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Increased erosion in biochar-amended soil: importance of integrating erosion control blankets and vegetation

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Abstract

Although biochar is widely recognized for enhancing various soil properties, its impact on soil erosion resistance remains unclear and sometimes shows contradictory results. The main objective of this study is to quantify the effects of corn-cob biochar amendment, both with and without erosion control blankets (ECB), as well as the influence of biochar/compost incubation time on erosion resistance of a silty sand. The study also investigates the effects of biochar on Atterberg limits, shear strength, and thermal conductivity. As biochar content increases from 0% to 20%, the liquid limit (LL), plastic limit (PL), and shrinkage limit (SL) rise by 8–10%, suggesting that biochar-amended soil (BAS) retains more water without losing strength. The addition of biochar has minimal impact on the shear strength of BAS at lower normal stresses (<45 kPa) but reduces its thermal conductivity by about 70%. Submerged jet erosion tests show that biochar alone increases soil erosion in BAS. However, when combined with ECB and vegetation, erosion is significantly reduced (up to 39%). Overall, this study underscores the importance of utilizing biochar in combination with ECB and such vegetation as ruzi grass to mitigate soil erosion in the silty sand.

Keywords: tropical soil, biochar, erosion, erosion control blanket, thermal conductivity, submerged jet erosion test

Article Highlights

- Biochar alone increases soil erodibility, yet combining it with erosion control blankets (ECB) and ruzi grass cuts erosion by up to 38%.
- Atterberg's limits of biochar-amended soil (BAS) tend to increase by 8–10%, suggesting that BAS can retain more water than bare soils without loosing its strength.
- Biochar has minimal impact on soil shear strength at shallow depths but slightly reduces it under higher pressures.
- With increased biochar content, thermal conductivity significantly drops.

1. Introduction

Soil erosion is recognized as a critical environmental issue, compromising soil fertility, agricultural sustainability, and posing risks of natural disasters [44, 54, 70, 71]. Various soil cover systems (e.g., capillary barrier systems, erosion control blankets, and multilayer covering systems) have gained considerable attention for mitigating soil erosion in infrastructure as well as minimizing infiltration in waste disposal facilities [19, 57, 61, 68, 75]. Among these, vegetation-based systems—often classified as a soft engineering approach—are particularly notable. Numerous studies have shown that vegetation plays an important role for such cover systems in preventing soil erosion [45, 64] improving slope stability [15, 58], and offering ecological values as well as other benefits [53]. Previous studies show that root-induced suction and root mechanical reinforcement play important roles in benefiting slope stability [68, 56, 52].

Soils that are typically considered suitable for engineering purposes often lack the essential nutrients and have a densely compacted structure, which can impede rapid vegetation establishment [28, 30]. Once the soil nutrients are depleted, plants may wither, contributing to root decay over time. This deficiency in vegetative cover and the potential for root decay, renders these soils particularly susceptible to erosion and stability issues [83, 46]. Biochar amendments present a potential solution to this issue. Biochar, a porous, carbon-rich material produced via pyrolysis—a process that heats biomass, such as agricultural or forestry residues, under high temperatures with minimal oxygen—has been recognized for its beneficial effects on soil structure, water retention, and nutrient availability [47]. Recent studies have demonstrated biochar's capacity to improve root strength, supporting enhanced root growth in agricultural crops like rice and maize [51, 18, 26] suggesting its applicability for improving root reinforcement for slope stabilization. Accordingly, biochar is now being explored for its utility in improving vegetated soil cover systems for erosion control along infrastructure, such as highways in Thailand [45].

Due to its high porosity and large specific surface area (SSA), biochar provides a favorable environment for microbial activity, which can significantly improve soil fertility and ecosystem health [74]. The pH of biochar is largely influenced by the type of feedstock used and the pyrolysis conditions. For instance, biochars derived from corn cobs and maize stalks often have a higher pH compared to those produced from manure or other nitrogen-rich feedstocks. This higher pH can help mitigate soil acidity prevalent in tropical areas, thereby improving soil conditions for plant growth [24, 26, 38]. Biochar-amended soil (BAS) has also gained popularity in geotechnical and geo-environmental applications due to its favorable characteristics, such as enhanced water retention, nutrient richness, reduced irrigation requirements, and potential for carbon sequestration [1, 40, 57, 78, 79, 80, 81, 42, 63, 73, 49, 76, 82].

In the field of geotechnics, considerable research has focused on biochar's impact on altering the soil-water characteristics curve [14, 57, 79, 38], water permeability [81, 27, 20], infiltration rate [29, 21, 10], and mechanical strength [66]. Reddy et al. [63] demonstrated that increasing amendment rates (from 5 to 20% biochar) increased hydraulic conductivity, reduced compressibility and increased shear strength. As the size of biochar particles decreased from 0.85mm to 0.425mm, the compressibility increased. Overall, they argued that by increasing the permeability of biochar-amended cover soil, gases like oxygen (O_2) would be allowed to diffuse more easily. This boosts aerobic microbial activity, enabling better methane (CH_4) oxidation and potentially improving the efficiency of the landfill cover in reducing greenhouse gas emissions.

