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Original article

PURIFICATION AND APPLYING DI LINH BENTONITE, LAM DONG, VIETNAM IN IMPROVING THE PROPERTIES OF CORAL SAND SOIL IN SEMI-ARID AND SALINE ISLANDS

C.T. Nguyen, D.N. Vu, T.H.T. Vo, T.T.T. Dinh, T.H. Le, M.T. Vu, V.T. Do, V.T. Nguyen

Abstract

Background. Vietnam's extensive coastline and numerous islands result in a large expanse of coral sand. This type of sand possesses distinct mechanical properties, including coarseness, low nutrient content, poor moisture and water retention, and high salinity. Globally, various methods are employed to improve sandy soils by modifying their physical, chemical, and nutritional properties to create favorable conditions for plant growth.

Purpose. The objective of this article is to evaluate the impact of bentonite on the surface structure of coral sand, with a focus on altering key factors such as density, bulk density, porosity, electrical conductivity (EC), cation exchange capacity (CEC), and the field moisture-holding capacity of sand particles.

Materials and methods. Bentonite powder used in this study was produced by Hiep Phu Lam Dong Joint Stock Company from the Di Linh bentonite mine in Lam Dong, Vietnam.

In this study, We use physicochemical analysis methods such as: X-ray diffraction (XRD) method, Fourier-transform infrared (FT-IR) spectroscopy, Scanning Electron Microscope (SEM) and some methods for determining the physicochemical properties of soils.

Results. In this study, raw bentonite from Di Linh, Lam Dong, supplied by Hiep Phu Lam Dong Joint Stock Company, was purified using the hydrocyclone method. The purified bentonite contains 69.0% montmorillonite and exhibits a cation exchange capacity (CEC) of 54.98 meq/100g, making it an excellent material for ameliorating the limitations of coral sand. Research findings demonstrated that the addition of bentonite in varying proportions significantly enhanced the physical and chemical properties of coral sand. Key improvements included the increases in soil density (2.5–2.6 g/cm³) and bulk density (1.25 g/cm³), leading to a soil porosity of 50.02%. Furthermore, properties such as moisture retention and water-holding capacity were markedly improved due to the intrinsic characteristics of bentonite. At a supplementation rate of 3%, the cation exchange capacity (CEC) increased by over 83%, while electrical conductivity (EC) reached 470 µS/cm.

Conclusion. These enhancements are promising for improving the nutrient retention and exchange capacity of coral sand, thereby fostering better plant growth.

Keywords: bentonite; coral sand soil; sandy soils; saline soil; soil amendments

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Introduction

The island soil in Vietnam predominantly comprises coastal sandy soil. In Khanh Hoa Province, this sandy soil is characterized by a coarse mechanical composition, with 80–85% sand—primarily coral sand. It exhibits low porosity, poor nutrient content, and limited water retention capacity. Studies on sediment and soil in the major islands of Khanh Hoa Province have classified the area into five main geographic groups: (I) Bird guano soil group, (II) Primitive coastal sandy soil group, (III) Seasonal shifting sand group, (IV) Consolidated coarse sediment group, and (V) Coral limestone group. Notably, groups I and II are situated within fortified embankments, rendering them less vulnerable to natural factors and potentially suitable for reclamation and agricultural or other productive uses [1].

The natural conditions on islands play a crucial role in shaping the physical and chemical properties of the soil, as well as influencing the growth and development of plants. The natural environment and climate on islands, particularly those located far offshore, are notably harsh. These islands endure constant sun and wind, frequent storms, and freshwater scarcity, with many islands lacking tree cover. Additionally, some weather phenomena on islands differ significantly from those on the mainland. The average annual temperature on these islands is 27.8°C. The average humidity in Vietnam's island and coastal areas ranges from 82% to 83%, while relative humidity is slightly lower, fluctuating between 79% and 82%. Furthermore, relative humidity shows a noticeable daily variation, typically around 6% to 7%. [2].

The salinity of seawater in Vietnam's coastal regions is relatively high, with surface water salinity in offshore areas typically not exceeding 3.5%. However, around unsubmerged islands or within submerged areas, salinity levels can be even higher. This increase is primarily due to elevated evaporation rates and limited water circulation with the surrounding areas [3]. Given the aforementioned climatic conditions, transforming coastal sandy soil into arable land has become an urgent priority. Achieving this goal requires the implementation of innovative, environmentally friendly, and highly efficient technologies.

Various technologies have been developed to improve the fertility of sandy soil by enhancing its moisture retention and nutrient-holding capacity. These approaches often involve the use of water-retaining technologies to optimize rainwater usage and reduce the need for irrigation around plant roots. Commonly used materials include bentonite clay, carboxymethyl cellulose (CMC), biochar, and water-retaining polymers [4-8]. These materials work by binding sand particles, stabilizing soil structure, and increasing both moisture and nutrient retention, thereby supporting the healthy growth of plants.

Bentonite is derived from volcanic ash, with montmorillonite as its primary mineral component. Montmorillonite features a layered structure, giving bentonite its distinctive properties, including high swelling capacity, viscosity, and the ability to adsorb various substances [9]. Due to these characteristics, bentonite has been widely utilized for soil improvement. Beyond its ability to retain moisture, bentonite can also retain nutrients, absorb pollutants, and cleanse the soil and environment [10-15]. Bentonite is a natural mineral containing over 45 chemical elements with significant nutritional value, including CaO, MgO, SiO_2, and Al_2O_3. These properties make it highly versatile, leading to its widespread use in agriculture across many countries. Applications include producing animal feed, manufacturing fertilizers, and improving soil quality [16].

The use of bentonite to enhance soil productivity has been extensively studied and effectively applied in many countries [17-20]. Due to its excellent moisture retention and high adsorption capacity, bentonite is recognized as one of the most effective natural materials for soil rehabilitation, particularly for improving the fertility of sandy soils, which require substantial amendments for cultivation. Sandy soils are characterized by high water permeability, poor water retention, and a natural deficiency in nutrients. When moist, the swelling properties of bentonite help reduce capillary channels in the soil, allowing sandy soil to retain water more effectively and decreasing its permeability. By increasing soil moisture, bentonite also improves the thermal conductivity and heat capacity of sandy soils, further contributing to their overall fertility and suitability for cultivation [18].

