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Engineering a bentonite-palm oil mill waste organo-mineral composite for peat soil amelioration and sustainable soybean production

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ABSTRACT

This study aims to develop and evaluate an engineered organo-mineral composite (CCBN674) derived from bentonite, palm oil mill sludge, and shell-derived limestone for improving the physicochemical properties of tropical peat soils and enhancing soybean (Glycine max) productivity under field conditions. The material was designed as a multifunctional peat soil ameliorant with combined nutrient retention, acidity neutralization, and slow-release fertilization functions. The composite formulation was optimized based on nutrient composition and soil neutralization performance. Mineralogical and structural characterization was performed using X-ray diffraction (XRD), while surface morphology and elemental composition were analyzed using scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM–EDS). Field experiments were conducted under tropical peatland conditions with treatments including control, conventional NPK fertilization, CCBN674 application, and combined NPK + CCBN674. The results showed that the composite contained montmorillonite and other aluminosilicate phases favorable for nutrient adsorption and retention. The optimized formulation exhibited nitrogen, phosphorus, and potassium contents of 2.101%, 1.680%, and 0.125%, respectively. Application of shell-derived limestone significantly increased the pH of the formulation above 12 and improved peat soil pH from strongly acidic conditions (pH 1–3) to near-neutral levels (pH 6.8–7.5). Field results indicated that soybean plants under control and sole NPK treatments failed to survive under extreme peat acidity, whereas CCBN674 treatment supported successful plant establishment, achieving plant heights of 34.33 ± 9.91 cm, leaf numbers of 19.67 ± 5.30, and 9.23 ± 3.66 filled pods per plant. The findings suggest that the composite improves plant performance through combined effects of acidity neutralization, nutrient adsorption–desorption regulation, and enhanced rhizosphere stability. A key limitation of the study is the absence of long-term field validation and multi-season assessment of soil stability and nutrient dynamics. Nevertheless, the developed material demonstrates strong practical potential as a low-cost and sustainable peat soil amendment for tropical agriculture. The originality of this work lies in the integration of mineral, organic, and alkaline waste streams into a single engineered system with demonstrated field-scale effectiveness in extreme peat conditions.

Keywords: bentonite, palm oil mill waste, peat soil, organo-mineral composite, soybean, soil amelioration, sustainable agriculture.

INTRODUCTION

Tropical peatlands represent one of the largest global carbon reservoirs and play an essential role in climate regulation, biodiversity conservation, and agricultural development (Page, 2024; Ribeiro et al., 2021). In Indonesia, extensive peatland areas are distributed across Sumatra, Kalimantan, and Papua, where large portions remain underutilized for food crop cultivation due to unfavorable physicochemical properties (Mishra et al., 2021). Peat soils are generally characterized by extremely low pH, high organic acidity, poor nutrient availability, weak structural stability, and elevated concentrations of soluble toxic elements such as Cd, Co, Cr, Cu, Ni, Pb, Zn (Piaszczyk et al., 2025). These conditions severely limit nutrient uptake, root development, and crop productivity, particularly for economically important food crops such as soybean. Soybean (*Glycine max* L.) is one of the most strategic food commodities in Indonesia due to its importance as a protein source and industrial raw material (Kumari et al., 2025). However, domestic soybean production remains insufficient to meet national demand, resulting in continuous dependence on imports. Expansion of soybean cultivation into suboptimal lands such as tropical peatlands has therefore become an important national priority. Nevertheless, successful soybean cultivation in peat soils remains highly challenging because conventional fertilization strategies are generally ineffective under highly acidic conditions. Nutrient losses through leaching, low cation exchange stability, and rapid nutrient immobilization frequently reduce fertilizer efficiency and plant survival in peatland environments.

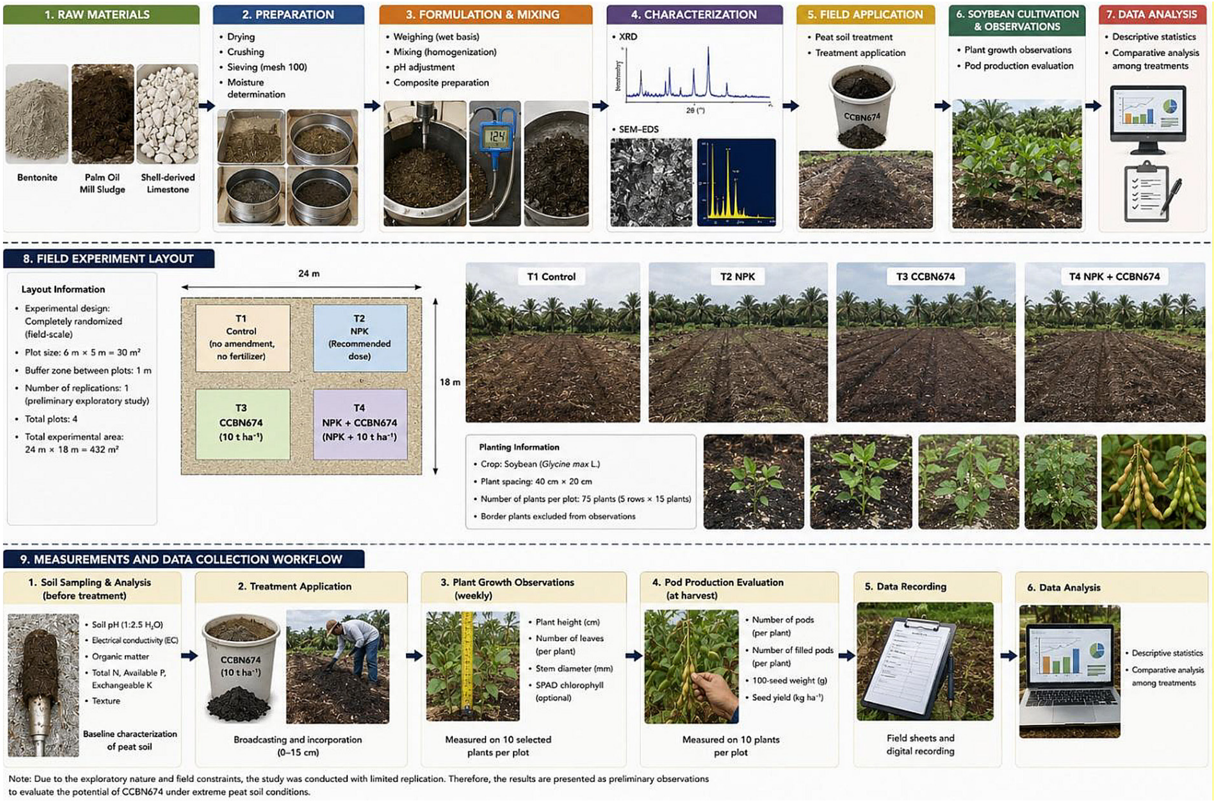
Previous studies have demonstrated that bentonite may improve nutrient retention through its high cation exchange capacity and adsorption properties, while organic amendments such as compost, palm oil mill waste, and biochar can supply nutrients and enhance soil organic matter content (An et al., 2020, 2020; Liew et al., 2017; Mutar et al., 2025). Liming materials have also been widely applied to reduce peat soil acidity and improve nutrient availability. However, these approaches have generally been investigated independently and often exhibit important limitations under highly acidic tropical peat conditions. Organic amendments alone may undergo rapid decomposition and nutrient loss through leaching, whereas mineral amendments such as bentonite or limestone primarily improve physicochemical properties without simultaneously supplying sufficient nutrients for sustained crop growth. In addition, previous studies have rarely evaluated the integration of adsorption-active clay minerals, organic nutrient sources, and alkaline buffering agents within a single engineered organo-mineral system specifically designed for tropical peatland agriculture under field conditions.

Several earlier investigations mainly focused on laboratory-scale characterization or short-term soil incubation studies without comprehensive evaluation of crop performance under extreme peat acidity. Moreover, limited information is available regarding how combined mineral–organic–alkaline systems influence nutrient retention dynamics, peat soil neutralization, and soybean growth simultaneously within highly porous peat environments. As a result, the effectiveness of integrated multifunctional peat soil ameliorants capable of concurrently improving soil pH, nutrient stabilization, and plant productivity remains insufficiently explored. Therefore, this study aimed to develop and evaluate an engineered organo-mineral composite (CCBN674) derived from bentonite, palm oil mill sludge, and shell-derived limestone for improving the physicochemical properties of tropical peat soils and supporting soybean cultivation under peatland conditions.

