

7.0 Conclusions

Despite the destructive nature of swelling clays in the aspect of building and construction, it has found significance in the retention of nutrients and pollutants and as drilling muds in oil and gas. Different environmentally friendly mechanisms aside from the natural biological dynamic influence (vegetation and microorganisms), such as bio-enzymes, agricultural waste fibers, and biochar amendment, have been developed in recent times. In addition to the common additives (salts, lime, and cement) used in the treatment of swelling clays, swelling clay soils have been inhibited through treatment with polyethers and polyhydroxyethers, and synthetic surfactants, thus reducing the adverse effects in oil and gas. Swelling clays have found great significance as adsorbents, carriers for drug delivery, and for the construction of repository barriers for the radioactive waste disposal. Swelling clays have also found significant use in agricultural purposes for the controlled release of fertilizers to soil. There is a need for more study on the use of biochar for stabilization; also, the use of swelling clays as nanocomposites should be vigorously explored. The research involving clinical trials of nanoclays in drug delivery systems is still quite limited.

8.0 Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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