Uses of bentonite for fertilizer and soil improvement: cation exchange properties; absorbent and binding properties; flocculation and rheological properties; high water absorption and water retention properties. In soil improvement, bentonite not only enhances moisture and water retention but also provides essential micronutrients to plants. Moreover, it is non-toxic and environmentally friendly, making it an ideal material for sustainable agricultural practices [20-25].

In 1973, Polish scientists from the Institute of Soil Science and Plant Cultivation in Pulawy, Poland, conducted pioneering research and applied bentonite for soil improvement [17]. Since then, numerous studies have been carried out globally. Starting in 2003, scientists from various countries, including Germany [4], Egypt [14], Tunisia [15], China [19; 25], Thailand [26-29], Vietnam [30-31], have further explored and applied bentonite to enhance soil quality.

Junzhen Mi et al. [12] and Lanying Zhang et al. [25] have studied the effects of bentonite as a soil amendment on field water-holding capacity, millet photosynthesis, grain quality, and the impact of combining bentonite with other amendments to improve soil quality for oat cultivation in semi-arid regions. Their studies demonstrated that bentonite significantly improved soil structure by decreasing soil bulk density and increasing soil porosity, microorganism activity, crop yield, and economic benefits. Furthermore, bentonite amendments enhanced the field water-holding capacity and increased the availability of water for plants.

The application of clay technology by farmers in northeast Thailand, specifically using bentonite clay, has significantly reversed soil degradation and increased economic returns through higher yields and improved output prices. Studies conducted by the International Water Management Institute and its partners in 2002–2003 focused on the use of locally sourced bentonite clays for rehabilitating degraded soils in the region. These studies involved structured field trials, which demonstrated that applying bentonite clay effectively enhanced the yields of forage sorghum cultivated under rain-fed conditions [26-27].

The application of bentonite also positively influenced the prices farmers received for their crops. Although production costs were higher, the increased yield and improved food quality enabled farmers using bentonite to invest in and grow more and better-quality food compared to those who did not use clay [28-29].

The South Central Coast of Vietnam (SCC VN) has approximately 339,000 hectares of sandy soils characterized by low clay content, low cation exchange capacity (CEC), low pH, low organic matter, and poor water and nutrient-holding capacities. As a result, these soils are infertile, leading to very low crop productivity [30]. Nguyen Hoai Chau et al. [31] studied the effects of bentonite on the cation exchange and moisture-retaining capacities of sandy soil in Ninh Thuan Province, focusing on its application for asparagus cultivation. Bentonite, a highly abundant natural soil improver in Vietnam, has an estimated reserve of more than 760,000 tons. These reserves are primarily concentrated in provinces such as Lam Dong, Binh Thuan, and Thanh Hoa, with montmorillonite mineral content ranging from 40% to 50% [32].

Researching, analyzing, evaluating, and applying Vietnamese bentonite resources to address the dry, drought-prone, and saline climate conditions of the Central Coast region holds significant scientific and practical value. However, there have been very few studies published on the composition of Vietnamese bentonite and its applications as a soil amendment in Vietnam.

The objective of this article is to evaluate the impact of bentonite on the surface structure of coral sand, with a focus on altering key factors such as density, bulk density, porosity, electrical conductivity (EC), cation exchange capacity (CEC), and the field moisture-holding capacity of sand particles.

Materials and methods

Materials and chemicals

Material: Bentonite powder used in this study was produced by Hiep Phu Lam Dong Joint Stock Company from the Di Linh bentonite mine in Lam Dong, Vietnam. The raw bentonite was collected from the mining site in Di Linh District, Lam Dong Province, and is locally referred to as Di Linh bentonite before undergoing preliminary treatment (Figure 1). Distilled water and HCl PA were also utilized in the study.

Fig. 1. Samples of bentonite (a) Bentonite ore; (b) Bentonite powder; c) Purification bentonite using the hydrocyclone method.

Analytical Methods

Fabrication of samples

Raw bentonite contains inorganic impurities and metal oxides located outside the crystal lattice, which can reduce its porosity. Therefore, treatment is required to obtain purified bentonite. According to Hiep Phu Lam Dong Joint Stock Company, bentonite samples were processed using the hydrocyclone method, as illustrated in the diagram in Figure 2 [33-35]. The processing steps involve crushing the bentonite ore into powder, dispersing it in clean water, and grading it using the hydrocyclone method to obtain a suspension. The suspension is then thickened, and residues are removed. Using centrifugal separation, water is extracted, and the material is filtered, pressed, dried, and ground to produce a pure bentonite sample. These purified samples, produced by Hiep Phu Lam Dong Joint Stock Company, are referred to as HP bentonite. The processed bentonite has a particle size of <100 μm, a bentonite suspension concentration of 5–10%, and is treated under a pressure of 5 psi.

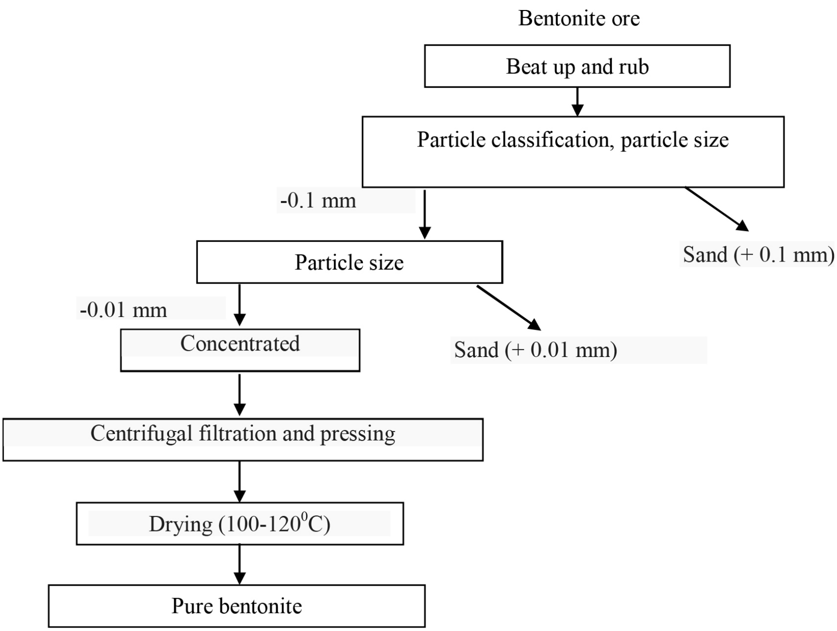

Fig. 2. Purification bentonite using the hydrocyclone method

Bentonite samples from Hiep Phu Lam Dong Joint Stock Company underwent further purification to enhance porosity using a 5% HCl solution. The samples were stirred thoroughly for 5 hours [34-35]. After soaking, the samples were allowed to settle, then washed to remove all traces of acid. Finally, the samples were dried and ground again to produce a pure bentonite sample, symbolized as P bentonite.