Therefore, The objective of this study is to develop and evaluate the effectiveness of a novel organo-mineral composite based on bentonite, palm oil mill waste, and a calcium-containing material for simultaneously improving the acid–base properties of tropical peat soils, enhancing nutrient retention, and promoting the growth and productivity of soybean (Glycine max) under field conditions. It is hypothesized that the application of this composite significantly increases peat soil pH compared to untreated soil and conventional fertilizers, improves the retention and availability of key nutrients such as nitrogen, phosphorus, and potassium, and that the combined mineral and organic components act synergistically to enhance overall soil fertility compared to their individual use. Furthermore, it is expected that the use of the composite will lead to a statistically significant improvement in soybean growth and yield relative to both conventional NPK fertilization and untreated control conditions.

MATERIALS AND METHODS

To improve methodological transparency and experimental reproducibility, the overall research workflow and major experimental stages are presented schematically in Figure 1. The figure summarizes the sequential procedures employed in this study, including raw material preparation, composite formulation, physicochemical characterization, field application, soybean cultivation, observational measurements, and comparative data analysis. This workflow visualization is



Note: Due to the exploratory nature and field constraints, the study was conducted with limited replication. Therefore, the results are presented as preliminary observations to evaluate the potential of CCBN674 under extreme peat soil conditions.

Figure 1. Schematic overview of the experimental workflow, preparation procedure of the CCBN674 composite, field application stages, soybean growth observations, and data collection process conducted under tropical peatland conditions

intended to provide a clearer step-by-step representation of how the experimental results were obtained under tropical peatland conditions.

Materials

Natural bentonite used in this study was collected from Sungai Puar, Mersam District, Batanghari Regency, Jambi Province, Indonesia. Palm oil mill sludge was obtained from the anaerobic primary pond of the wastewater treatment plant (WWTP) of a local palm oil mill in Jambi Province, Indonesia. Shell waste used as the calcium source for limestone preparation was collected from local shellfish processing residues. Tropical peat soil used for incubation and field experiments was collected from agricultural peatland located in Desa Solok, Kumpeh Ulu District, Muaro Jambi Regency, Jambi Province, Indonesia.

Soybean (*Glycine max* L.) seeds were used as the test crop for field application studies. Analytical-grade reagents were used throughout the study, including sodium hydroxide (NaOH, ≥98%, Merck), potassium nitrate (KNO_3, ≥99%, Merck), potassium persulfate ($K_2S_2O_8$, ≥99%, Sigma-Aldrich), hydrochloric acid (HCl, 37%, Merck), sulfuric acid (H_2SO_4, 98%, Merck), nitric acid (HNO_3, 65%, Merck), ethanol (96%, Merck), potassium chloride (KCl, ≥99%, Merck), ammonium molybdate tetrahydrate ($(NH_4)_6Mo_7O_{24}\cdot 4H_2O$, ≥99%, Sigma-Aldrich), potassium antimonyl tartrate ($K(SbO)C_4H_4O_6\cdot ½H_2O$, Sigma-Aldrich), ascorbic acid ($C_6H_8O_6$, ≥99%, Merck), potassium dihydrogen phosphate (KH_2PO_4, ≥99%, Merck), phenolphthalein indicator, and distilled water.

Instrumentation

Mineralogical characterization was conducted using an X-ray diffractometer (XRD, PANalytical X'Pert PRO, Netherlands) equipped with Cu-Kα radiation (λ = 1.5406 Å), operated at 40 kV and 30 mA with a scanning range of 5–80° (2θ). Surface morphology and elemental composition analyses were performed using scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM–EDS, JEOL JSM-6510LV, Japan). Nitrogen analysis was conducted using the Kjeldahl digestion-distillation method. Phosphorus concentration was measured using a

UV–Visible spectrophotometer (Shimadzu UV-1800, Japan), while potassium content was determined using atomic absorption spectroscopy (AAS, PerkinElmer AAnalyst 400, USA). pH measurements were performed using a digital pH meter (Hanna Instruments HI2211, USA). Drying processes were carried out using a laboratory oven (Memmert UN55, Germany). Grinding and homogenization were conducted using a mechanical grinder and laboratory mixer. Particle size separation was performed using stainless-steel sieves with mesh sizes of 80 and 170 mesh. All weighing procedures were performed using an analytical balance (Ohaus Pioneer PA214, USA) with ±0.0001 g precision.

Preparation of raw materials

Natural bentonite was washed several times using distilled water to remove surface impurities and suspended particles. The cleaned bentonite was dried under sunlight for 24 h followed by oven drying at 105 °C for 2 h to remove residual moisture. The dried material was crushed using a mechanical crusher, ground into powder, and sieved through a 170-mesh sieve to obtain homogeneous particle size. Palm oil mill sludge was air-dried at ambient temperature (25–30 °C) for 48 h and subsequently oven-dried at 105 °C for 2 h. The dried sludge was ground using a laboratory grinder and sieved through a 170-mesh sieve. Shell waste was cleaned thoroughly with distilled water to remove adhering impurities and dried prior to grinding into fine powder. The shell powder was used as the limestone source for alkalinity enhancement.

Preparation of bentonite-palm oil mill waste organo-mineral composite

The organo-mineral composite was prepared by mixing bentonite and dried palm oil mill sludge at different mass ratios to determine the optimum formulation. The investigated bentonite-to-sludge ratios included 1:2, 1:3, 1:4, 1:5, 2:5, 3:4, 4:5, and several additional compositions. The mixtures were homogenized using a laboratory mechanical mixer with different mixing times of 5, 10, 15, and 25 min to evaluate the effect of mixing duration on nutrient distribution and formulation stability. After determination of the optimum composition, shell-derived limestone was incorporated into the mixture to improve alkalinity and peat soil neutralization capacity. The final optimized formulation was designated as CCBN674. For larger-scale preparation, 3–4 kg bentonite was mixed with 6–10 L palm oil mill sludge followed by the addition of 1–2 kg shell-derived limestone. The mixture was stirred continuously until homogeneous and subsequently air-dried before field application.

Characterization of raw materials and composite

Mineralogical characterization of bentonite, palm oil mill sludge, and formulated composites was performed using XRD analysis. Powdered samples were scanned over a 2θ range of 5–80° at room temperature. Mineral phases were identified using the International Centre for Diffraction Data (ICDD) database. Morphological structures and elemental compositions of the samples were analyzed using SEM–EDS. Samples were mounted on aluminum stubs using conductive carbon tape and coated with a thin conductive layer prior to analysis. Moisture content was determined gravimetrically by drying samples at 105°C until constant weight. Organic carbon content was analyzed using the Walkley–Black method. Total nitrogen content was determined using the Kjeldahl method involving digestion, distillation, and titration stages. Phosphorus concentration was measured spectrophotometrically using the molybdenum blue method at a wavelength of 880 nm. Potassium concentration was determined using atomic absorption spectroscopy after acid digestion of the samples using HNO_3.

Optimization of composite formulation

Optimization of the organo-mineral composite was conducted based on nutrient content (N, P, and K), pH characteristics, and peat soil neutralization performance. The pH of each formulation was measured using a calibrated pH meter. To evaluate soil neutralization performance, selected formulations were mixed with 500 g peat soil followed by equilibration under ambient conditions before pH determination. Different limestone dosages ranging from 1 to 10 g were investigated to determine the optimum composition capable of increasing peat soil pH toward near-neutral conditions.

Field experiment

Field experiments were conducted on tropical peatland located in Desa Solok, Kumpeh Ulu

District, Muaro Jambi Regency, Jambi Province, Indonesia (Figure 2). Prior to planting, the experimental site was manually cleared from weeds and plant residues using conventional agricultural tools. The soil was subsequently tilled and formed into experimental beds measuring approximately 60 × 600 cm. The peat soil at the study site was characterized by extremely acidic conditions and poor nutrient availability. Soybean (*Glycine max* L.) seeds were planted at a spacing of 40 × 20 cm with an approximate planting depth of 3 cm. Three seeds were placed in each planting hole to ensure uniform germination and compensate for potential seed mortality during early growth stages. Replanting was conducted at 6 days after planting for plots exhibiting poor germination.