A study by Kumar et al. [49] reported minimal effects of biochar (5% and 10%) on erosion in compacted silty sand, with erosion decreasing as water content rose due to particle reorientation along the compaction curve. They also demonstrated that the addition of biochar reduced erosion in the dry state, while the opposite effect was observed in the wet state. Despite these insights, the specific role of biochar in mitigating soil erosion and preventing rainfall-induced landslides in tropical residual soils has received less attention. Most field studies on biochar-amended soil (BAS) focus on erosion potential from an agricultural perspective [43, 39, 25, 2, 67, 50]. The wettability (i.e., hydrophobicity or hydrophilicity) of biochar, as noted by Das et al. [23], is significantly influenced by the feedstock type and the production technology used. This property can also potentially impact the erosion behavior of BAS.

Erosion control is likely achieved not solely through biochar application but through the combined effects of biochar-enhanced root reinforcement and increased plant cover. Prats et al. [60] found that straw-biochar mulching mitigated post-fire soil erosion under extreme rainfall. The benefits of biochar in promoting vegetation growth often become more pronounced in the second or third year after application [59]. However, field evidence from bioengineered slopes in Thailand suggests that biochar-amended soil, when combined with compost, can significantly enhance vegetation growth and effectively control erosion even within the first year [45]. Despite this, during the early stages of plant establishment, particularly within the first month of slope cover installation, slopes remain more vulnerable to erosion due to incomplete vegetation cover. Consequently, additional cover such as erosion control blanket can be used to mitigate the erosion risk during this early period. While biochar-amended soil (BAS) shows promise, detailed experimental data quantifying its erosion resistance, especially when used as bared soil or alongside erosion control blankets during early plant establishment, are still limited. In addition, excessive application of biochar can have negatively impact on plant growth by overly increasing soil pH, altering nutrient availability, and weakening the engineering properties of biochar-amended soil (BAS) in some cases as summarized by Lin et al. [48] and Brtnicky et al. [17].

This study investigates the novel application of the submerged jet erosion test to evaluate the erosion resistance of biochar-amended silty sand collected from an erosion-prone highway slope in Northern Thailand. It uniquely examines the combined effects of corn-cob biochar and erosion control blankets (ECB), along with vegetation (*Urochloa ruziziensis* or ruzi grass), on erosion mitigation. Biochar was incorporated at varying percentages (3.5% to 20% by weight) to assess its impact under different treatments, including biochar alone, biochar with ECB, and biochar with ECB and vegetation. The study also explores the incubation effect of biochar with compost on soil erosion potential, while evaluating saturated shear strength and thermal conductivity. By integrating the jet erosion test with these innovative treatment combinations, this research offers new insights into optimizing biochar-based soil stabilization strategies, particularly during early slope stabilization stages.

2. Materials and methods

2.1. Tropical silty sand

The study utilized a silty sand (SM), classified according to ASTM D2487-11 [7], which was collected from a 45° back slope of Highway No. 1192 (18°3036.57 N, 98°2550.18E) in Chiang Mai province, Northern Thailand [45, 38]. The material is derived from weathered granitic rock, which generally decomposes into silty and clayey sand (SM and SC). Being highly erodible (Fig. 1(a)), the slope suffered severe rills, sheets, and gullies especially at the toe. This toe erosion often leads to shallow (<1m deep) translational soil slides along the back slope of this highway route. Soil samples were collected from the topsoil layer (upper 1 meter) near the toe of the slope. These samples were air-dried and homogenized before specimen preparation. The soil composition was 1.8% gravel (>4.75 mm), 58.2% sand (0.075 to 4.75 mm), 21.8% silt (0.005 to 0.075 mm), and 18.2% clay (<0.005 mm). The Atterberg limits were determined as follows: the liquid limit (LL) was 39.8%, the plastic limit (PL) was 26.1%, and the plasticity index (PI) was 13.68. This sandy soil composition is typical of landslide-prone areas in Thailand and other tropical regions [62, 58, 55].