During the dissolution process with 5% HCl, substances such as CaO, Fe_2O_3, and Al_2O_3 present in bentonite can be separated and removed through the following reactions:

$Fe_2O_3 + HCl = 2FeCl_3 + 3H_2O$

$CaO + 2HCl = 2CaCl_2 + H_2O$

$Al_2O_3 + 6HCl = 2AlCl_3 + 3H_2O$

$MgO + 2HCl = 2MgCl_2 + H_2O$

The P bentonite was mixed with coral sand soil at weight ratios of 1%, 2%, 3%, 4%, 5%, 6%, and 7%.

Chemical composition

The bentonite sample was treated with a mixture of two acids, HCl and HNO_3. All elements dissolved into the solution, except silica (SiO_2), which was determined using gravimetric analysis. The other elements, including Al, Fe, Mg, Ca, Na, and K, were analyzed using an Atomic Absorption Spectrophotometer (AAS). The analysis was conducted with a Shimadzu AA-6800 atomic absorption spectrometer (Japan).

Physicochemical characteristics of bentonite

Determination of Mineral Composition by X-ray Diffraction

The X-ray diffraction (XRD) method is one of the most common and effective techniques for determining the structure and crystallinity of materials. From the obtained XRD spectra, the structure and phase composition can be identified based on the quantity, position, and intensity of the peaks, allowing for the inference of lattice types and the determination of the material's nature. XRD is particularly effective in identifying the names and concentrations of minerals and clay minerals present in samples. In this study, material samples were analyzed using the XRD8–Advance system (Bruker, Germany) at the Institute of Chemistry, Vietnam Academy of Science and Technology.

Fourier-transform infrared spectroscopy (FT-IR)

Fourier-transform infrared (FT-IR) spectroscopy is used to identify the characteristic atomic groups within the structure of clay. This method complements X-ray diffraction by providing insights into the vibrational frequencies of functional groups present in the clay structure. The absorption of infrared radiation depends on the vibrational modes of groups such as OH, tetrahedral units (AlO_4 and SiO_4), and octahedral units (AlO_6, MgO_6). For analysis, bulk samples (approximately 1–2 mg) were milled, wet sieved to <40 μm, and dispersed in 120 mg of KBr. The mixtures were then pressed into pellets with a diameter of 13 mm. FT-IR spectra were recorded in the mid-infrared range (400–4000 cm^{-1}) using a Nicolet Magna-IR 760 spectrometer (USA). The analyses were conducted at the Institute of Tropical Ecology, Joint Vietnam-Russia Tropical Science and Technology Research Center.

Determination of Surface Structure

The morphology of the bentonite and sandy soil samples was analyzed using a Scanning Electron Microscope (SEM), Jeol JSM-IT200, at the Institute of Tropical Ecology, Joint Vietnam-Russia Tropical Science and Technology Research Center. Elemental composition analysis was conducted using the Energy Dispersive X-ray (EDX) method on an MS-7001F device (Jeol, Tokyo, Japan). The surface area of the samples was measured using a Tristar 3000 Micromeritics system, while thermal analysis was performed on a Labsys TG/DSC 1600, TMA-SETARAM machine, with a differential thermogravimetric analyzer (TG-DT-8121, France).

Determination of Density

Bulk density was determined based on ISO 11508:1998. After being dried to a constant weight, the soil samples were weighed using an analytical balance with a precision of 0.001 mg at the Laboratory of Biochemistry, Department of Biotechnology, Joint Vietnam-Russia Tropical Science and Technology Research Center.

Determination of Porosity

Soil porosity refers to the percentage of void spaces within the soil relative to its total volume. The porosity P(%) of the soil is calculated based on its density and bulk density.

The formula for determining porosity is:

$$P(\%) = \left(1 - \frac{d}{D}\right).100$$

Where: *d:* bulk density (g/cm^3)

D: density (g/cm^3)

Determination of Electrical Conductivity (EC)

The electrical conductivity (EC) of soil is commonly used to evaluate soil salinity or the concentration of other conductive substances that may impact crop yield and development. This measurement is typically performed by determining the EC of soil water or a solution in contact with the soil. The EC of the mixture is measured using an EC meter, with results expressed in units of mS/cm or µS/cm.

Determination of Water Retention Capacity

Water retention capacity was measured using the Funnel Method (FM)[10].

Determination of Field Water-Holding Capacity (WHC)

The Water-Holding Capacity (WHC), also known as water retention capacity, measures the total amount of water that can be absorbed per gram of material. The maximum WHC is determined using the cylindrical sand soaking method [11].

Determination of Cation Exchange Capacity (CEC)

The mixed samples were treated with a 150 mg/L methylene blue solution for a specific duration. The absorption was then measured at a wavelength of 666 nm using a UV-Vis spectrophotometer equipped with a 10 mm glass cuvette (Model: 3101PC, Shimadzu, Japan) [12].

Results and discussion

Chemical composition of the HP bentonite

Based on the compositional analysis results of HP bentonite presented in Table 1, the largest component is SiO_2, accounting for 55.3%. The alkali metal elements are present in moderate to small amounts, including TiO_2 (0.63%), Al_2O_3 (23.9%), Fe_2O_3 (5.7%), MgO (0.9%), and CaO (0.4%). Other components constitute approximately 13.2% of the composition. The relatively high proportion of Al_2O_3 indicates a significant montmorillonite (MMT) content. The SiO_2 ratio of approximately 2.5 further supports the high MMT content. Additionally, the light brown color of the bentonite reflects its low iron content and high quality. The analysis also highlights the contributions of CaO and MgO to the cation exchange capacity (CEC) of the bentonite.