The experiment consisted of four different treatments, namely untreated peat soil (control), conventional NPK fertilizer, CCBN674 organo-mineral composite, and a combination of NPK fertilizer with CCBN674. The organo-mineral composite was applied at a dosage of 100 g plant^{-1}, whereas NPK fertilizer was applied at 2 g plant^{-1}. Fertilization was carried out periodically during vegetative growth stages at 1, 2, and 5 weeks after planting. During the generative phase, potassium chloride (KCl) fertilizer was additionally applied at 2 g plant^{-1} to support pod development and seed formation. The field experiment was conducted under natural environmental conditions throughout the soybean cultivation period. Plant growth responses under each treatment were evaluated to determine the effectiveness of the engineered organo-mineral composite in improving peat soil productivity and supporting soybean cultivation under acidic peatland conditions.

Figure 2. Preparation of experimental field

Plant growth measurements

Plant growth observations were performed weekly from the second until the fifth week after planting. Agronomic parameters evaluated in this study included plant height, number of leaves, and number of filled pods as indicators of vegetative and generative growth performance. Plant height was measured using a ruler from the soil surface to the highest point of the plant after gently straightening the stem. Leaf number was determined by counting all fully expanded leaves on each plant. Measurements were conducted at weekly intervals to evaluate growth dynamics under different fertilization treatments. At harvest stage, the number of filled pods per plant was determined manually. Pods were classified as filled when at least one fully developed seed was present inside the pod. Harvesting was carried out approximately 70 days after planting, corresponding to physiological maturity characterized by yellowing leaves, drying stems, and brownish mature pods. Plant survival and overall growth performance were also visually monitored throughout the cultivation period to evaluate the adaptability of soybean plants to peat soil conditions following application of the engineered organo-mineral composite. Experimental data were subsequently processed using descriptive statistical analysis and expressed as mean ± standard deviation.

Experimental scope and methodological limitations

The present study was designed as a preliminary exploratory field evaluation of an engineered organo-mineral amendment developed for highly acidic tropical peat soils. The primary objective was to assess the practical feasibility of the CCBN674 composite for improving peat soil conditions and supporting soybean establishment under severe acidity stress. Formulation development was conducted through empirical screening based on physicochemical observations, including pH neutralization performance, nutrient composition, material homogeneity, and handling stability. Accordingly, the selected CCBN674 formulation should be interpreted as a practically optimized composition within the scope of this exploratory investigation rather than a statistically optimized formulation derived from factorial or response surface methodologies.

Field experiments were conducted under practical peatland conditions using comparative treatments consisting of untreated peat soil, conventional NPK fertilization, CCBN674 application, and combined NPK + CCBN674 application. Due to logistical and environmental constraints associated with tropical peatlands, the study was not performed as a fully replicated randomized agronomic trial. Consequently, the generated data are primarily descriptive and comparative in nature, and the observed treatment responses should be interpreted as preliminary field-scale observations rather than definitive agronomic validation.

Several additional limitations should also be considered when interpreting the results. The experiment was conducted over a single cultivation season, preventing assessment of the long-term stability of soil physicochemical improvements and sustained crop productivity following composite application. Spatial replication was limited, and the inherent heterogeneity of tropical peat soils may have introduced variability that was not fully captured within the current experimental design. Furthermore, environmental variables such as rainfall variation, water table fluctuation, and microenvironmental differences were not continuously controlled during the cultivation period and may have influenced plant growth responses.

The present study also did not evaluate the long-term dynamics of nutrient release, nutrient depletion, or transformation processes beyond the soybean growth cycle. Similarly, potential accumulation, mobility, or environmental risks associated with trace elements originating from waste-derived materials were outside the scope of the current investigation. In addition, the mechanistic pathways proposed for nutrient adsorption, nutrient release regulation, and rhizosphere stabilization were inferred from physicochemical characterization and agronomic observations rather than directly quantified through kinetic or molecular-scale analyses.

Despite these limitations, the study provides an important proof-of-concept demonstrating the feasibility of integrating bentonite, palm oil mill sludge, and shell-derived alkaline materials into a multifunctional organo-mineral composite for peat soil amelioration. The findings establish an initial scientific foundation for future multi-season, multi-site, and mechanistic investigations aimed at validating the long-term agronomic and environmental performance of the developed material under tropical peatland conditions.

RESULT AND DISCUSSION

Mineralogical characteristics and physicochemical properties of bentonite and palm oil mill sludge

The mineralogical characteristics of bentonite and palm oil mill sludge play a crucial role in determining the functionality of the engineered organo-mineral composite developed in this study. XRD analysis revealed that the bentonite consisted predominantly of bavenite, kaolinite, quartz, and montmorillonite phases (Figure 3a), this result in line with the previous study (Kgabi and Ambushe, 2023). Among these minerals, montmorillonite is considered the most important component for agricultural and environmental applications because of its expandable layered aluminosilicate structure, high cation exchange capacity (CEC), swelling behavior, and strong adsorption capability toward nutrient ions and water molecules (Manjaiah et al., 2019; Mondal et al., 2021). These characteristics are particularly beneficial for tropical peat soils, which generally exhibit poor nutrient retention and severe leaching losses due to their porous structure and high organic acidity.

The presence of montmorillonite within the bentonite matrix likely contributed significantly to the slow-release behavior of the CCBN674 composite. The interlayer structure of montmorillonite can adsorb nutrient ions such as NH_4^+, K^+, Ca^{2+}, and PO_4^{3-} through electrostatic interactions and subsequently release them gradually into the rhizosphere (Edussuriya et al., 2023, 2023). This adsorption-desorption equilibrium is highly advantageous under peatland conditions where soluble nutrients supplied by conventional fertilizers are commonly lost through leaching before effective plant uptake occurs. Furthermore, the swelling behavior of montmorillonite may improve water retention within the root zone, thereby supporting nutrient diffusion and root development under fluctuating moisture conditions typical of tropical peatlands.

In addition to montmorillonite, the presence of kaolinite and quartz may also contribute to the physicochemical stability of the composite. Quartz-rich phases can enhance structural rigidity and mechanical stability, whereas kaolinite may support additional adsorption sites for nutrient interactions (Ramanamane & Pita, 2025; Totsche et al., 2018). Although kaolinite generally possesses lower CEC than montmorillonite, its inclusion within the composite matrix may improve particle aggregation and reduce rapid structural collapse under saturated peat conditions (Skic et al., 2023; Zaini et al., 2024). The XRD profile of palm oil mill sludge (Figure 3b) demonstrated a predominance of silica-rich quartz phases accompanied by nutrient-associated mineral components. Palm oil mill sludge contained relatively high concentrations of nitrogen, phosphorus, and potassium (Lim et al., 2014), indicating its strong potential as an organic nutrient reservoir. The high organic matter content observed in the sludge is particularly important because organic materials may improve microbial activity, soil aggregation, and nutrient cycling following soil application (Cui et al., 2023; Khosro Mohammadi, 2011). Organic compounds within the sludge can undergo gradual mineralization, releasing nutrients into the soil solution over extended periods.

The combination of bentonite and palm oil mill sludge therefore creates a synergistic organo-mineral system in which each component performs complementary functions. Palm oil sludge primarily acts as a nutrient donor and organic carbon source, while bentonite functions as a mineral carrier and nutrient-retaining matrix. Such synergy is highly important in peat soils because organic-derived nutrients alone are often highly unstable under acidic conditions and susceptible to rapid leaching. This condition in line with several studies that showed researchers focus on developing the composite fertilizer (Firmanda et al., 2022; Pogorzelski et al., 2020; Samara et al., 2019). The incorporation of bentonite likely stabilized nutrient availability by reducing nutrient mobility and increasing adsorption capacity within the soil environment.

The physicochemical analyses further demonstrated clear differences between bentonite and sludge materials before and after oven drying (Table 1). Palm oil mill sludge exhibited substantially higher moisture content than bentonite due to its organic and colloidal nature. Following oven treatment at 105 °C, the moisture content decreased significantly, indicating efficient removal of physically adsorbed water. Interestingly, oven-dried sludge exhibited increased organic carbon and macronutrient concentrations relative to non-dried sludge. This increase was likely associated with concentration effects resulting from water removal, leading to enrichment of detectable

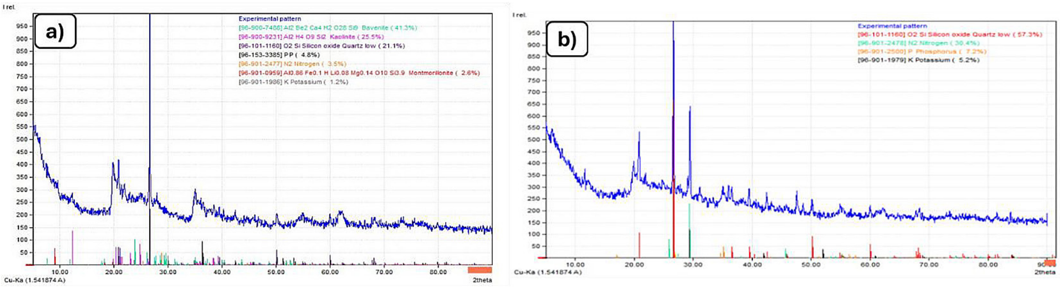


Figure 3. XRD of bentonite (a) and palm oil mill sludge (b)

nutrient fractions within the dried material. The sludge samples also exhibited relatively low C/N ratios (9.43–10.72), indicating favorable conditions for microbial decomposition and nutrient mineralization. Organic materials with lower C/N ratios generally decompose more rapidly, thereby facilitating nitrogen release into the soil. This characteristic is advantageous for agricultural applications because nutrient availability becomes more synchronized with plant nutrient demand during vegetative growth stages.