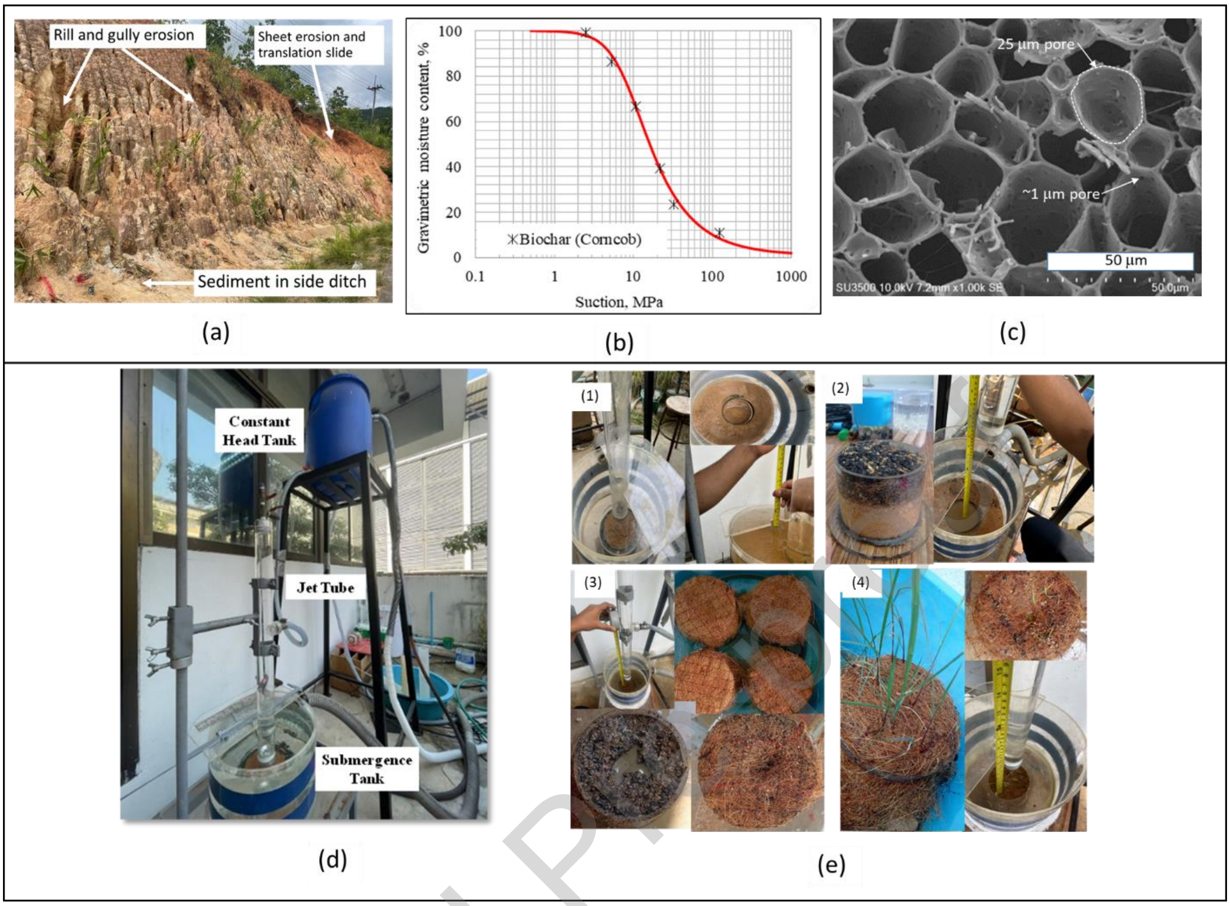

Fig. 1. Information on materials and test methods, (a) erosion problem at the soil sampling site; (b) biochar water-retention curve; (c) biochar image from scanning electron microscopy (SEM); (d) submerged jet test device in this study; and (e) photographs of samples and the submerged jet test: (1) bare soil; (2) biochar amended soil; (3) soil + biochar + ECB; (4) soil + biochar +ECB + ruzi grass (Note: biochar was used with variable concentrations of 3.5, 5, 10, and 20% by weight)

2.2 Biochar properties

The biochar specimen was obtained from the Warm Heart Foundation situated in Chiang Mai Province, Thailand, which was typical of those produced by local farmers in Northern Thailand [38]. The biochar was produced from corncob feedstock using top-lit updraft (TLUD) technology. Adeniyi et al. [3] observed that the use of TLUD technology resulted in the production of high-quality biochar with various usages, e.g. soil amendment, adsorbent for wastewater treatment. The previous study by [38] presents the laboratory data in detail about the physical and chemical properties of this corncob biochar.

To quantify the water retention capacity of biochar, an investigation was carried out to determine the relationship between its gravimetric water content and water potential, using the WP4C Potentiameter for measurements. Fig. 1(b) shows that biochar can retain up to 67% moisture content, even under a suction pressure of 10 MPa. This finding aligns with the scanning electron microscopy (SEM) image in Fig. 1(c), which reveals numerous pores, ranging in size from about 1 to 25 μm in diameter. These pores significantly enhance water retention. The honeycomb-like arrangement of the pores creates a network that not only holds water efficiently but also provides a habitat for microbial activity, which in turn promotes plant growth. The specific gravity of the biochar particles was measured at 1.48, and the bulk density was 4.36 kN/m³. Further details on the chemical properties of biochar are available in [38].