Table 1.

Chemical composition of bentonite

MxOy	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Other Components
%	55.3	0.63	23.9	5.7	0.92	0.4	13.2

Physicochemical characteristics of bentonite

Mineral Composition of Bentonite

The results of the X-ray diffraction (XRD) analysis of the bentonite samples are presented in Figure 3. The XRD spectrum of Hiep Phu bentonite reveals the main characteristic peaks of montmorillonite (MMT), with a layer spacing d001 of 15 Å observed at a diffraction angle 2θ of approximately 6.94°, 19.81°, 35.92°, and 61.84° (Figure 3(c)) [38]. The predominant montmorillonite (MMT) structure in the Hiep Phu bentonite sample accounts for its high swelling capacity and water absorption ability.

The X-ray diffraction analysis in Figure 3(a) identifies Hiep Phu bentonite as an alkaline earth bentonite. The primary ion-exchange cations are Ca and Mg. The main mineral composition of Hiep Phu bentonite ore is montmorillonite, while the impurities include quartz (10–12%), feldspar (11–12%), goethite (8–10%), hydromica (10–12%), chlorite (5–7%), and trace amounts of kaolinite and calcite. The montmorillonite content in Hiep Phu bentonite ranges from 55% to 57%. Compared to bentonite from other countries, such as Wyoming bentonite in the United States, which has a montmorillonite content of up to 80% [36], the montmorillonite content in Hiep Phu bentonite is relatively low. Therefore, cleaning and enrichment processes are necessary to increase the montmorillonite content for applications requiring high-quality bentonite.

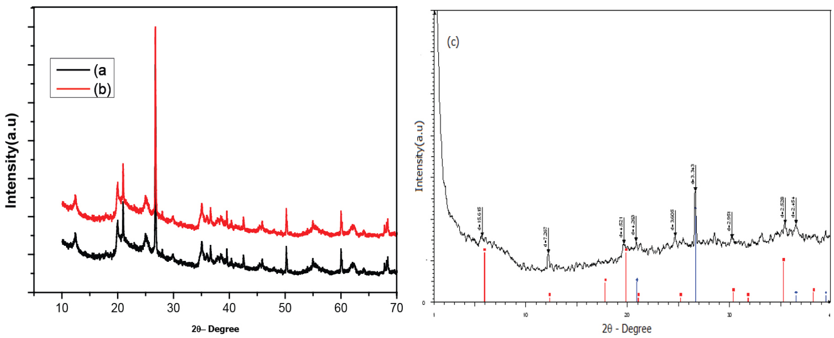

Fig. 3. XRD spectrum of the bentonite. (a) HP bentonite; (b, c) P bentonite

In Figure 3(b), the montmorillonite content is shown to have increased to 69%, with minimal quartz impurities (SiO_2) remaining. Additionally, metal oxide impurities located outside the bentonite crystal lattice, such as TiO_2, Al_2O_3, and Fe_2O_3, were almost entirely removed, leaving only undetectable traces. These findings are consistent with previous research results [38].

From the X-ray diffraction analysis, the montmorillonite (MMT) content was determined to be 69%, and the cation exchange capacity (CEC) measured at 54.98 meq/100g. Compared to other bentonite samples, these values are relatively high, indicating the potential for enhanced moisture retention and nutrient-holding capacity.

Surface structure analysis by SEM method:

The SEM image of the bentonite sample after cleaning with a 5% HCl solution shows uniform particle sizes with a round shape, ranging from 5 to 10 µm.

Analysis of the bentonite sample treated with 5% HCl using the SEM-EDX method revealed a significant reduction in the content of impurities such as Fe, Ti, and Al compared to the untreated Hiep Phu bentonite sample.

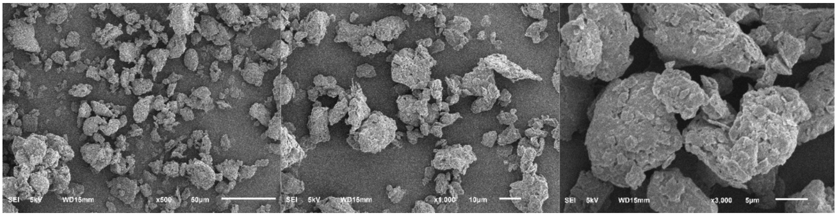

Fig. 4. Image SEM of bentonite after cleaning with 5% HCl solution (P bentonite).

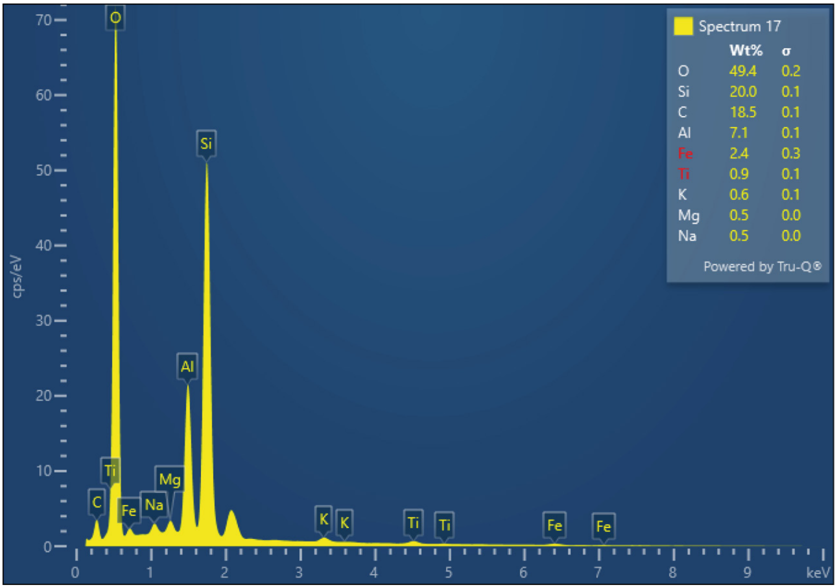

Fig. 5. EDX spectrum analysis of Hiep Phu bentonite sample after cleaning with 5% HCl solution (P bentonite).