In contrast, bentonite exhibited relatively low organic carbon content but maintained stable mineral characteristics suitable for nutrient adsorption and pH buffering. The comparatively higher C/N ratio observed in bentonite samples reflects the inorganic-dominant nature of the clay material. Nevertheless, the role of bentonite in this system is not primarily as a nutrient source but rather as a physicochemical stabilizer capable of improving nutrient retention efficiency within the composite matrix. One important observation in this study is the influence of drying treatment on nutrient composition. Oven drying appeared to reduce certain phosphorus fractions in bentonite while increasing detectable nutrient concentrations in sludge samples. Thermal treatment may alter surface functional groups, mineral hydration states, and organic matter structures, thereby affecting nutrient detectability and adsorption behavior (Johnston, 1996; Li et al., 2023). Such physicochemical transformations may influence nutrient release dynamics after soil application and therefore should be carefully considered during composite preparation.

Overall, the mineralogical and physicochemical results indicate that the engineered combination of bentonite and palm oil mill sludge possesses strong potential as a multifunctional peat soil ameliorant. The integration of adsorption-active clay minerals, nutrient-rich organic matter, and alkaline buffering agents provides a favorable platform for improving nutrient retention, reducing acidity stress, and supporting plant growth under highly acidic tropical peatland conditions. These findings also demonstrate the feasibility of transforming locally available mineral and agro-industrial waste materials into value-added organo-mineral composites for sustainable agricultural applications.

Optimization of organo-mineral composite formulation

Optimization of the bentonite–palm oil mill sludge composite was conducted to identify the most suitable formulation capable of simultaneously providing nutrient enrichment, physicochemical stability, and effective peat soil amelioration. In highly acidic peat environments, fertilizer performance is not determined solely by nutrient concentration but also by nutrient retention capacity, buffering ability, and the stability of nutrient release under fluctuating soil conditions (Osman, 2018; Pinsonneault et al., 2016; Sharma et al., 2025). Therefore,

Table 1. Physicochemical properties of bentonite and sludge samples before and after oven drying

Sample	Moisture Content (%)	Carbon (C, %)	Nitrogen (N, %)	Phosphorus (P, %)	Potassium (K, %)	C/N Ratio
Non-oven-dried bentonite	03.14	0,0631	0.049	9.034	0.0106	18.57
Oven-dried bentonite	00.00	0,0444	0.053	7.48	0,07291667	12.07
Non-oven-dried sludge	38.80	0,9277	2.307	0.41	0.35	9.43
Oven-dried sludge	03.33	30.16	2.811	1.20	0.84	10.72

optimization of both mixing duration and material composition was essential to produce a multifunctional organo-mineral composite with balanced agronomic properties.

The results demonstrated that mixing time strongly influenced nutrient distribution within the composite matrix. Increasing mixing duration promoted better homogenization between bentonite particles and sludge-derived organic matter, resulting in more uniform nutrient incorporation throughout the material. Nitrogen concentration generally increased with longer mixing durations, indicating that extended mechanical interaction may improve adsorption of ammonium-containing compounds and organic nitrogen fractions onto bentonite surfaces. This behavior is likely associated with electrostatic interactions between negatively charged clay surfaces and positively charged nitrogen species.

In contrast, phosphorus and potassium concentrations exhibited slight fluctuations at prolonged mixing times. This phenomenon may be attributed to partial adsorption and redistribution of nutrient ions within the interlayer structure of montmorillonite. Bentonite minerals possess active adsorption sites capable of temporarily immobilizing nutrient ions through ion exchange mechanisms (Maged et al., 2020). Consequently, nutrient concentrations measured in the extractable phase may vary depending on the extent of nutrient adsorption within the clay matrix.

The optimum mixing duration was observed at 25 min, which produced the most balanced nutrient composition and stable formulation characteristics. Adequate mixing is particularly important for organo-mineral composites because insufficient homogenization may lead to heterogeneous nutrient distribution and inconsistent soil performance following field application. Furthermore, longer mixing durations may facilitate stronger interactions between organic functional groups from the sludge and mineral surfaces of bentonite, thereby improving structural integrity and nutrient stabilization.

Variation of bentonite-to-sludge ratios also produced substantial differences in nutrient composition (Table 2). Formulations containing higher sludge proportions generally exhibited increased nitrogen and phosphorus concentrations due to the nutrient-rich organic nature of palm oil mill sludge. The highest nitrogen concentration (2.101%) and phosphorus concentration (1.680%) were obtained in formulation C with a bentonite-to-sludge ratio of 1:4. This result confirms that palm oil mill sludge serves as the principal nutrient contributor within the composite system.

Table 2. Determination of the optimal composition of bentonite and dried palm oil mill sludge waste mixtures

Sample code	Weight ratio		Nutrient parameters (%)		
	Bentonite	Palm oil mill sludge	N	P	K
A	1	2	1.712	0,4930	0.0798
B	1	3	1.943	1.324	0.0861
C	1	4	2.101	1.680	0.0868
D	1	5	1.954	1.308	0.0805
E	2	1	0.4	0.6027	0.051
F	2	3	1.525	0.0868	0.093
G	2	5	1.819	1.497	0.0812
H	3	1	0.48958333	0.3659	0.044
I	3	2	1.109	0.4590	0.067
J	3	4	1.476	1.241	0.0743
K	3	5	1.060	1.201	0.099
L	4	1	0.35486111	0.15902778	0.037
M	4	3	1.112	0.64236111	0.067
N	4	5	1.944	1.034	0.090
O	5	1	0.30555556	0.21111111	0.029
P	5	2	0.59930556	0.30138889	0.059
Q	5	3	1.167	0.38888889	0.084
R	5	4	1.103	0.29791667	0.076

However, although increasing sludge proportion enhanced nutrient content, excessive sludge addition may compromise physicochemical stability and adsorption performance. Organic-rich formulations tend to possess weaker structural stability and may release nutrients too rapidly under highly acidic peat conditions (Bakri et al., 2025). Such rapid nutrient release could increase nutrient losses through leaching and reduce fertilizer use efficiency (Zhang et al., 2018). Therefore, incorporation of bentonite is critically important to regulate nutrient mobility and create a slow-release nutrient delivery system. The role of bentonite within the composite extends beyond simple physical mixing. Clay minerals such as montmorillonite are capable of forming organo-mineral associations with organic compounds derived from sludge materials (Sarkar et al., 2018). These interactions may stabilize organic matter against rapid decomposition while simultaneously increasing nutrient adsorption capacity. In acidic peat soils, this mechanism is particularly advantageous because nutrient losses through runoff, leaching, and fixation are among the major limitations restricting crop productivity.

Potassium concentrations in the formulations remained relatively lower than nitrogen and phosphorus concentrations. Nevertheless, the presence of exchangeable potassium within bentonite interlayers may contribute to gradual potassium release during soil incubation. Potassium mobility in peat soils is generally high due to weak retention by organic colloids (Wijayanti et al., 2025); therefore, even relatively low potassium concentrations within a slow-release system may still provide agronomic benefits through prolonged nutrient availability. The selection of the final optimized formulation was not based solely on nutrient concentration. Instead, formulation selection considered overall performance, including pH characteristics, nutrient balance, physical stability, and peat soil neutralization capacity. This approach is important because highly nutrient-rich formulations may not necessarily perform optimally under field conditions if nutrient release is unstable or if the formulation lacks buffering capacity.

