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REVIEW ARTICLE

The role of montmorillonite in sustainable agriculture and environmental sustainability: A critical review

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ABSTRACT

This paper examines some of the properties and potential applications of montmorillonite, which is a type of clay in the smectite group, and its importance in achieving some of the Sustainable Development Goals. This paper points to some of the unique attributes that the mineral has, most of which lie in its capacity to retain water and provide essential nutrients, thus improving soil quality. Soilless growth media that contain montmorillonite can improve plant growth and make better use of resources. This study is specifically concerned with the application of montmorillonite for the development of sustainable agriculture and the preservation of the environment. It will look into the application of montmorillonite for agricultural purposes, water filtration, and the preservation of the ecosystem. This study will examine the characteristics and potential application of montmorillonite, a clay mineral belonging to the smectite group, and its contributions to the development of some of the Sustainable Development Goals (SDGs). It will be comprised of some information on the application of montmorillonite for agricultural purposes, water filtration, and environmental preservation techniques, as well as the exposure of the agricultural environment to montmorillonite. Moreover, this paper presents some of the benefits of montmorillonite and addresses the second goal of sustainable development, including poverty alleviation and food security improvement, which can benefit people worldwide.

Keywords: montmorillonite; clay minerals; sustainable development goals; soil fertility; sustainable agriculture

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1. Introduction

Clay minerals are made of aluminosilicates, which are highly compacted layers of atoms[1]. They are usually minute crystals whose physical properties allow them to absorb water and swell in size with water and heat in the soil. Generally, clay minerals are tiny particles that cannot be identified with the naked eye, produced through physical, chemical, and biological weathering[2]. Clay minerals are present in large quantities in the soil due to the fact that they are among the major components of the soil, and they play a great role in most of the environmental and agricultural processes[3]. Montmorillonite, which is one of the vital clay minerals classified as a member of the smectite group, has a 2:1 structure. It is a vital constituent of the fertility of the soil, which is essential in attaining the Sustainable Development Goals (SDGs). Moreover, it is renowned for its high cation exchange capacity and adsorption ability, two important properties that improve soil characteristics and sustainability[4]. There is a need for sustainable agriculture because the global population is increasing. Especially under the pressure of climate change[5]. Understanding these processes helps maintain healthy soil as it retains water and provides the nutrients that enable plants to develop[6]. Due to environmental problems, the world is facing at present, it is important to utilize clay minerals, such as montmorillonite, for sustainable agriculture and conservation of biodiversity[7]. This review aims to critically analyze the physicochemical properties of montmorillonite and evaluate its role in sustainable agriculture and environmental management in relation to the Sustainable Development Goals.

1.1. General Properties of Montmorillonite Mineral

It is important to highlight, before presenting the agricultural and environmental applications of montmorillonite, that it is fundamental to understand some of the main physicochemical properties of this material, as this will allow for an understanding of how this material behaves in relation to soil functionality.

1. High cation exchange capacity (CEC)
   Montmorillonite is characterized by its high cation exchange capacity that can reach up to 110 cmol kg^{-1}. The exchange cations that are present between the interlayer spaces of montmorillonite enable it to interact with the soil solution. The interaction enables the soil to retain nutrients; this is what makes montmorillonite contribute to soil fertility[8].
2. Large specific surface area
   Montmorillonite minerals have a very large surface area. This enables the soil to adsorb and exchange nutrient ions due to the negatively charged surface. This improves the soil's ability to retain essential plant nutrients such as potassium (K), calcium (Ca), and sodium (Na)[9,10].
3. Isomorphic substitution
   Another characteristic feature of montmorillonite is the isomorphic substitution in its crystal structure, in which ions are replaced by other ions in the tetrahedral layers [SiO4][SiO_4][SiO4] and the octahedral layers [AlO6][AlO_6][AlO6]. The process increases the rate of ion exchange reactions in the soil[11].
4. High water-holding capacity
   Montmorillonite is known to have a unique property of absorbing and retaining water, thus improving water retention in soils. This property is significant in controlling several physical processes, such as swelling and shrinking, thus enabling soils to react dynamically to environmental factors. Moreover, these properties help in improving soil aggregation and reducing erosion, thus promoting sustainable land management practices[12].