2.3 Compost properties

Mixing biochar with soil alone may not yield immediate benefits for plant growth. As highlighted by several previous studies [12, 13, 24], the incubation and microbial inoculation of biochar can enhance soil microbial activity and promote plant growth, even in challenging environments. In this study, commercially available compost was utilized for biochar inoculation, and its properties were analyzed as presented in Table 1. The compost had a pH of 7.94 (measured at a 1:2 ratio of compost-to-water), indicating a near-neutral condition, which is conducive to supporting a wide range of plant species. The electrical conductivity (EC) of 12.86 ds/m, measured at a 1:10 ratio of compost-to-water, indicates a moderate level of soluble salts, necessitating cautious application to prevent potential soil salinity issues. With a high organic matter content of 46.65%, the compost serves as a rich source of carbon, enhancing soil fertility, structure, and microbial activity. The total nitrogen content of 1.75% underscores the compost's potential to supply plants with a readily accessible nitrogen source, supporting vital growth processes. Furthermore, the compost contains 1.5% total phosphorus (in the form of P_2O_5) and 0.95% total potassium (in the form of K_2O), essential nutrients for plant development, root formation, and overall metabolic functions.

Table 1 Basic properties of compost in this study

Property	Measurement	Value	Unit
pH	pH (1:2)	7.94	-
Electrical Conductivity	EC (1:10)	12.86	ds/m
Organic Matter	OM	46.65	%
Total Nitrogen	Total N	1.75	%
Total Potassium	Total P_2O_5	1.5	%
Total Phosphorus	Total K_2O	0.95	%

2.4 Erosion control blanket

An erosion control blanket (ECB) functions like a protective cover made of natural or synthetic materials that is commonly placed on sloping ground to prevent soil from washing away due to wind or water. It helps keep the surface soil in place, allowing plants to grow and establish strong roots, which further stabilize the soil to a greater depth. Additionally, the blanket helps regulate soil temperature and moisture, similar to the effects of mulching, thereby promoting plant growth. In this study, the erosion control blanket ECB (SS model) from Green Ground Solutions co. Ltd was used. This product is made from natural coconut fibers sandwiched between two layers of reinforcing polypropylene netting, which resist tensile forces when applied to slopes. In Thailand, it is common practice to use this type of ECB in combination with ruzi grass (*Urochloa ruziziensis*) seed sowing or vetiver grass (*Chrysopogon zizanioides*) sapling planting for erosion control and slope stabilization. Further details on the engineering properties of the ECB are provided in Table 2.

Table 2 Engineering properties of erosion control blanket (ECB)

Item	Test method	ECB (SS model)
Material type		Coconut fiber
Thickness (mm)	[9]	3.4
Mass per unit area (g/m^2)	[6]	311
MD Tensile strength (kN/m)	[8]	4.1
CD Tensile strength (kN/m)	[8]	2.2
MD Elongation (%)	[8]	18
CD Elongation (%)	[8]	17

Machine Direction (MD) and Cross-machine Direction (CD)

2.5 Submerged Jet Test

In numerous studies, soil erosion parameters, such as critical shear stress and erosion rate have been assessed using various techniques. Among these methods, the submerged jet test (JET - Jet Erosion Test) stands out for its applicability in both in situ and laboratory settings [32, 34, 36, 37, 69]. Based on the time-dependent variation in the maximum scour depth induced by an impinging jet, Hanson [33] developed a soil-dependent jet index that can be used to characterize erosion resistance of soil in earth structure.

The JET device used in this study consists of three main components (Fig. 1(d)): a submergence tank, a jet tube, and a constant head tank. It generates a circular jet with uniform velocity, producing radial shear stress on the soil surface, which leads to the formation of a scour hole. Various treatments were considered in the testing programme of the submerged jet tests. Key parameters systematically varied include soil density, biochar concentration, the use of erosion control blankets (ECBs), the incorporation of ruzi grass, and biochar-compost incubation periods of 0, 21, and 42 days, (the incubation process will be detailed later in this study). Soil density was varied across four levels (13.1, 15, 17, and 19 kN/m^3) with a fixed 5% biochar concentration (by weight). Biochar concentrations ranged from 0% to 20% (by weight), maintaining a fixed soil density of 13.1 kN/m^3 to represent the field dry density. In this study, the biochar content (*Bc*) is defined as the ratio between biochar mass and bare soil mass, both in an air-dried condition. This range of biochar content reflects typical application rates commonly used in practice. Treatment combinations included (a) soil + biochar (varied concentrations) with a fixed density of 13.1 kN/m^3; (b) soil (varied density) + 5% biochar; (c) soil + biochar + ECB + ruzi grass, and (d) soil + biochar + ECB. Fig. 1(e) shows photos of specimens during the submerged erosion tests with different treatments. Notably, the 5% biochar treatment was selected for further investigation of density and incubation time, based on findings from a previous study (Hossain et al. [38]), which identified this concentration as optimal for improving water retention and increasing suction stress.

In this experiment, soil specimens measuring 10 cm in diameter and 15 cm in height (including a biochar-amended soil layer of approximately 5 cm in height on the top), were meticulously prepared using the static compaction method to achieve a dry unit weight of 13.1 kN/m^3. This unit weight represented field conditions, corresponding to 69% of the standard Proctor compaction of the bare soil and simulated the commonly achievable dry unit weight of soil fill within the geocell compartment of a capillary barrier system in Thailand [45]. For the ruzi grass treatment, approximately 4 seeds per cm^2 were evenly distributed across the upper soil surface, and tests were conducted 10 days after sowing to represent the critical condition of slope surface after installation of erosion control system.