The optimized composite, designated as CCBN674, demonstrated favorable integration between nutrient enrichment and physicochemical functionality. The combination of nutrient-rich sludge, adsorption-active bentonite, and alkaline limestone created a multifunctional material capable of simultaneously supplying nutrients, improving soil pH, and stabilizing nutrient availability within the peat soil environment. Such multifunctionality represents a major advantage compared with conventional fertilizers, which generally supply nutrients without addressing the fundamental limitations of acidic peat soils. Another important aspect of the optimized formulation is its potential role in reducing nutrient leaching. Peat soils possess low mineral content and high porosity, resulting in weak nutrient retention capacity. Nutrients applied in soluble form are therefore highly susceptible to loss before effective root uptake occurs (Pierre and Regmi, 2026). The adsorption capability of bentonite likely reduced nutrient mobility by temporarily retaining nutrient ions within the clay structure, thereby extending nutrient residence time in the rhizosphere (Mi et al., 2021). This mechanism may explain the superior soybean growth performance observed following application of the organo-mineral composite compared with conventional NPK fertilization alone.

From a sustainability perspective, the optimization results also demonstrate the feasibility of transforming palm oil mill sludge from an agro-industrial waste into a value-added agricultural material. Palm oil processing industries generate large quantities of sludge waste that may pose environmental challenges if improperly managed. Incorporation of this waste into engineered organo-mineral composites therefore supports circular economy approaches through simultaneous waste valorization and sustainable soil improvement. Overall, the optimization study confirmed that careful control of bentonite-to-sludge ratio and mixing conditions is essential for developing a stable and effective organo-mineral composite suitable for peatland agriculture. The optimized CCBN674 formulation exhibited balanced nutrient composition, improved physicochemical stability, and strong potential as a multifunctional peat soil ameliorant capable of supporting sustainable soybean cultivation under highly acidic tropical peat conditions.

Peat soil neutralization performance

One of the most critical constraints associated with tropical peat soils is their extremely acidic nature, which severely limits nutrient availability and plant growth (Osman, 2018). The peat soil used in this study exhibited initial pH values ranging from approximately 1 to 3, indicating highly acidic conditions unsuitable for sustainable soybean cultivation. Under such conditions, excessive concentrations of soluble hydrogen ions promote nutrient immobilization and increase the solubility of potentially toxic metals. These factors collectively inhibit root elongation, nutrient absorption, microbial activity, and overall plant development.

The incorporation of shell-derived limestone into the bentonite-sludge composite substantially improved the alkalinity of the formulated material. Prior to limestone addition, the bentonite–sludge mixtures exhibited near-neutral pH values around 6.57–6.58, indicating that the combination of bentonite and sludge alone already provided moderate buffering capability. However, after limestone incorporation, the pH of the composite increased dramatically to values exceeding 12. This substantial increase demonstrates the strong alkaline buffering effect provided by calcium carbonate derived from shell waste. The details of experimental design to find the best composition can be seen in Table 3.

The increase in alkalinity following limestone addition is primarily associated with dissolution of calcium carbonate ($CaCO_3$), which consumes hydrogen ions present within acidic environments according to the following neutralization mechanism (Wang et al., 2026):

$$\mathrm{CaCO_3} + 2\mathrm{H}^+ \rightarrow \mathrm{Ca}^{2+} + \mathrm{CO_2} + \mathrm{H_2O} \quad (1)$$

Through this reaction, excess acidity in peat soil can be effectively reduced, thereby increasing soil pH toward more favorable conditions for nutrient availability and plant growth. The release

Table 3. Determination of the optimal composition of bentonite and dried palm oil mill sludge waste mixtures

Composition ratio (g)			pH of formulated composition
Bentonite	Palm oil mill waste	Limestone	
1	3	–	06.58
1	5	–	06.58
2	5	–	06.58
3	4	–	06.57
1	3	1	12.18
1	5	1	12.19
2	5	1	12.25
3	4	1	12.26
1	3	1	3.29
3	4	1	3.79
2	5	1	3.43
1	5	1	3.41
3	4	2	4
3	4	3	5
3	4	4	5.8
3	4	5	6.5
6	8	4	6.8
6	8	6	6.8
6	8	8	6.8
6	8	10	6.9
8	10	8	7.5
10	12	8	7
12	14	8	7.3
14	16	8	7
8	10	10	7.3
10	12	10	7.5
12	14	10	7.5
14	16	10	7.3

of calcium ions may additionally contribute to improvement of soil aggregation and stabilization of soil colloids within the peat matrix. Following soil application, the engineered composite progressively increased peat soil pH from strongly acidic conditions toward near-neutral values. Initial formulations containing low limestone dosages increased peat soil pH to approximately 3–4, whereas higher limestone incorporation successfully elevated soil pH to 6.8–7.5. This near-neutral range is highly favorable for agricultural applications because most essential nutrients become more available under moderately acidic to neutral conditions.

The observed pH improvement has several important implications for nutrient dynamics within peat soils. Under extremely acidic conditions, phosphorus is commonly immobilized through precipitation and adsorption with Fe and Al compounds, making it unavailable for plant uptake (Johan et al., 2021). Simultaneously, toxic soluble aluminum species may damage root tissues and inhibit nutrient absorption (Ur Rahman et al., 2024a). Increasing soil pH reduces the solubility of these toxic metals while enhancing phosphorus availability, thereby improving the overall nutrient environment within the rhizosphere. Besides the direct neutralization effect of limestone, bentonite may also contribute to pH stabilization through ion exchange mechanisms. Montmorillonite-rich bentonite contains negatively charged interlayer surfaces capable of adsorbing exchangeable cations such as Ca^{2+}, Mg^{2+}, and K^{+} (Yener et al., 2012). These exchange processes may help buffer rapid fluctuations in soil acidity and maintain a more stable chemical environment following application. Furthermore, the adsorption capacity of bentonite may reduce proton mobility within the soil solution, indirectly supporting pH stabilization over longer periods.

Another important aspect is the synergistic interaction between bentonite, sludge organic matter, and limestone. Organic compounds derived from palm oil sludge may complex with soluble metal ions, thereby reducing metal toxicity and improving nutrient accessibility. At the same time, bentonite acts as a stabilizing mineral matrix that slows nutrient release and prevents rapid nutrient loss under highly porous peat conditions. This integrated interaction likely contributed to the gradual yet effective pH improvement observed during soil incubation. The optimization results also demonstrated that limestone dosage strongly influenced peat soil neutralization efficiency. Increasing limestone concentration progressively elevated soil pH toward neutral conditions. However, excessively high alkalinity may potentially create nutrient imbalance or micronutrient deficiency under long-term application. Therefore, optimization of limestone dosage is essential to achieve balanced pH conditions suitable for plant growth without inducing excessive alkalization.

The near-neutral pH conditions generated by the optimized formulations represent a major improvement relative to untreated peat soils. Soil pH values around 6.5–7.5 are generally considered optimal for nutrient uptake because essential macronutrients such as nitrogen, phosphorus, and potassium become more bioavailable, while toxic metal solubility decreases substantially (Tripti et al., 2022). Such improvements likely contributed directly to the enhanced soybean survival and growth observed in the field experiment. Compared with conventional liming alone, the engineered CCBN674 composite offers several additional advantages. Conventional limestone application primarily functions to neutralize acidity but does not substantially improve nutrient retention or slow nutrient release. In contrast, the organo-mineral composite developed in this study combines alkalinity enhancement with nutrient enrichment and adsorption-based stabilization mechanisms. This multifunctional behavior is particularly advantageous in peat soils where acidity, poor nutrient retention, and nutrient leaching occur simultaneously.

From an environmental perspective, utilization of shell-derived limestone also supports sustainable waste recycling approaches. Shell waste is often discarded as an environmental burden in coastal and aquaculture regions. Converting this waste into a functional alkalinity source for peat soil amelioration therefore represents an environmentally beneficial valorization strategy that simultaneously reduces waste accumulation and improves agricultural productivity. Overall, the results demonstrate that the engineered bentonite–palm oil mill waste composite possesses strong peat soil neutralization capability through synergistic interactions among alkaline limestone, adsorption-active bentonite, and nutrient-rich organic sludge. The substantial improvement in soil pH provides a more favorable environment for nutrient retention, microbial activity, and soybean root development, thereby establishing an important foundation for sustainable agricultural utilization of tropical peatlands.