The thermal analysis (TGA) results of the bentonite sample (Figure 6) revealed four endothermic peaks at temperatures of 70°C, 100.68°C, 287.5°C, and 498.62°C. The first and second peaks, at 70°C and 100.68°C, and the third peak at 287.5°C, are attributed to the physical dehydration of clay and the loss of organic matter, with a total mass loss of 1.17 wt%. The fourth peak at 498.62°C corresponds to the decarbonation of the sample, resulting in a mass loss of 6 wt%.

The results of BET surface area analysis (Figure 7) indicate that the treated bentonite sample has an average surface area of 45.716 m^2/g. The average pore size during the adsorption process is 8.7907 nm, while during the desorption process it is 7.4202 nm. The average pore size suggests that the adsorption process of bentonite substances occurs due to changes in the capillary pore structure. In comparison, the untreated sample had an average surface area of 30.255 m²/g. This comparison demonstrates that treatment and cleaning with 5% HCl significantly improved the surface area of the bentonite sample.

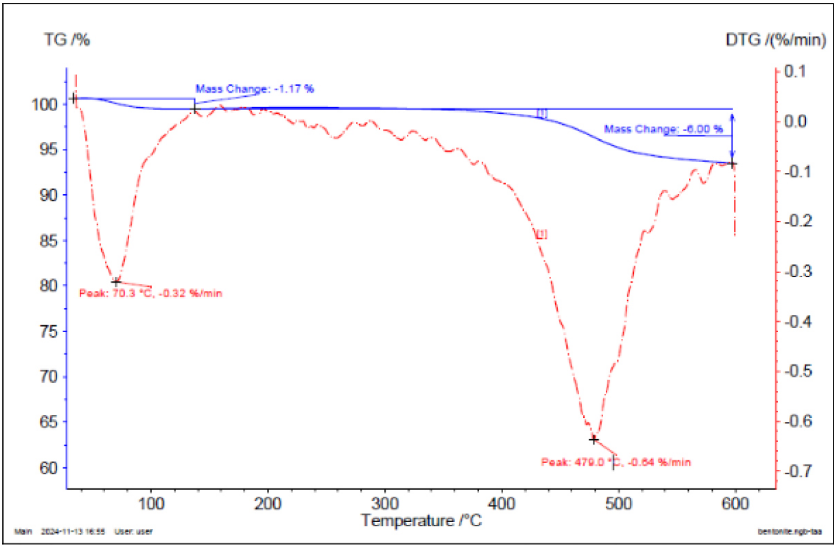

Fig. 6. TGA of P bentonite

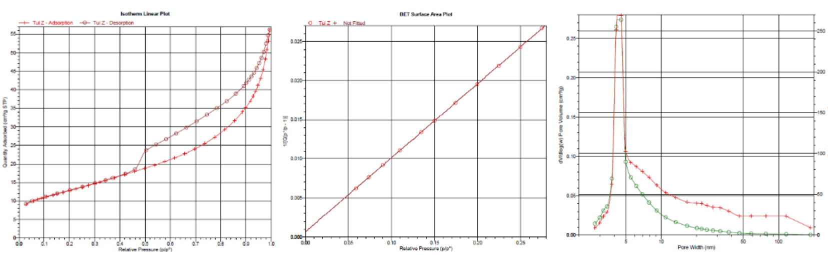

Fig. 7. (a) Adsorption isotherm N_2 adsorption of P bentonite; (b)BET plot of P bentonite; (c) Pore diameter distribution of P bentonite

From Figure 7(c), the pore size distribution of P bentonite is observed to be narrow and exhibit high intensity, indicating a uniform capillary system with pore sizes of less than 5 nm.

Fourier-transform infrared spectroscopy (FT-IR)

The FT-IR absorption spectra of the bentonite samples (Fig. 8) are characterized by absorption peaks around 3697, 3621, and 3454 cm^{-1}, intense peaks around 1032 cm^{-1}, and weak peaks near 912.7 and 796.9 cm^{-1}. Additionally, the Si-O bands at approximately 1040 cm^{-1} are indicative of montmorillonite. The characteristic spectral peaks for bentonite include the Si-O deformation vibration in the SiO_4 tetrahedron, observed in the range of 420–470 cm^{-1}, and the Al-O bond in the octahedron, found at 815 cm^{-1}. The OH^- group in the structure is represented by the spectral band in the range of 3400–3600 cm^{-1}. These peaks confirm the montmorillonite structure of the bentonite [38- 41].

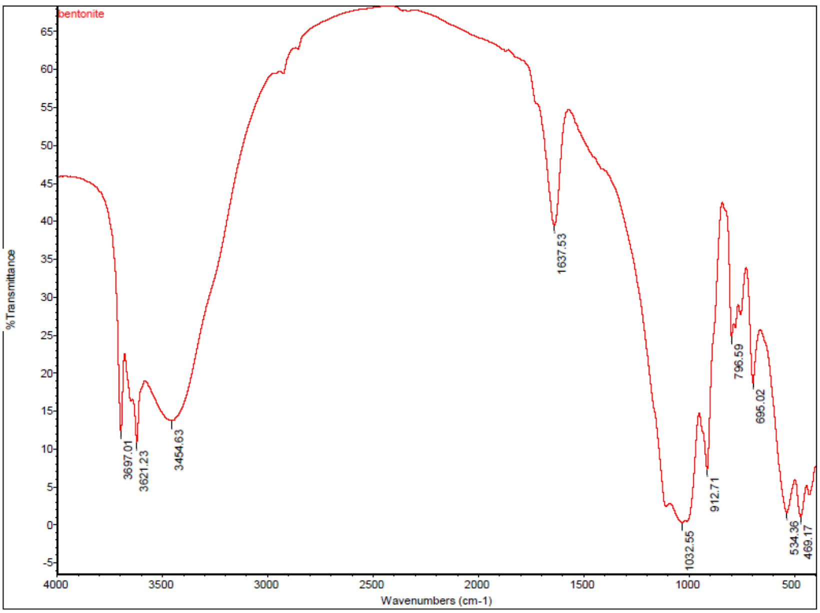

Fig. 8. FT-IR spectra of P bentonite.