For this reason, montmorillonite clay particles are of great significance in soil systems owing to their unique physicochemical properties.

1.2. Comparison with Other Clay Minerals

Montmorillonite can be compared to other clay minerals like kaolinite, illite, and vermiculite on the basis of the difference in the physicochemical properties of the clay minerals. It has been observed that clay minerals with a 2:1 structure, like montmorillonite and vermiculite, have a higher cation exchange capacity (CEC) and a higher specific surface area than 1:1 clay minerals like kaolinite[13]. The cation exchange capacity of montmorillonite varies from 80 to 150 cmolc kg^{-1} and has a very large surface area, which makes it capable of retaining considerable water and nutrient content in the soil system[14]. On the other hand, kaolinite has a low cation exchange capacity, as well as limited swelling, owing to the stability of its crystal structure. In the case of illite, the clay has a fair nutrient retention ability, but it does not have a high swelling ability owing to the presence of potassium ions, which fix the crystal structure. On the other hand, montmorillonite has a higher surface area, permanent charge, as well as a high ability to adsorb water, thus playing a more important role than other clay minerals in the retention of water, nutrients, as well as the adsorption of pollutants[15]. A summary of the main physicochemical differences of the most common clay minerals is presented in **Table 1**.

Table 1. Physicochemical comparison of common clay minerals.

Mineral	CEC (cmolc kg⁻¹)	Specific surface area (m² g⁻¹)	Water retention	Swelling behavior	Pollutant adsorption
Montmorillonite (Smectite)	80–150	700–800	Very high	High	High
Kaolinite	3–15	5–40	Low	Very low	Low–Medium
Illite	10–40	10–150	Moderate	Low	Medium
Vermiculite	100–200	500–760	High	Moderate	High

These differences in physicochemical properties make montmorillonite play a major role in enhancing soil fertility and adsorbing water and pollutants compared to other clay minerals. The high CEC and surface area of montmorillonite make it more effective in enhancing soil fertility and adsorbing water and pollutants.

1.3. Structural Composition of Montmorillonite Mineral

Understanding the structural composition of montmorillonite is essential for explaining its physicochemical properties and behavior in soils. The structural composition of minerals in this group consists of two tetrahedral sheets and one octahedral sheet. **Figure 1** illustrates the typical layered structure of montmorillonite consisting of two tetrahedral sheets and one octahedral sheet[16]. The tetrahedral sheets are linked to the octahedral sheet through shared oxygen atoms. These apical oxygen atoms connect with hydroxyl groups of the octahedral layer, forming a stable layered structure as illustrated in **Figure 1**[17]. The stacking of these layers forms the basic structural unit of montmorillonite. Weak Van der Waals forces between layers allow water molecules and exchangeable cations to enter the interlayer space, leading to swelling and shrinkage behavior that significantly influences soil physical properties. This expansion is reversible, meaning that the mineral structure can return to its original state when environmental conditions change. As a result, minerals of the smectite group are characterized by a high capacity for swelling and shrinkage, which strongly affects many physical properties of soils[18].

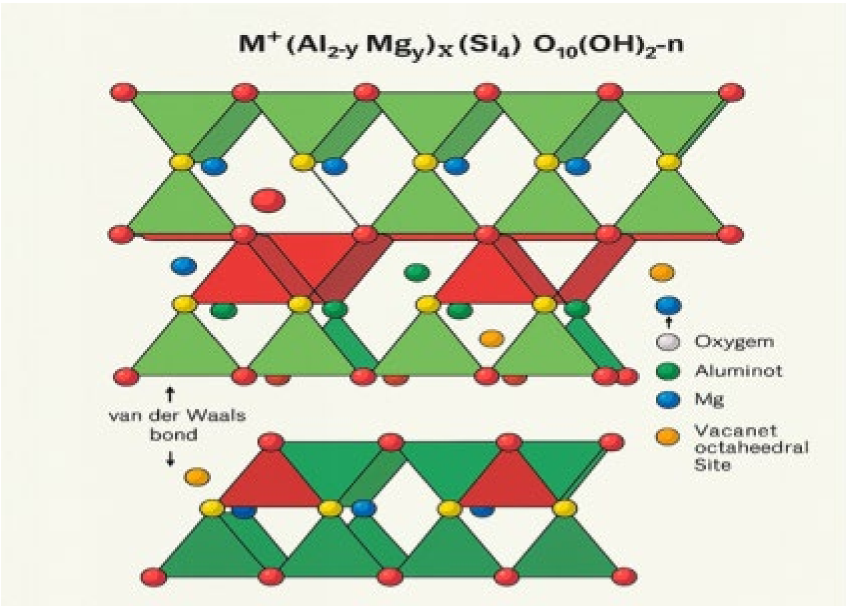

Figure 1. Theoretical formula and structure of montmorillonite source: Nanocor Inc., IL (USA)[18].