Proposed mechanism of CCBN674 in peat soil

The improvement of soybean growth observed following CCBN674 application is likely governed by multiple synergistic physicochemical and biological mechanisms operating simultaneously within the peat soil environment. Unlike conventional fertilizers that primarily function as direct nutrient suppliers, the engineered CCBN674 composite acts as a multifunctional peat soil ameliorant capable of modifying soil acidity, stabilizing nutrient dynamics, improving rhizosphere conditions, and enhancing nutrient retention efficiency under highly acidic tropical peatland conditions. The mechanism involves four major integrated processes, namely acidity neutralization, nutrient adsorption–desorption regulation, organic matter-mediated nutrient cycling, and rhizosphere stabilization. Figure 4 showed the field observation of soybean growth after added the CCBN674 application.

The first and most immediate mechanism involves neutralization of excessive soil acidity through dissolution of calcium carbonate derived from shell-based limestone. Tropical peat soils generally contain large concentrations of hydrogen ions and soluble organic acids, resulting in extremely low pH conditions unfavorable for plant growth (Fujii, 2014; Osaki et al., 2021). The addition of shell-derived limestone increases soil alkalinity through the release of Ca^{2+} ions and consumption of H^+ ions, thereby shifting soil pH toward more favorable conditions for nutrient availability and root development. Improvement of soil pH likely reduced the solubility of toxic Al and Fe species that commonly inhibit root elongation and nutrient uptake in acidic peat environments. Beyond direct acidity neutralization, calcium ions released from limestone may also improve aggregation and stabilization of peat colloids. Calcium-mediated bridging between negatively charged organic matter and mineral surfaces may strengthen soil structural integrity and reduce excessive dispersion within saturated peat systems (Rowley et al., 2018). Such stabilization potentially improves root penetration and enhances the physical environment surrounding the rhizosphere.

The second major mechanism involves nutrient adsorption and slow-release regulation by bentonite minerals, particularly montmorillonite. Montmorillonite possesses expandable interlayer structures and high cation exchange capacity capable of adsorbing nutrient ions (Wibowo et al., 2025) such as NH_4^+, K^+, Ca^{2+}, and various phosphate-associated species. Under peat soil conditions, where soluble nutrients are highly susceptible to leaching due to weak mineral retention capacity, bentonite likely functioned as a nutrient reservoir capable of temporarily immobilizing

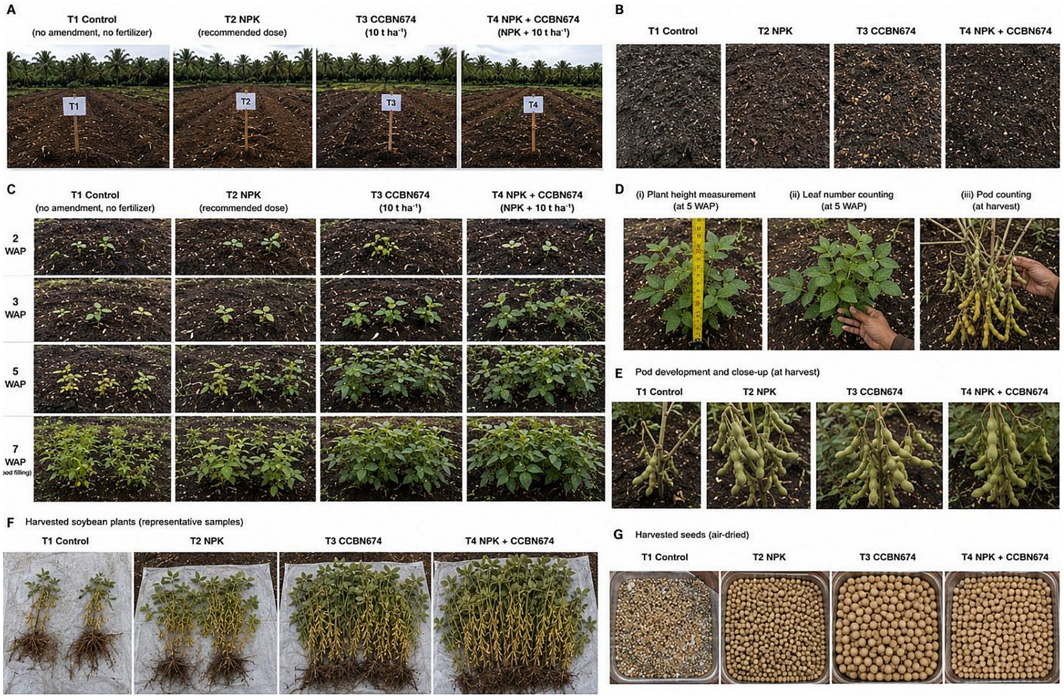


Figure 4. Field observation and soybean growth under different treatments in peat soil

nutrients and releasing them gradually according to concentration gradients within the soil solution. This adsorption–desorption equilibrium is particularly important because tropical peat soils often exhibit rapid nutrient depletion following fertilizer application (Bakri et al., 2025). Conventional soluble fertilizers may initially increase nutrient concentration but are rapidly lost through leaching and runoff before efficient root uptake occurs. In contrast, the bentonite-rich structure of CCBN674 likely prolonged nutrient residence time within the rhizosphere, thereby increasing nutrient use efficiency and sustaining nutrient availability throughout vegetative and generative growth stages.

The swelling behavior of montmorillonite may additionally contribute to water retention within the peat soil matrix (Reddy et al., 2020). Water retention is critically important in tropical peat systems because fluctuating moisture conditions strongly influence nutrient mobility and microbial activity (Marwanto et al., 2018). By improving water-holding capacity around the root zone, bentonite may facilitate nutrient diffusion and maintain more stable root hydration conditions during plant growth. The third mechanism involves gradual nutrient mineralization from palm oil mill sludge organic matter. Palm oil sludge acts as the primary nutrient donor within the engineered composite due to its relatively high nitrogen, phosphorus, and potassium content. Following soil incorporation, organic compounds derived from sludge may undergo microbial decomposition and mineralization, gradually releasing nutrients into plant-available forms. This controlled mineralization process complements the adsorption behavior of bentonite, creating a combined slow-release nutrient delivery system within the peat environment.

Organic matter from palm oil sludge may also contribute to complexation of soluble metal ions such as Fe^{3+} and Al^{3+}, thereby reducing their phytotoxicity under acidic conditions. Humic-like substances generated during decomposition may bind toxic metals and decrease their bioavailability, indirectly protecting root tissues and improving nutrient absorption efficiency (Maffia et al., 2025; Nabi et al., 2025). Furthermore, decomposition of organic matter may stimulate microbial activity within the rhizosphere, promoting nutrient cycling and enhancing biological fertility of the peat soil (Ali et al., 2025). Another important mechanism is the formation of organo-mineral associations between sludge-derived organic compounds and bentonite mineral surfaces (Afsar et al., 2023). Such interactions may stabilize organic matter against rapid decomposition while simultaneously enhancing nutrient adsorption capacity. The resulting organo-mineral complexes likely contribute to improved structural stability of the composite and reduced nutrient mobility under saturated peat conditions.

The synergistic interaction among bentonite, limestone, and palm oil sludge therefore creates a multifunctional soil-conditioning system that addresses several major limitations of peat soils simultaneously. Limestone reduces acidity stress, bentonite stabilizes nutrient retention and water availability, while palm oil sludge provides nutrient enrichment and organic matter input. This integrated mechanism explains why the engineered composite performed substantially better than conventional NPK fertilization alone under highly acidic peatland conditions. Importantly, the effectiveness of CCBN674 appears to depend not only on nutrient concentration but also on the controlled regulation of nutrient availability within the rhizosphere. The gradual nutrient release mechanism likely prevented excessive nutrient losses and maintained more stable nutrient concentrations during soybean growth. Such nutrient stabilization is particularly advantageous in peat soils where weak mineral fractions and high porosity generally reduce fertilizer efficiency.

The proposed mechanism also highlights the importance of integrating mineral and organic components in the development of sustainable peat soil ameliorants. Pure organic amendments may release nutrients rapidly but often lack sufficient adsorption and buffering capacity, whereas mineral amendments alone may improve soil physicochemical properties without supplying adequate nutrients (Luo et al., 2024). The engineered organo-mineral structure of CCBN674 therefore represents an effective strategy for simultaneously improving chemical, physical, and biological properties of tropical peat soils.

From a sustainability perspective, the mechanism proposed in this study demonstrates the feasibility of converting locally available agro-industrial waste materials into high-value multifunctional agricultural amendments. Palm oil mill sludge and shell waste are commonly regarded as environmental liabilities; however, their integration with adsorption-active bentonite generated a functional organo-mineral composite capable of improving agricultural productivity in suboptimal peatland environments. Overall, the proposed mechanism suggests that the effectiveness of CCBN674 is governed by synergistic interactions among alkalinity enhancement, nutrient retention, slow nutrient release, metal toxicity reduction, and rhizosphere stabilization. These combined mechanisms collectively transformed highly acidic peat soil into a more favorable growth medium capable of supporting sustainable soybean cultivation under tropical peatland conditions.