Effects of Bentonite on Some Physical and Chemical Properties of Coral Sand Soil

Density

Density is a crucial parameter for assessing soil porosity. The density values for each mixture formulation can be determined using the previously described density measurement method. This allows for the identification of the optimal formulation and the determination of appropriate component ratios to achieve the desired density values.

Soil density varies based on its type, composition, and structure. Density measurements will be carried out using the method previously described .

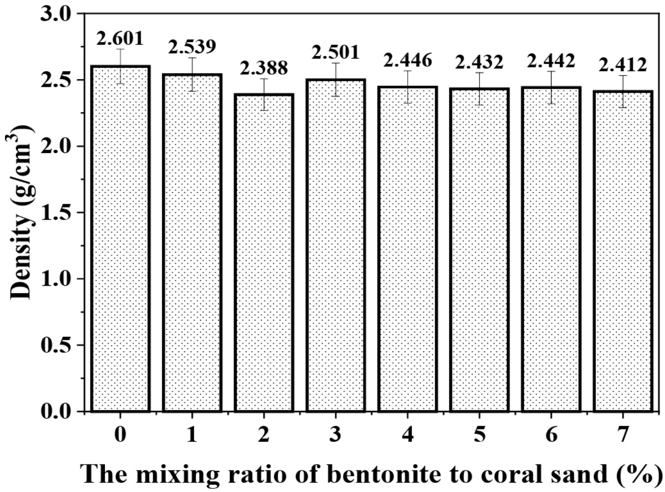

Fig. 9. Density of Coral Sand and Bentonite-Added Samples.
The data in the graph represents the average values of three repetitions. Data points with different superscripts (a, b, c, etc.) indicate significant differences at the 95% confidence level in the one-way Tukey comparison.

The measurement results indicate that the densities of the soil samples are relatively high, ranging from 2.5 to 2.6 g/cm³, which is characteristic of sandy soils primarily composed of coral sand particles. The addition of bentonite at concentrations of 1% to 7% slightly reduces the density of the sandy soil. This reduction can be attributed to the addition of bentonite, which alters the soil's mechanical composition by increasing the proportion of lighter clay particles, thereby lowering the overall density. Furthermore, incorporating more clay components helps balance the soil composition and enhances its fertility.

Bulk Density

Bulk density is closely related to soil porosity; higher porosity results in lower bulk density. For arable soils, an appropriate bulk density typically ranges between 1.0 and 1.25 g/cm³. A comparison will be made with the data presented in the accompanying graph.

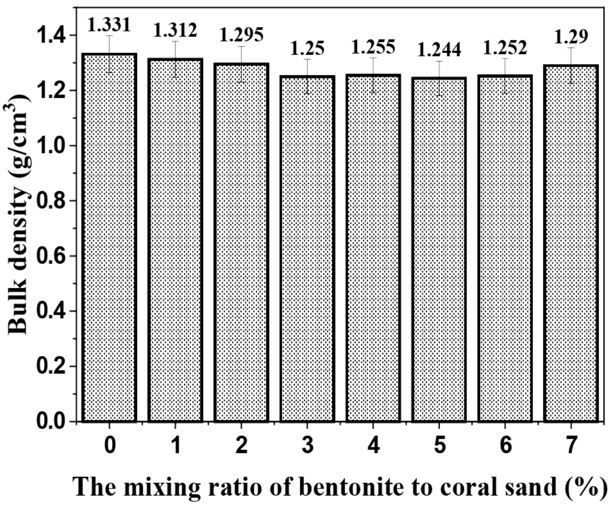

Fig. 10. Bulk Density of Coral Sand and Bentonite-Added Samples. *The data in the graph represents the average values of three repetitions. Data points with different superscripts (a, b, c, etc.) indicate significant differences at the 95% confidence level in the one-way Tukey comparison.*

It can be observed that at bentonite ratios of 3%, 4%, and 5% (w/w), the bulk density of the soil falls within the optimal range of 1.0–1.25 g/cm³, meeting the bulk density criterion for normal arable soil. However, at lower ratios (1–2%) or higher ratios (>5%), the bulk density deviates from this range, becoming either too high or too low. This deviation directly affects the soil's porosity and its suitability as arable land.

Porosity

Soil porosity refers to the small pores or open spaces within the soil. A porosity greater than 50% promotes good soil aeration, enabling CO_2 and nutrients to permeate quickly and easily. This is beneficial for soil organisms and root development. At a bentonite ratio of 3%, the soil mixture achieves a porosity of 50.02%, which is highly suitable for modifying soil properties. This can be attributed to the influence of factors such as particle structure, sample composition, compaction, and the amount of organic material present. Finer-textured samples exhibit a greater capacity to retain water compared to coarser samples. The 3% bentonite ratio provides an optimal particle structure, making it a promising solution for improving soil properties and enhancing agricultural cultivation.

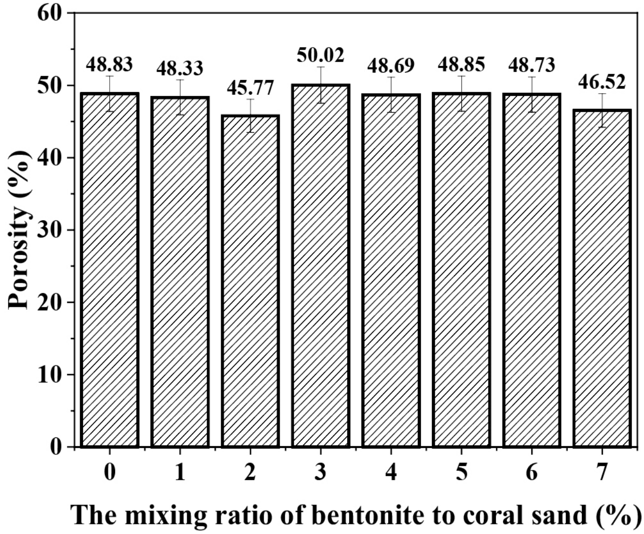

Fig. 11. Porosity of Coral Sand and Bentonite-Added Samples. *The data in the graph represents the average values of three repetitions. Data points with different superscripts (a, b, c, etc.) indicate significant differences at the 95% confidence level in the one-way Tukey comparison.*

Electrical Conductivity (EC)

Electrical conductivity (EC) reflects the mineral salt content in soil, often referred to as mineral nutrients for crops. An EC range of 200–1200 μS/cm is considered optimal for plant growth. Values below 200 μS/cm indicate nutrient deficiency, whereas values above 1200 μS/cm suggest nutrient surplus.