1.4. Occurrence of Montmorillonite in Soil

Montmorillonite occurs in soils as a function of the environmental conditions that influence the formation and dissemination of smectite clay minerals. The smectite group includes several minerals **Figure 2**. Trioctahedral smectites include hectorite (Li-rich), saponite (Mg-rich), and sauconite (Zn-rich), whereas dioctahedral smectites include montmorillonite, beidellite, and nontronite. The unit layer consists of two inward-facing tetrahedral sheets sandwiched between a central alumina octahedral sheet. The layers are continuous in the a and b directions but are poorly bonded between layers and have extremely good cleavage, allowing water and other molecules to enter between the layers and produce expansion in the c direction[19]. Smectites are typical weathering products of basic rocks. Smectite minerals are commonly formed in poorly drained, flat to gently sloping terrains, slightly alkaline [such as in marine conditions], and with high Si and Mg potentials. Additional conditions that promote the formation of Smectite include the presence of Calcium and the absence of potassium. A high water table plays an important role in the development of montmorillonite as it increases the activity and mobility of ions in the soil solution. Under freely drained conditions, the ions can be leached and smectite clay development inhibited. Poor drainage, slightly alkaline conditions, and high silicon (Si) and magnesium (Mg) potentials favor the formation of montmorillonite[20]. Also, the presence of magnesium in the environment is highly significant in smectite mineral formation. Experiments have confirmed that magnesium is of paramount significance in montmorillonite synthesis, especially under low-temperature conditions[21]. It was discovered that high-iron percent parent rocks form the mineral Nontronite, or so-called iron-rich smectite resulting from serpentinite weathering of rocks, while magnesium-rich rocks are a source of High-Mg Smectite formation, such as in the mineral Saponite. Beidellite occurs in soils that have developed on parent rocks with mica and chlorite[22]. Smectite group minerals are typically prevalent in soils of the B-horizon, Vertisol B-horizon, and overlying directly parent rocks. Both locations possess high silicon ion concentration and cations needed for the formation of smectite. This is because waterlogged conditions reduce the leaching of base cations (Mg^{2+} and Ca^{2+}) and silica, resulting in an alkaline, high-silica condition favoring the development of smectite. Well-drained soils, in contrast, lose these base cations and silica rapidly, and hence favor an acidic condition to kaolinite formation, a 1:1 variety clay, as illustrated along a soil catena correlation along a catena [succession of landforms], the uplands with good drainage show kaolinite soils, while poorly drained low-lying areas show smectite soils[23]. These environmental and geological conditions play an important role in determining the distribution of montmorillonite in soils and explain its prevalence in specific soil horizons and climatic regions.