Soil characteristics after CCBN674 added

The physicochemical and elemental characteristics of peat soil after application of the engineered CCBN674 composite were evaluated using SEM–EDS analysis to investigate changes occurring within the soil matrix following treatment. The SEM micrographs and EDS spectra are presented in Figure 5, while the elemental composition is summarized in Table 4.

The SEM images revealed substantial modification of the peat soil surface morphology following incorporation of CCBN674. The treated soil exhibited heterogeneous granular aggregates with irregular porous structures, indicating successful interaction among bentonite particles, palm oil mill sludge organic matter, and peat soil components. The formation of aggregated mineral-organic structures suggests that the composite promoted stabilization of the peat matrix and improved particle association within the rhizosphere environment. The observed aggregation behavior is likely associated with the combined effects of bentonite swelling, calcium-mediated flocculation, and organic matter interactions. Bentonite minerals, particularly montmorillonite, possess expandable layered structures capable of absorbing water and forming cohesive aggregates with surrounding organic materials (L. Wang, 2025). Simultaneously, calcium ions released from shell-derived limestone may act as bridging agents between negatively charged clay surfaces and peat organic colloids, thereby enhancing structural stability and reducing excessive dispersion within the peat system.

The porous microstructure observed in the SEM images is particularly advantageous for agricultural applications because porous matrices facilitate water retention, gas exchange, microbial colonization, and nutrient diffusion around plant roots. Improved pore connectivity may also enhance root penetration and rhizosphere aeration, both of which are commonly limited in highly saturated peat soils. EDS analysis further confirmed the successful incorporation of mineral and nutrient components into the peat soil following

Table 4. Elemental composition of peat soil after application of CCBN674 determined by SEM–EDS analysis

Element	Weight (%)
N	00.50
O	34.25.00
Al	18.33
Si	28.41.00
P	00.34
S	02.06
K	0,18194444
Ca	04.17
Fe	07.07
Co	01.05

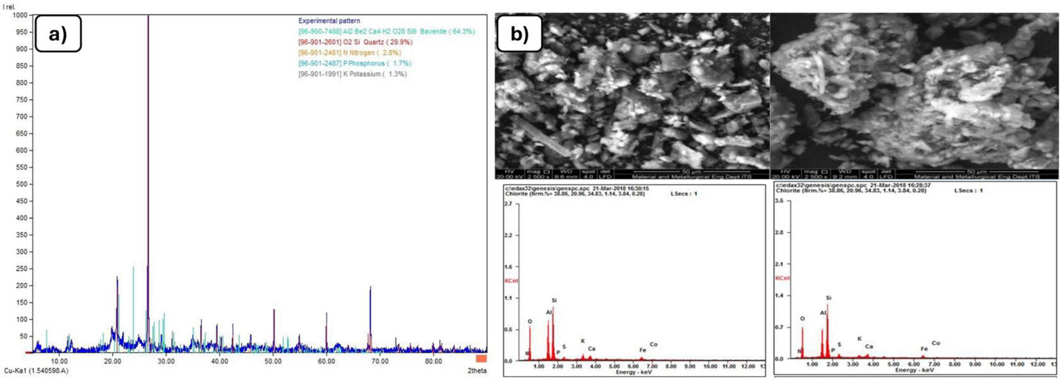


Figure 5. XRD (a) and SEM micrographs and EDS (b) spectra of peat soil after application of the engineered CCBN674 composite showing the formation of organo-mineral aggregates and the distribution of nutrient-associated elements within the treated peat soil matrix

composite application. Silicon (Si) and aluminum (Al) were detected as dominant inorganic elements, with weight percentages of 28.41% and 18.33%, respectively. These elements primarily originated from aluminosilicate minerals within bentonite and confirm the persistence of clay mineral structures within the treated soil matrix.

The relatively high silicon content is important because silicon-rich minerals may improve soil structural integrity and contribute to stabilization of nutrient adsorption sites (Gao et al., 2026; Li et al., 2026). In addition, silicon has been reported to improve plant tolerance toward abiotic stress conditions, including acidity stress and metal toxicity, although its direct role in soybean physiology under peat conditions remains complex (Bhardwaj et al., 2023; Mostofa et al., 2021; Souri et al., 2021). Oxygen (O) represented the largest elemental fraction (34.25%), reflecting the abundance of oxygen-containing mineral and organic functional groups within the peat–composite system. The coexistence of oxygen-rich organic matter and aluminosilicate minerals suggests the formation of organo-mineral associations capable of improving nutrient retention and stabilizing soil organic matter against rapid decomposition.

Nitrogen (N), phosphorus (P), potassium (K), and calcium (Ca) were also detected within the treated soil, indicating that nutrient elements from palm oil mill sludge and shell-derived limestone remained available after soil incorporation. The presence of nitrogen and phosphorus confirms that the engineered composite successfully functioned as a nutrient carrier capable of supplying essential macronutrients to the soil environment. Although potassium concentration was relatively low, the persistence of exchangeable potassium within the bentonite-rich matrix may still contribute to gradual nutrient release during plant growth. Potassium ions adsorbed within clay interlayers are less susceptible to rapid leaching compared with soluble potassium fertilizers, thereby potentially improving potassium use efficiency under peatland conditions.

The detection of calcium further supports the role of limestone in peat soil neutralization and structural stabilization. Calcium ions may reduce peat acidity, improve aggregation, and suppress the mobility of toxic elements through precipitation and ion exchange mechanisms (Huang et al., 2023; Urban et al., 1995). These interactions likely contributed to the improved soybean survival and growth observed in the field experiment. Iron (Fe) was still detected in the treated soil at 7.07%; however, its presence does not necessarily indicate phytotoxicity. Under improved pH conditions, soluble Fe species may precipitate into less toxic forms, thereby reducing their inhibitory effects on root development (Snowden and Wheeler, 1995; Violante et al., 2003; Zahra et al., 2021). Furthermore, complexation of Fe by organic compounds from palm oil sludge may additionally reduce Fe bioavailability and toxicity within the rhizosphere.

The presence of sulfur (S) may be associated with residual organic sulfur compounds and mineral-associated sulfate species originating from sludge materials. Sulfur is an essential secondary nutrient involved in protein synthesis and enzymatic activity, and its presence may provide additional agronomic benefits for soybean growth (Narayan et al., 2023). Interestingly, cobalt (Co) was also detected at low concentration. Although present only in trace amounts, cobalt may play beneficial roles in biological nitrogen fixation because cobalt is involved in vitamin B12 synthesis within symbiotic nitrogen-fixing microorganisms (Hu et al., 2021). Trace cobalt availability may therefore indirectly support soybean productivity through enhancement of rhizosphere microbial processes.

Overall, the SEM–EDS results demonstrate that application of CCBN674 substantially altered the physicochemical characteristics of peat soil through formation of integrated organo-mineral structures enriched with nutrient-bearing mineral phases. The coexistence of adsorption-active aluminosilicates, alkaline calcium sources, and nutrient-rich organic matter likely created a more stable and favorable rhizosphere environment capable of supporting nutrient retention, reducing acidity stress, and improving soybean growth under tropical peatland conditions. The findings further support the proposed multifunctional mechanism of CCBN674 as both a peat soil ameliorant and a slow-release organo-mineral fertilizer. The engineered composite not only improved soil chemical properties but also modified the microstructural characteristics of the peat matrix, thereby contributing to enhanced soil functionality and agricultural productivity.

Soybean growth performance

The field experiment demonstrated that application of the engineered organo-mineral composite substantially improved soybean growth and survival under highly acidic peat soil conditions

(Figure 6). In contrast, soybean cultivated in untreated peat soil and under conventional NPK fertilization alone failed to survive throughout the experimental period, indicating that nutrient supplementation without prior soil amelioration was insufficient to overcome the severe physicochemical limitations of the peat environment.

The complete mortality observed in control and NPK-only treatments highlights the extreme acidity and poor nutrient retention characteristics of the peat soil used in this study. Under strongly acidic conditions, root systems are highly susceptible to aluminum and iron toxicity, while essential nutrients become poorly available due to immobilization and rapid leaching (Ofoe et al., 2023; Ur Rahman et al., 2024b). Conventional soluble fertilizers applied to peat soils are therefore often ineffective because nutrients are rapidly lost before plant uptake can occur. This phenomenon explains why NPK fertilization alone was unable to support soybean establishment despite the addition of macronutrients.