The experimental setup of the JET erosion test involved securely installing the soil sample in a mold designed for a submerged jet tank. An acrylic plate was used to cover the soil surface for protecting erosion before the start of each test. The water, from the head tank connected to the jet tube, was filled to the submerged tank until the constant head (water level from head and submerged tank) was achieved. The JET erosion test was initiated by removing the acrylic plate, beginning a systematic time count for depth measurements at intervals of 1, 2, 4, 8, 15, 30, 45, and 60 minutes. Erosion parameters were calculated using the scour-depth solution method, developed by [22].

2.6 Incubation Process

In this study, a laboratory experiment was conducted to assess the impact of the incubation period of a biochar/compost mixture on erosion mitigation. The incubation period was designed to stimulate microbial activity within the biochar/compost mixture, thereby enhancing soil fertility before the introduction of ruzi grass seeds. During the incubation process, a careful blend of air-dried soil, biochar, and compost was carefully prepared, adhering to a defined ratio of 1:1:20 by weight for biochar, compost, and soil, respectively. The manual mixing of these components spanned 20 minutes, emphasizing the importance of achieving a homogeneous mixture. To this blend, tap water was carefully added, ensuring that lump formation was minimized, and the moisture content was adjusted to 34% volumetric water content (26%

gravimetric water content) equal to the water holding capacity based on the soil-water retention curve (SWRC) at 33 kPa suction, as shown in the previous study [38]. The resulting moist soil or soil-biochar mixes were placed in lid-covered plastic buckets and underwent incubation for designated periods of 0, 21, and 42 days in a dark environment with an ambient temperature range in the laboratory of about 25 ± 4 °C. The incubation periods of 21 and 42 days were chosen to represent conditions during the early stages of plant establishment on bioengineered slopes. This period is critical for evaluating the effectiveness of biochar-amended soils before vegetation is fully established. Throughout the incubation period, the buckets were loosely capped, and weekly aeration, accompanied by brief cap removal, was implemented. This facilitated an optimal incubation environment. Regular weight measurements were conducted, and water additions were made as necessary to sustain the 34% (volumetric water content) water holding capacity.

3. Results and discussion

3.1 Effects of biochar on index properties

The basic index properties of BAS are illustrated in Fig. 2(a). It can be observed that as the percentage of biochar increases from 0% (bare soil) to 20%, most of the Atterberg limits—liquid limit (LL), plastic limit (PL), and shrinkage limit (SL)—tend to increase, with the exception of the plasticity index (PI), which shows a fluctuating trend. Sharma and Bora [72] demonstrated that the undrained shear strength of a soil at the liquid limit is around 1.7 kN/m². The approximately 10% increase in the LL with 20% biochar addition (Fig. 2(a)) suggests that the material can retain about 10% more water without losing its strength. A similar trend is observed for the plastic limit (PL), which defines the moisture content at which soil transitions from a semi-solid to a plastic state, corresponding to an undrained shear strength of approximately 170 kN/m² [72]. With a 20% biochar amendment, the BAS also shows about a 10% increase in moisture content at the PL state.

Similarly, the shrinkage limit (SL) increases by approximately 8% with the addition of 20% biochar. Since SL represents the water content below which soil no longer shrinks as it dries, this increase suggests that the BAS can retain more moisture in this state. Interestingly, the plasticity index (PI) initially decreases as biochar content increases to 10%, but then returns to a similar value when the biochar content reaches 20%. The PI, which indicates the range of water contents producing a 100-fold variation in undrained shear strength [11, 72], appears to be only slightly affected by biochar addition. The highly porous nature of biochar likely contributes to the increase in Atterberg limits, signifying an enhancement in the soil's water retention capacity, as also noted in a previous study by [38]. Furthermore, the plasticity chart shows that the fine contents of all biochar-amended soils fall within the low-to-medium plasticity silt classification, suggesting that this rate of biochar addition does not significantly alter the fundamental plasticity characteristics of the soil.