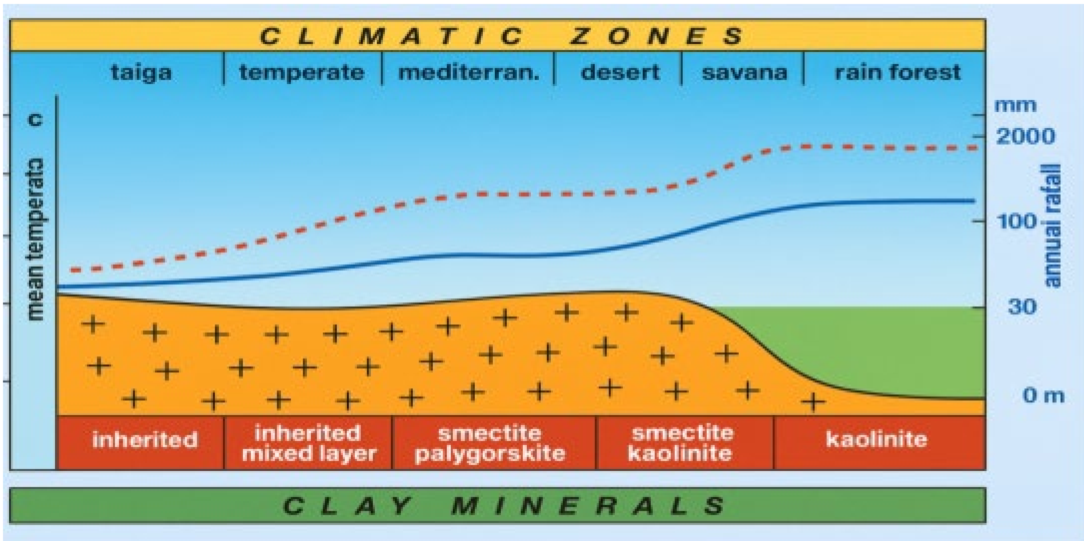

Figure 2. Relationship between climate, precipitation, temperature, and weathering depth in the formation of montmorillonite.

Additionally, under poor drainage conditions, the illite clay mineral can be transformed into smectite through the leaching of potassium and the replacement of hydrated cations in the interlayer spaces. High percentages of smectite minerals have been found in the B-horizon of soils[24]. Studies show that the Montmorillonite mineral is widely distributed in the Nile River Delta soils, particularly in Vertisols, which cover an approximate area of 10,000 km^2. They exhibit characteristic shrink-swell behavior due to the high content of smectite group clays, mainly montmorillonite. Montmorillonite has been reported to make up 40–60% of the clay fraction of these soils, which is mainly accountable for their physical and chemical properties. The smectite group of minerals was also reported to constitute approximately 40% of the low-lying, poorly drained black soils of Australia. India has black smectite soil that developed from basalt rocks. Many studies have also indicated that smectite group minerals also occur in the soil of volcanic ash deposits in some regions of the United States of America[25]. Many studies revealed that the smectite minerals settle in the clay fraction of Mollisol soils, and their chemical properties vary with respect to prevailing drainage conditions and the type of ions predominant in these soils. The presence of members of this group in the soil largely accounts for its mineral and chemical nature, and is the result of the fixation and retention of a number of nutrient elements such as potassium, aluminum, copper, zinc, and manganese. They also play a key role in the swelling and shrinkage process in soils that alternate between dryness and wetness, causing self-plowing, like in Vertisol soils, with a high smectite content, having a high percentage of irrigation water running through them. Beneath cracks, especially during the dry season, this can reduce irrigation efficiency. Thus, the presence of any member of this group of minerals in the soil is of prime importance in the control of deficiency, fertilization, and their therapy[26,27].

1.5. Sources of Montmorillonite Formation in Soil

Montmorillonite minerals form in the soil from a number of sources, maybe it can inherit mostly from mica minerals and then has the characteristics of mica due to potassium stabilization, or the minerals are altered from chlorite type directly by replacing the interior hydroxide layer by altering the reducing of the medium's reaction rate, or the directly out of solution from the soil in the situation when there takes place proper environment to gain proper pH formation medium reaction along with increasing efficacy of earth bases. With high concentrations of silicon, magnesium, and aluminum[28].

1.6. Transformation From Mica Minerals

Due to the similarity of the crystal structure between mica and smectite minerals, as they belong to the 2:1 mineral group, which facilitates the transformation process from mica towards the expanded smectite mineral group[29]. The crystal structure of mica minerals is similar to the crystal structure of smectite minerals with a slight difference, which is the replacement of aluminum for part of the silicon in the tetrahedra layer, and that this replacement is equal to a minimum of a quarter of the silicon atoms in the tetrahedra layer, which causes a negative charge to overflow on the surfaces of mica minerals, which are characterized by a high external charge[30]. This condition helps mica minerals to trap the potassium ion (K) within the hexagonal openings of their crystal structure, in order to balance the excess negative charge. Studies observed that the size of clay particles greatly affects the quality of the minerals formed during the mica-to-smectite mineralization process. In a study published in the journal Clay Science, the transformation of mica in clay samples of different sizes was compared: fine clay (<0.2 µm) and coarse clay (0.2-2 µm)[31]. **Figure 3**.