In contrast, soybean treated with CCBN674 exhibited substantial vegetative development throughout the cultivation period. Plant height increased progressively from 12.01 ± 3.12 cm at week 2 to 34.33 ± 9.91 cm at week 5, indicating sustained vegetative growth under peatland conditions. Similarly, leaf number increased from 7.80 ± 3.12 to 19.67 ± 5.30 leaves during the same observation period (Table 5). The continuous increase in both plant height and leaf production demonstrates that the engineered composite successfully improved rhizosphere conditions and nutrient availability required for soybean growth.

The superior growth performance observed under CCBN674 treatment is likely associated with multiple simultaneous mechanisms operating within the peat soil system. First, the alkaline properties of shell-derived limestone effectively reduced soil acidity and minimized toxic effects associated with excessive Fe and Al solubility. Improvement of soil pH toward near-neutral conditions likely enhanced nutrient bioavailability

Figure 6. Effect of CCBN674 application on soybean development during vegetative growth stages under tropical peat soil conditions

Table 5. Number of filled soybean pods under different fertilization treatments following cultivation on tropical peat soil

Fertilizer type	Plant height (cm) at week				Number of leaves at week				Number of filled pods
	2	3	4	5	2	3	4	5	
Control	0	0	0	0	0	0	0	0	0
NPK fertilizer	0	0	0	0	0	0	0	0	0
CCBN674 fertilizer	12.01 ± 3.12	16.83 ± 5.61	26.59 ± 8.54	34.33 ± 9.91	7.80 ± 3.12	10.78 ± 3.97	14.63 ± 4.40	19.67 ± 5.30	9.23 ± 3.66
NPK + CCBN674 fertilizer	8.98 ± 2.86	12.36 ± 2.98	18.24 ± 4.39	23.20 ± 5.52	6.16 ± 2.28	9.50 ± 2.83	13.22 ± 3.29	15.94 ± 4.81	7.53 ± 4.53

and facilitated root nutrient uptake. Second, bentonite-rich mineral phases within the composite likely improved nutrient retention through adsorption-desorption interactions involving exchangeable nutrient ions. Peat soils generally possess weak mineral colloids and limited capacity to retain soluble nutrients (Osman, 2018). The presence of montmorillonite within bentonite may therefore have functioned as a nutrient reservoir capable of gradually releasing nutrients into the rhizosphere according to plant demand. This slow-release mechanism is particularly important in peat soils where nutrient losses through leaching are typically severe. Third, the organic matter derived from palm oil mill sludge likely contributed to improvement of microbial activity and nutrient cycling within the soil environment. Organic substrates may stimulate microbial mineralization processes that gradually release nitrogen and phosphorus into plant-available forms. Furthermore, organic compounds may improve root-zone aggregation and water retention, thereby supporting more stable root development under fluctuating peat moisture conditions.

The combined treatment of CCBN674 and NPK fertilizer also improved soybean growth relative to untreated soil, although overall performance remained lower than that observed for the single CCBN674 treatment. Soybean treated with the combined formulation achieved plant heights of 23.20 ± 5.52 cm and leaf numbers of 15.94 ± 4.81 by week 5. Interestingly, the combined treatment exhibited lower standard deviation values than the single CCBN674 treatment, suggesting more uniform growth among plants. The slightly lower performance of the combined treatment may indicate that excessive nutrient availability from additional NPK fertilization was not fully beneficial under peatland conditions. Rapid nutrient release from soluble NPK fertilizer may have partially disrupted the gradual nutrient stabilization mechanism provided by bentonite adsorption sites. Alternatively, excessive ionic concentrations in localized root zones may have influenced nutrient uptake balance during early growth stages.

The effect of the engineered composite became even more evident during the generative phase of soybean development. Plants treated with CCBN674 successfully produced filled pods, whereas control and NPK-only treatments failed to reach productive stages. The CCBN674 treatment produced the highest pod number, reaching 9.23 ± 3.66 filled pods per plant, while the combined treatment produced 7.53 ± 4.53 pods per plant. Successful pod formation indicates that the engineered composite not only supported vegetative growth but also maintained sufficient nutrient availability during reproductive development. Soybean reproductive stages generally require stable phosphorus and potassium availability for flowering, pod initiation, and seed filling. The ability of the composite to sustain nutrient availability throughout the cultivation cycle likely contributed to improved reproductive performance.

The findings of this study demonstrate that soil amelioration is fundamentally more important than direct nutrient addition in highly acidic peatlands. Conventional fertilization approaches may fail entirely if severe soil acidity and nutrient instability are not addressed simultaneously. The engineered CCBN674 composite effectively integrated multiple functions, including acidity neutralization, nutrient retention, gradual nutrient release, and rhizosphere stabilization, thereby enabling soybean survival and productivity under otherwise unsuitable peat conditions. Another important observation is the apparent adaptability of soybean plants to improved peat soil conditions following composite application. Visual observations indicated healthier leaf coloration, stronger stem development, and more vigorous canopy formation under CCBN674 treatment relative to other treatments. These characteristics suggest improved photosynthetic performance and overall plant physiological activity resulting from enhanced nutrient availability and reduced environmental stress.

From a broader agricultural perspective, the results indicate that engineered organo-mineral composites such as CCBN674 may offer significant potential for sustainable utilization of suboptimal tropical peatlands. The integration of mineral adsorbents, organic waste-derived nutrients, and alkaline buffering agents provides a multifunctional approach capable of addressing multiple soil limitations simultaneously. Such strategies may contribute to expansion of food crop cultivation into marginal peatland areas while simultaneously promoting sustainable recycling of agro-industrial waste materials. Overall, the soybean growth results clearly demonstrate that the engineered bentonite–palm oil mill waste composite effectively transformed highly acidic peat soil into a more productive growth medium capable of supporting both vegetative and generative soybean development. These findings confirm the strong potential of CCBN674 as a multifunctional peat soil ameliorant and sustainable organo-mineral fertilizer for tropical peatland agriculture.

CONCLUSIONS

The findings of this study demonstrate that the engineered organo-mineral composite CCBN674 successfully improved the physicochemical conditions of highly acidic tropical peat soil and supported soybean establishment under field conditions where untreated and conventional NPK-fertilized peat soils failed to sustain plant growth. The observed increase in peat soil pH from extremely acidic conditions (pH 1–3) to near-neutral conditions (pH 6.8–7.5), together with improved soybean vegetative and generative performance, indicates that the proposed multifunctional peat amelioration concept was supported under the exploratory conditions of this study. However, because the field evaluation was conducted as a preliminary field-scale investigation with limited replication, the findings should be interpreted as proof-of-concept evidence rather than definitive agronomic validation. A major contribution of this study is the successful integration of adsorption-active bentonite, nutrient-rich palm oil mill sludge, and shell-derived alkaline material into a single multifunctional organo-mineral system specifically designed for tropical peatland conditions. Unlike previous studies that generally evaluated mineral amendments, organic wastes, or liming materials separately, the present work demonstrates the feasibility of combining these components into a unified material capable of simultaneously improving soil acidity, nutrient retention, and soybean growth under extremely acidic peat conditions.

The study also provides new preliminary evidence that engineered organo-mineral composites may perform more effectively in peat soils than conventional soluble fertilization approaches alone, particularly under conditions characterized by severe acidity and weak nutrient retention capacity. The formation of organo-mineral aggregates observed through SEM–EDS analysis further suggests that structural modification of the peat matrix may contribute to improved rhizosphere conditions and nutrient stabilization following composite application. Importantly, the work addresses an existing research gap regarding the practical field-scale application of integrated mineral–organic–alkaline systems for peatland agriculture. Previous investigations have largely focused on laboratory incubation studies or single-component amendments without direct field observations under extreme peat acidity conditions. The present findings therefore provide an initial experimental basis for future development of multifunctional peat soil ameliorants derived from locally available agro-industrial waste materials. Future studies should focus on multi-season and multi-location field validation, replicated agronomic trials, long-term nutrient release dynamics, greenhouse gas emissions, heavy metal safety assessment, and mechanistic investigations involving nutrient adsorption kinetics and rhizosphere interactions. Such investigations are necessary to determine the long-term environmental sustainability and large-scale agricultural applicability of the developed composite under tropical peatland ecosystems.

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