The results of the EC determination for the coral sand samples are presented in Figure 12.

The survey results indicate that when bentonite ratios greater than 2% are added to the sand, the EC index of the samples reaches an acceptable level, aligning with the goals of soil improvement. This finding is consistent with previous research by Hassan et al. [13], which evaluated the effects of bentonite on certain cereal crops in Egypt. This outcome can be attributed to the mineral components of bentonite, which enhance the cation exchange capacity (CEC) of sandy soil. The increased CEC boosts the soil's electrical conductivity, ensuring sufficient nutrients for plant growth and development following remediation.

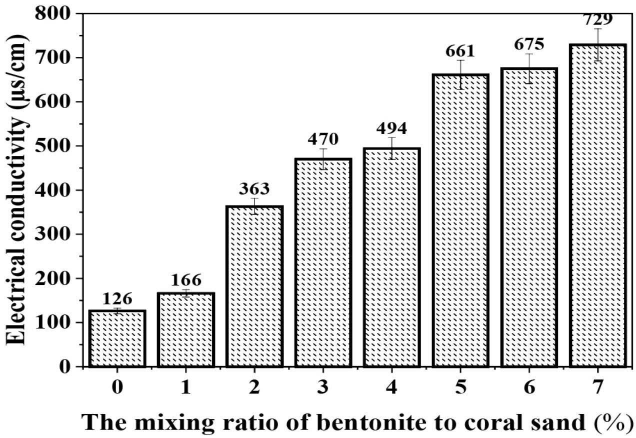

Fig. 12. Electrical Conductivity (EC) of Coral Sand and Bentonite-Added Samples. *The data in the graph represents the average values of three repetitions. Data points with different superscripts (a, b, c, etc.) indicate significant differences at the 95% confidence level in the one-way Tukey comparison.*

Assessment of Changes in the Surface Structure of Coral Sand

Observing Figure 13, the surface of the coral sand appears uneven (Figure 12a), with numerous edges, angles, and pores between the sand particles. This rough surface provides good adhesion for stabilizing materials.

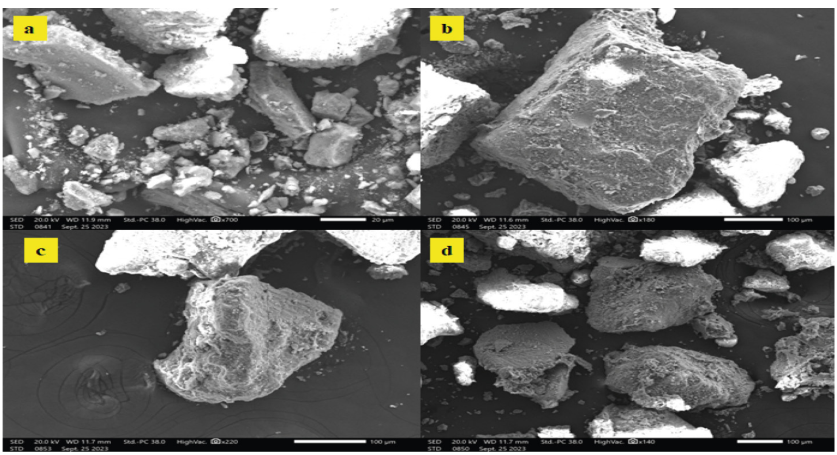

Fig. 13. SEM Images of Four Samples *(a) Coral Sand; (b) Coral Sand + 2%* BT;(c) Coral Sand + 3% BT; (d) Coral Sand + 5% BT.

For sand samples with 2–3% bentonite added (Figures 13b, 13c), a layer of bentonite is clearly visible covering the sand particles. This layer acts as a binding agent between the sand grains, increasing the surface area, filling the pores, stabilizing the soil structure, and enhancing moisture and nutrient retention. The addition of 5% bentonite yields similar results, where the bentonite surrounds, overlaps, or connects the sand grains. At 2% bentonite content, the bentonite-bound sand grains begin to form aggregates (Figure 13d), further contributing to soil stabilization and improved properties.

Water Retention and Moisture Storage

Water Retention

The experimental results indicate that coral sand has a relatively fast drainage rate and poor water retention capacity, leading to significant nutrient leaching with draining water. However, when bentonite is added to the coral sand, the drainage rate decreases sharply. At bentonite ratios of 1–3%, the drainage rate drops significantly, demonstrating a marked improvement in the water retention capacity of the bentonite-enhanced sand mixture (Figure 14).

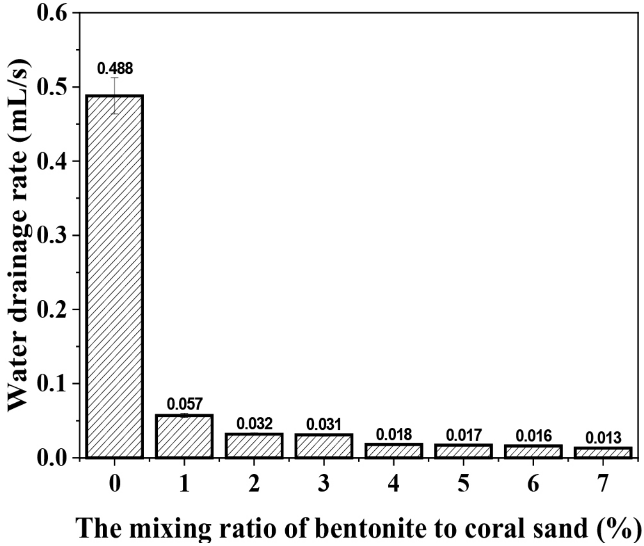

Fig. 14. Water Drainage Rate of Sandy Soil Before and After Bentonite Addition. *The data in the graph are the average values of three repetitions. Data with different superscripts (a, b, c, etc.) indicate significant differences at a 95% confidence level in one-way Tukey comparisons.*

This can be attributed to bentonite adhering to the sand particles, increasing their surface area. This bonding reduces the movement of water through the soil's voids, thereby decreasing drainage [10, 12]. At bentonite ratios of 4–7%, the water flow through the bentonite-enhanced sand mixture continues to decrease compared to the 3% ratio. However, excessively low drainage rates may lead to prolonged waterlogging in the lower soil layers, increasing the risk of flooding. This condition can result in root rot or damage to the root growth apex, adversely affecting crop health.