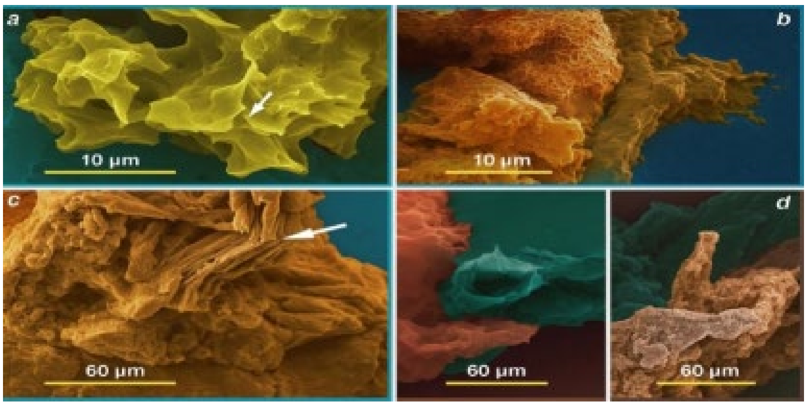

Figure 3. SEM images showing smectite formation on mica and feldspar surfaces during mineral transformation[31].

1.7. Transformation From Chlorite

The structural composition of chlorite consists of four sheets [2:1:1], three of which form [2:1] layers, which are similar to the structural composition of smectite minerals, as they usually contain two tetrahedra and one octahydra layer as shown in **Figure 4**[32]. The rest of the structure is described as an interlayer hydroxide sheet. Several hypotheses have been put forward about the formation of smectite from chlorite, especially the highly unstable chlorite, which is called mafic chlorite, which is characterized by a high ability to weather **Figure 4**. [Weathering index = 4][33].

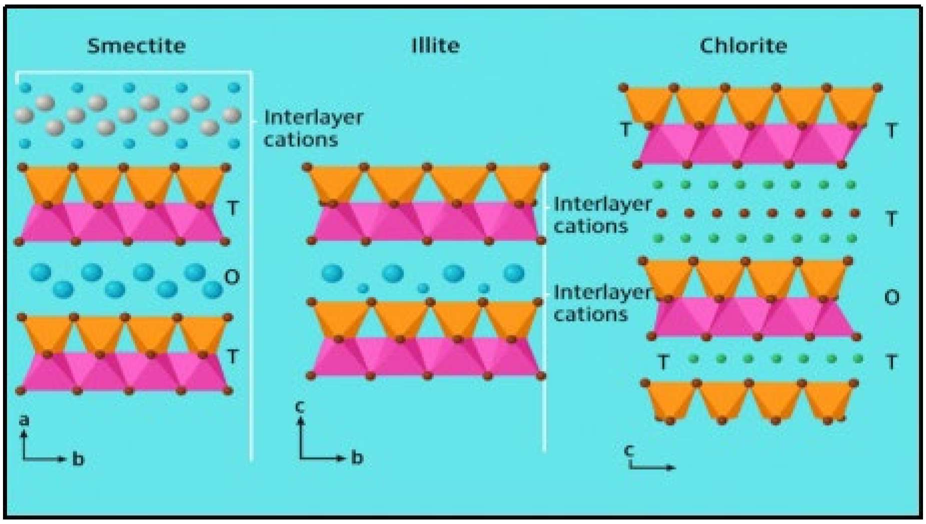

Figure 4. Schematic Diagram of the Transformation of Smectite to Chlorite Interstratified Minerals, Showing Smectite, Illite, and Chlorite Structures[33].

Smectite minerals are directly precipitated from the solution in soil by a process termed as "Neogenetic Smectite". Precipitation of this type of smectite requires silicon ion-enriched environments. It is characterized by elevated levels of earth bases such as calcium (Ca^{2+}) and magnesium (Mg^{2+}) and a pH value between 6 and 7. Such environmental conditions enhance the stability of the precipitated metal because the stability is largely a function of silicon ion activity and precipitating environment pH. It has been confirmed through research that montmorillonite, which is a smectite, precipitates in larger quantities in arid seasons, leading to increased silicon and magnesium ion concentration in the environment of formation[34].