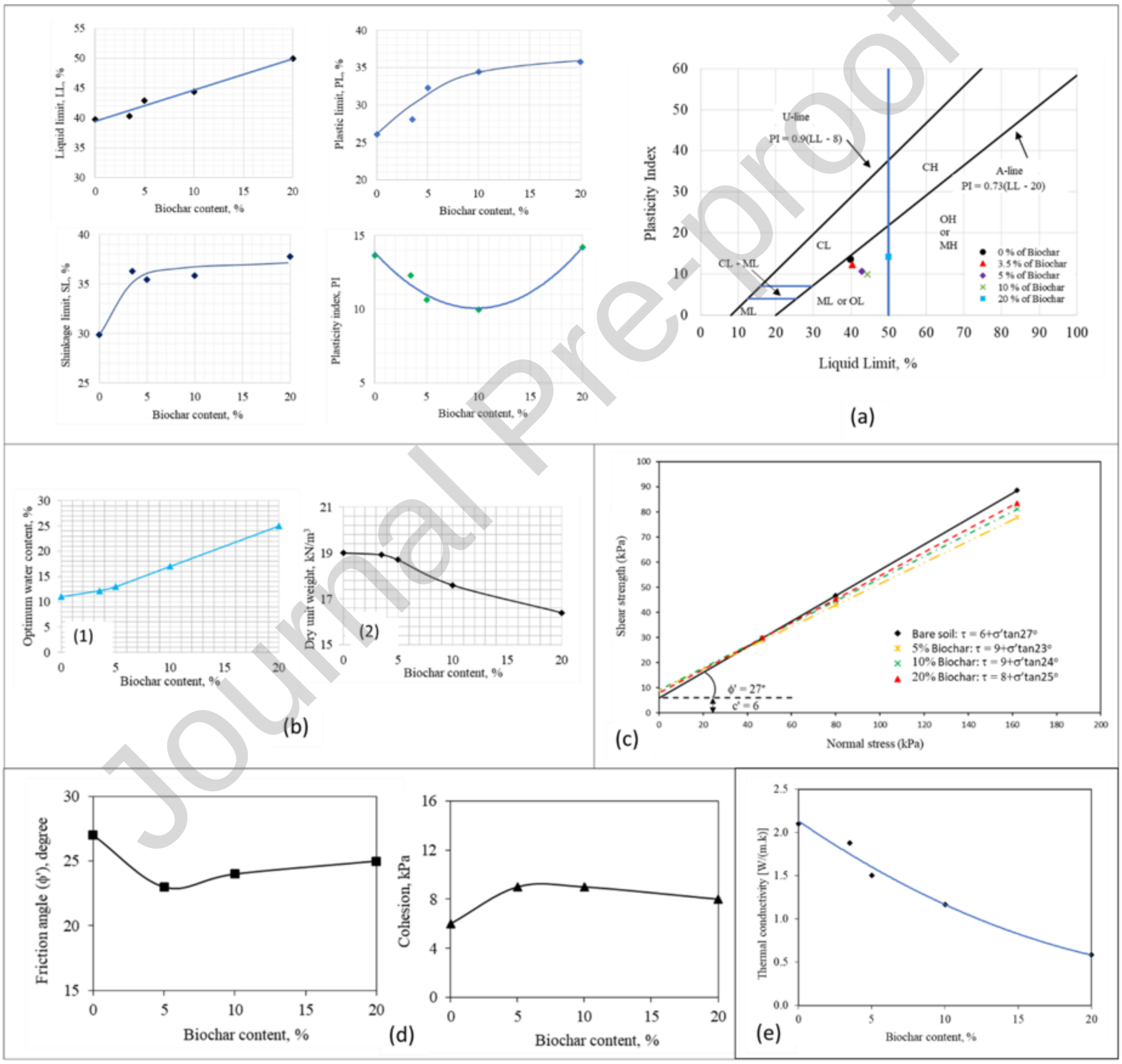

Fig. 2. Properties of biochar-amended residual silty sand (SM): (a) Atterberg's limits; (b) compaction properties; (c) saturated failure envelopes from direct shear tests; (d) variations of angle of friction and cohesion with biochar contents; (e) thermal conductivity

Fig. 2(b) shows the influence of biochar addition on compaction behaviour of the soil under Standard Proctor condition in terms of the optimum moisture content (OMC) and the maximum dry unit weight. Due to the biochar's greater water absorption, the optimum moisture content (OMC) of BAS increases from 11% to 25%. The addition of biochar leads to a decrease in the maximum dry unit weight (from 19 to 16.4 kN/m^3) as a result of the lower specific gravity of the biochar [38].

3.2 Effect of biochar on saturated shear strength

This study examined the shear strength of saturated bare soil and soil amended with varying concentrations (5%, 10%, and 20% by weight) of biochar, using direct shear tests (constant pressure) in accordance with ASTM D 3080 [4]. The tests were conducted at effective normal stresses ranging from 45 to 160 kPa in drained conditions (slow tests) with a shearing rate of 0.025 mm/min. Fig. 2(c) & (d) presents the failure envelopes and the relationships between friction angle (ϕ', in degrees) and cohesion (kPa) as a function of biochar content (%). After the addition of 5% biochar, the friction angle decreases by up to 4 degrees, while cohesion increases by approximately 3 kPa. This could be attributed to the compressibility (crushability) of biochar particles, which becomes more pronounced at higher normal stresses (160 kPa), collectively leading to a reduced friction angle and an increase in cohesion. This effect is lessened as biochar content increases to 20%. A deeper understanding of this mechanism requires further investigation into the microstructure of the biochar-amended soil (BAS) at varying biochar concentrations, which will be explored in future studies. Overall, Fig. 2(c) suggests that at lower normal stresses (<45 kPa), typical of soil cover systems on slopes, the addition of biochar has minimal impact on the shear strength of BAS.