Field Water Holding Capacity

The results of the field water-holding capacity measurement (Figure 15) indicate that the increase in maximum water-holding capacity for sandy soil samples with 1–2% bentonite was minimal compared to the original sand. However, at a 3% bentonite ratio, the water-holding capacity increased significantly, reaching 14.7%, and continued to rise slightly with bentonite ratios of 4–7%. These findings align with studies by O. Semalulu (2013) [14], who utilized Ca-bentonite to enhance moisture retention and nutrient conservation in sandy soils in drought-affected areas of Uganda, and by Junzhen Mi et al. [15], who conducted similar experiments in the arid regions of northern China.

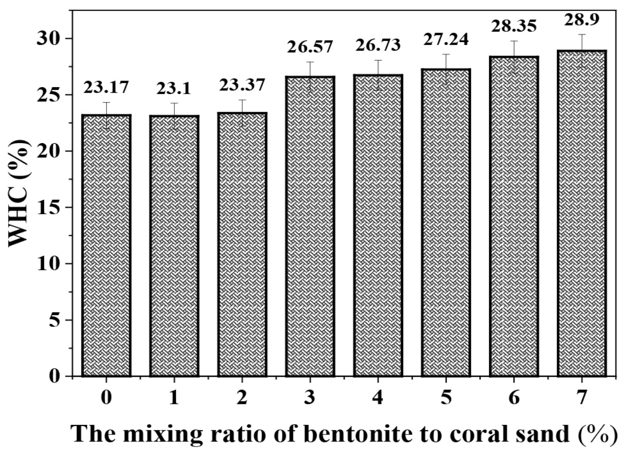

Fig. 15. Increase in Maximum Water Retention Capacity of Coral Sand and Bentonite-Amended Samples.

The data in the graph are the average values of three repetitions. Data with different superscripts (a, b, c, etc.) indicate significant differences at a 95% confidence level in one-way Tukey comparisons.

This can be attributed to the ability of water molecules to penetrate the structure of montmorillonite when water comes into contact with the soil. These molecules are retained within the crystal lattice of montmorillonite, resulting in improved soil moisture retention.Therefore, to enhance the moisture retention capacity of coral sand to 10% or higher, a bentonite ratio of at least 3% is necessary.

Cation Exchange Capacity (CEC)

The analysis of cation exchange capacity (CEC) (Figure 16) demonstrates a clear linear increase with the addition of bentonite to sandy soil. The CEC reaches an average value of over 83% at a 3% bentonite ratio and over 51% at a 2% bentonite ratio. These findings are consistent with previous research by Nissaf Karbout [16], who observed similar effects when bentonite was added to sandy soil in the arid regions of Tunisia.

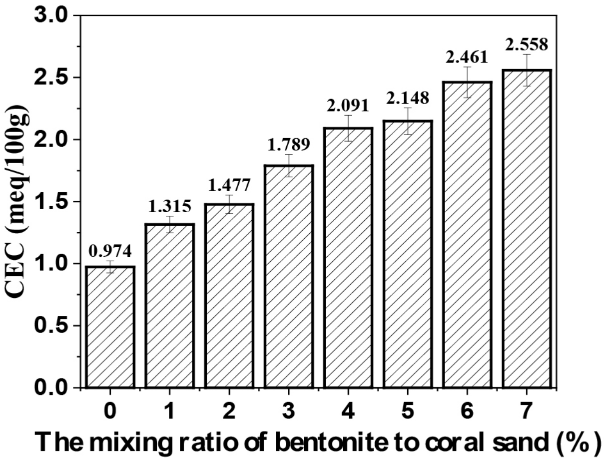

Fig. 16. CEC Changes in Sandy Soil Amended with Bentonite.
The data in the graph are the average values of three repetitions. Data with different superscripts (a, b, c, etc.) indicate significant differences at a 95% confidence level in one-way Tukey comparisons.

This can be explained by the varying amounts of bentonite added to the sand. Montmorillonite, the primary mineral in bentonite, is well-known for its high adsorption and ion exchange capacity. This high adsorption capacity arises from ion exchange occurring not only on the external surfaces of the crystals but also within the crystal structure, specifically between the basic layer packets. Consequently, the greater the amount of bentonite added, the higher the CEC value.

Conclusion

This study refined montmorillonite (MMT) from Di Linh bentonite, Lam Dong, using the hydrocyclone method, achieving an MMT content of >69% with a particle size of approximately 5 μm. The physicochemical properties and chemical composition of the refined bentonite were analyzed using XRD, SEM-EDX, BET, and other methods. The study evaluated the impact of bentonite on the surface structure of coral sand particles, influencing key soil properties such as specific gravity, bulk density, porosity, field moisture retention, and nutrient retention. At a 3% bentonite addition, SEM images revealed that bentonite effectively bonded sand particles, stabilizing the soil structure and significantly enhancing its physical and nutritional properties. Specifically, porosity increased to 50.02%, electrical conductivity (EC) rose 3.7 times to 470 μS/cm, and moisture retention improved substantially to 14.7%. These results demonstrate that incorporating a 3% bentonite ratio into coral sand is an effective strategy for converting coral sand into arable land.

Bentonite, which is abundant in Vietnam, offers a stable, long-term solution as it requires only a single application, unlike synthetic water-absorbing polymers that degrade over time and require periodic reapplication. Thus, applying bentonite may be a practical and effective approach for improving millet production in arid regions of the South Central Coast of Vietnam or in regions with similar environmental conditions.

This research serves as an initial study. Future work will focus on investigating the effects of bentonite on microbial activity, crop productivity, and the associated economic benefits.

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Duy Nhan Vu: study conception, editing of the draft of the manuscript.
Thi Hoai Thu Vo: writing of the manuscript.
Vinh Truong Do: editing of the draft of the manuscript.
Van Tu Nguyen: editing of the draft of the manuscript.
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