Pathogenically formed Smectites are normally devoid of potassium fixing properties of Smectites of mica minerals because Smectites obtain potassium fixing properties from their parental mineral, mica **Figure 5**[35].

Figure 5. Microscopic Image Showing the Distribution of Minerals, Including Montmorillonite, in Soil Samples[35].

2. The Role of Montmorillonite in Sustainable Development: Clay Minerals and Sustainable Agriculture

2.1. Clay Minerals and Sustainable Agriculture

Clay minerals such as montmorillonite play an important role in promoting sustainable agriculture because of their strong influence on soil fertility and nutrient dynamics. Montmorillonite has a high adsorption capacity for organic and inorganic substances, which improves nutrient availability and supports plant growth[36]. Its ability to retain water and nutrients is also essential for maintaining stable soil conditions and enhancing agricultural productivity[37]. The incorporation of clay minerals into agricultural systems has considerable potential for improving sustainability by enhancing soil quality and reducing dependence on excessive chemical fertilizers and pesticides[38]. In addition, the use of organic fertilizers in combination with clay minerals can further improve soil fertility while reducing environmental pollution associated with intensive agricultural inputs[39]. Montmorillonite may also contribute to improved soil health by increasing soil organic carbon content and supporting better soil structure[40]. Furthermore, clay minerals play an important role in soil carbon conservation, which contributes to ecosystem stability and the long-term sustainability of agricultural systems[41]. They also provide a favorable environment for soil microorganisms, which are essential for nutrient cycling and soil biological activity[42]. The interaction between clay minerals and soil microbial communities can improve soil functioning and may reduce the need for synthetic fertilizers and pesticides, thereby supporting more sustainable agricultural practices[43].

2.2. How Montmorillonite Improves Soil Properties

Additionally, montmorillonite is a very effective clay mineral in improving soil structure, which is vital for enhancing soil quality. Its functionality is mainly dependent on the modification it causes in soil structure, resulting in effective aggregation, aeration, and water movement in the soil[44]. One of the unique characteristics of montmorillonite is its high water absorption. This property makes it possible for the soil to retain more moisture, such that soil moisture can be sustained even in areas with dry climate conditions. Thus, it is expected that crop resilience to drought will be improved through the application of montmorillonite to soil. In addition to its property of retarding soil moisture loss, montmorillonite has the ability to adsorb other nutrients[45]. Montmorillonite increases soil fertility and agricultural productivity. This component makes soil more resistant to erosion by improving soil stability. These changes in soil structure, moisture retention, and nutrient availability highlight the role of montmorillonite in sustainable agricultural practices and the Sustainable Development Goals related to food security and sustainable use of resources[46].

2.3. Contributions to Water Retention and Soil Ecosystem Stability

Montmorillonite is very important in improving the soil's ability to retain water and regulate the movement of water in the soil by improving soil structure and porosity[47]. The promotion of soil porosity helps in the reduction of runoff and enhances the infiltration of water into the soil as well as the recharge of groundwater resources; therefore, the management of water in agricultural fields is more efficient in arid and semi-arid regions[48]. The use of clay minerals, like montmorillonite, improves water-use efficiency by reducing the loss of water as well as the dependence on unsustainable groundwater sources. The ability to improve the structure of the soil as a result of the application of montmorillonite enables sustainable crop growth and supports the Sustainable Development Goals in the conservation of water and sustainability in agriculture[49,50]. Montmorillonite helps sustain biological processes in the soil through the creation of a favorable water and nutrient environment for microbes[51]. The increase in biodiversity of the soil enhances soil aggregation, stability, and resistance to environmental stresses. Together with proper agricultural practices, the usage of montmorillonite helps improve resistance of the soil to degradation and supports agricultural sustainability and productivity. These aspects emphasize how montmorillonite improves water management in soil and are directly related to the Sustainable Development Goals, specifically to Goal 6: Water Conservation and Goal 2: Food Security through sustainable agricultural systems[52].