3.3 Effect of biochar on thermal conductivity of soil

Thermal conductivity of biochar-amended soil was determined using the thermal needle probe test following ASTM-D5334-00 [5]. This thermal property characterization is relevant in this study given the potential increase in ground temperature fluctuation due to global warming, posing risks to soil stability. The soil specimens were soaked in water for several days prior to testing. The calculation of the thermal conductivity, λ, is presented as follows.

$$\lambda = \frac{Q}{4\pi(T_2 - T_1)} ln \frac{t_2}{t_1} \tag{1}$$

$$Q = \frac{I^2R}{L} = \frac{EI}{L} \quad (2)$$

; where E is the measured voltage (V), I is the current flowing through heater wire (A), L is the length of the heater wire (m), λ is the thermal conductivity [W/(m.k)], Q is the power consumption of heater wire in watts per unit length that is assumed to be equivalent of heat output per unit length of wire, R is the total resistance of heater wire (Ω), T_1 is the initial temperature (k), t_1 is the initial time (s), T_2 is the final temperature (k), and t_2 is the final time (s).

Fig. 2(e) illustrates a clear inverse relationship between biochar content and thermal conductivity. As the biochar percentage increases from 0% to 20%, thermal conductivity decreases significantly from 2.10 W/(m·K) to 0.58 W/(m·K). This decline in thermal conductivity aligns with findings from previous studies [77, 84, 85], which attribute the thermal insulating properties of biochar to its porous structure and the inherently low thermal conductivity of char particles, both of which inhibit heat transfer. Such thermal insulation can be beneficial for plant growth by mimicking the effects of mulching, which helps regulate soil temperature. This effect may become even more advantageous as climate change increases the risk of heatwaves, reduced vegetation cover, increasing diurnal ground temperature fluctuations. Furthermore, this property has potential applications in engineering fields that require efficient thermal management, such as underground cable installations and geothermal systems.

3.4 Effect of biochar on soil erosion

Fig. 3(a) illustrates erosion depth over time during submerged jet erosion tests on biochar-amended soil (BAS) with biochar alone. As shown in Fig. 3(a1), the early stages of testing (during the first 8 minutes) reveal that the addition of biochar alone increases soil erosion rather than mitigating it. This can be attributed to the lightweight nature of biochar particles and the absence of significant soil aggregation. Soil aggregates facilitate a stable soil structure that resists disintegration under raindrop impact and erosive forces (Rajamanthri et al. [62]). This aggregate stability minimizes the detachment and transport of soil particles, reducing erosion. However, the benefit of biochar in enhancing soil aggregate stability was expected to occur only after a period of incubation up to six months driven by microbial activity (Han et al. [31]) and root reinforcement. Notably, Kumar et al. [49] also found that adding biochar (5% and 10% by weight) increased erosion in wet conditions. This challenge is recognized in practice, where it is common to either cover BAS with the erosion control blanket or contain BAS within geosynthetic structures, such as geocells, particularly for cover systems on steep slopes [45]. It is interesting to note that after 15minutes of testing, the difference in erosion depth between biochar content became insignificant. This is attributed to a significant portion of the biochar being washed away during the test. Notably, the thickness of the biochar-amended soil (BAS) layer at the top surface of the specimen was 50 mm, while the eroded depth reached approximately 40 mm after 15 minutes of testing. This indicates that over 80% of the biochar content in the top layer would have likely been removed by that time.

However, maintaining a constant biochar content of 5% while increasing the dry density from 13 to 19 kN/m³ clearly reduces soil erosion by approximately 4% to 16%, as shown in Fig. 3(a2). This suggests that one effective strategy to counter the initial adverse effect of biochar on erosion could be to densify the BAS, thereby enhancing its erosion resistance. Fig. 3(b). shows the effect of utilizing erosion control blanket (ECB) with or without ruzi grass in reducing erosion of the BAS with biochar content ranging from 3.5% to 20%. It is noted that these tests were conducted on BAS compacted at a consistent dry unit weight of 13 kN/m³. Clearly, by covering the BAS with ECB, the erosion depth reduced significantly by 25% to 31% as compared to bare soil. When ruzi grass was incorporated with ECB (at 10 days old), further reduction in erosion depth could be observed across all percentages of biochar content. As a combined soil cover including biochar, ECB and ruzi grass, the system showed a reduction in erosion depth from 36% to 39% when compared to bare soil (see Fig. 3(b).