2.4. Environmental Aspects of the Role of Montmorillonite

Montmorillonite is significant in the application of the Sustainable Development Goals owing to its environmental attributes. Using montmorillonite in agriculture ensures proper management and improves the health of the ecosystem through enhanced water-holding capacities in the soil, hence ensuring lower water consumption and maximizing the use of the available water[53]. Proper water management through montmorillonite helps ensure food security and sustainable agricultural practices despite environmental stress[54]. One of the fundamental concepts in sustainable development is lessening excessive usage of chemical fertilizers and pesticides. Use of montmorillonite in agriculture aids in lessening contamination of the environment by reducing the usage of chemical substances in favor of environmentally friendly substances like natural clay minerals[55,56]. Moreover, montmorillonite increases the potency of helpful microorganisms in the soil, resulting in a harmonious environment in the soil, which in turn leads to healthy crops with less negative exposures related to chemical fertilizers[57]. Another role of Montmorillonite is the enhancement of soil structure and the root interaction with soil, thereby making it easier to access nutrients in the soil and promoting the productivity of plants[58]. As one of the natural soil conditioner materials, it serves as an environmentally sustainable substitute for fertilizers and pesticides in order to promote healthier plants, improved soil, and minimized environmental contamination[59]. Moreover, its function in the augmentation of biodiversity in agricosystems in the sustainable life on land and the management of natural resources. Due to its characteristics, Montmorillonite has great potential in the management of natural resources in an environmentally sustainable manner and in sustainable agriculture[60]. The contributions of montmorillonite to sustainable agricultural practices are summarized in **Table 2**.

Table 2. Contribution of montmorillonite to sustainable agricultural practices.

Factor	Description	Benefit
Water retention	Improves soil's ability to retain water	Enhances climate adaptability and reduces irrigation needs
Availability of nutrients	Increases the capacity to absorb nutrients	Boosts crop growth and yields
Biological diversity	Supports various microorganisms in the soil and plant life	Contributes to sustainable ecosystems
Reduction of chemical inputs	Less reliance on synthetic fertilizers and pesticides	Aligns with sustainable development goals for responsible consumption

3. Applications of Montmorillonite

Montmorillonite is generally used in agriculture as a potent soil additive that helps increase the productivity of the soil **Figure 6**. Its use in making soil more receptive to water and having better nutrient uptake properties is very important in addressing challenges in modern agriculture[61]. This adoption of montmorillonite technologies is a sign of the shift towards sustainable agriculture, which results in improving crop quality, reducing environmental hazards, and contributing to the achievement of Sustainable Development Goals related to food security and sustainability[62,63].

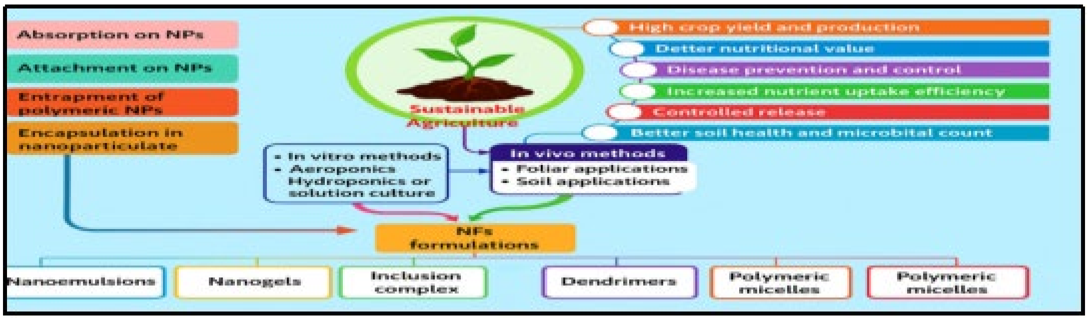

Figure 6. Schematic Overview of Nanofertilizers (NFs) in Sustainable Agriculture: Methods, Formulations, and Benefits[63].

Montmorillonite has a significant function in preventing environmental pollution and soil deterioration by absorbing pollutants and assisting in the restoration of the ecosystem[64,65]. Due to growing pollution of the natural environment and climatic change, the application of natural resources like montmorillonite has become a necessity in designing eco-efficient systems for agricultural and environmental sustainability[66]. Current research endeavors assist in improved agricultural productivity by applying innovative approaches in the utilization of montmorillonite in achieving the Sustainable Development Goals[67]. The current research is focused on the preparation of montmorillonite-based amendments, which will meet specific agricultural demands at a given site. **Table 3** show the addition of montmorillonite significantly decreases the bioavailability of heavy metals such as cadmium in the contaminated soils, which makes it an effective substance for limiting the uptake of heavy metals by plants and thus improving the quality of the contaminated site[68]. Moreover, the addition of modified montmorillonite with humic substances has also been shown to be an effective method for the treatment of zinc- and lead-contaminated sites[69].

Table 3. Uses of montmorillonite in agriculture and environmental impacts.

Applications of Montmorillonite	Benefits	Environmental Impact
Soil Amendments	Increases nutrients and improves soil structure	Increases biodiversity, reduces surface runoff
Organic Fertilizers	Stabilizes essential nutrients, boosts vegetable production	Reduces reliance on synthetic fertilizers, mitigates pollution
Focus on Drought Resistance	Helps crops withstand drought conditions	Conserves water resources and supports sustainable irrigation

4. Comparison with Other Soil Amendments

In addition to clay minerals **Table 4**, other soil amendments such as biochar and zeolite are also widely used to improve soil quality and agricultural sustainability. Biochar is known for its porous structure and its ability to improve soil carbon storage, enhance microbial activity, and increase soil water retention. Zeolite, on the other hand, has a high cation exchange capacity and strong adsorption properties that help retain nutrients and reduce nutrient leaching[70,71]. Compared with these materials, montmorillonite is particularly effective due to its expandable layer structure and high surface area, which allow it to retain large amounts of water and exchangeable nutrients in soil systems[72]. While biochar mainly contributes to long-term carbon stability and zeolite improves nutrient retention, montmorillonite plays an important role in improving soil structure, water retention, and pollutant adsorption. Therefore, the combined use of these soil amendments may provide complementary benefits for improving soil fertility and promoting sustainable agricultural practices[73].

Table 4. Comparison between montmorillonite and common soil amendments used in sustainable agriculture.

Soil Amendment	Main Properties	Agricultural Benefits	Environmental Role
Montmorillonite	High cation exchange capacity, expandable layered structure, large surface area	Improves soil fertility, enhances water retention, increases nutrient availability	Adsorbs pollutants and heavy metals, improves soil structure
Biochar	Highly porous carbon-rich material, stable organic structure	Improves soil organic carbon, enhances microbial activity, increases water retention	Contributes to carbon sequestration and reduces greenhouse gas emissions
Zeolite	Crystalline aluminosilicate with high ion exchange capacity	Retains nutrients such as ammonium and potassium, reduces nutrient leaching	Helps reduce groundwater contamination and improves nutrient efficiency

5. Future research directions

Although many studies have demonstrated the beneficial role of montmorillonite in improving soil fertility, water retention, and pollutant adsorption, further research is still required to better understand its long-term effects in different soil environments[74]. Future studies should focus on field-scale experiments to quantify the impact of montmorillonite on crop productivity, water retention efficiency, and soil microbial activity under different climatic conditions[75]. In addition, comparative studies between montmorillonite and other soil amendments such as biochar and zeolite could provide valuable insights into their relative effectiveness in sustainable agriculture. Further research is also needed to evaluate the potential environmental risks and optimal application rates of montmorillonite in agricultural soils to ensure its safe and efficient use[76-86].

6. Conclusion

Montmorillonite is a type of mineral that is applied in agriculture to improve the efficiency of the soil under different environmental conditions. It increases soil fertility and enables it to retain water for a longer period. This enhances the ability of the plants to resist drought. Additionally, the use of montmorillonite helps reduce the application of fertilizers and pesticides that cause high levels of pollution. In addition, the montmorillonite clay supports the use of resources in an efficient manner and supports goals related to food security as well as the protection of the environment. Further studies are therefore required concerning the use of montmorillonite in different soil types and climatic conditions. The findings summarized in this review indicate that montmorillonite has significant potential as a sustainable soil amendment due to its high cation exchange capacity, water retention ability, and pollutant adsorption properties. However, further field-based studies are required to better quantify its long-term effects on soil productivity, crop yield, and environmental sustainability under different climatic and soil conditions. In addition, comparative evaluations with other soil amendments such as biochar and zeolite could provide deeper insight into the most effective strategies for improving soil health and supporting sustainable agricultural systems.

Conflict of interest

The authors declare no conflict of interest.

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