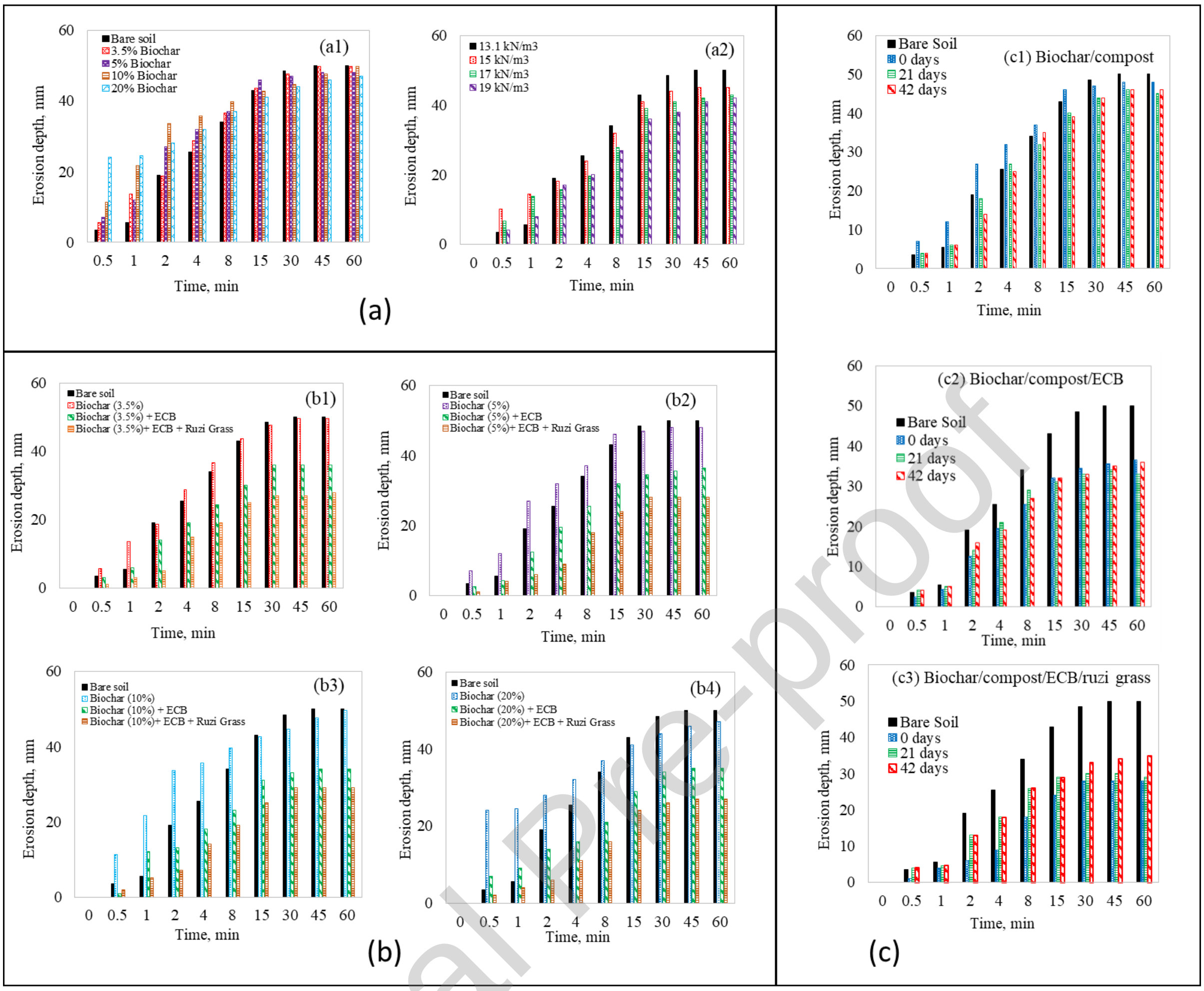

Fig. 3. (a) erosion depth with time in the submerged jet erosion tests on BAS with biochar alone: (a1) 13 kN/m^3 dry unit weight with biochar contents of 3.5%, 5%, 10%, and 20% by weight; (a2) 5% biochar with dry unit weight ranging from 13 to 19 kN/m^3; (b) erosion depth with time of BAS with and without ECB and ruzi grass (10 days old): (b1) 3.5% biochar (b2) 5% biochar (b3) 10% biochar and (b4) 20% biochar; (c) erosion depth with time of BAS with incubation effect: (c1) 5% biochar and compost; (c2) 5% biochar & compost + ECB; (c3) 5% biochar & compost + ECB + Ruzi grass

3.5 Incubation effect

The incubation effect of biochar and compost over 21 and 42 days was illustrated in Fig. 3(c). The jet erosion tests were carried out using the same procedure as decribed previously but with a mixture of 5% biochar and 5% compost at a dry density of 13 kN/m³ and incubated for 21 and 42 days. It should be noted that no plants were introduced at the incubation stage. For the treatment with ruzi grass, the seeds were sown after the incubation period, on the upper surface of the specimen and allowed to grow for 10 days before jet erosion testing. This condition represents the early stage of plant establishmen in erosion control work for slopes.

As shown in Fig. 3(c1), prolonging the incubation time for biochar-compost combination could help further reduce the erosion depth. However, for biochar-compost-ECB (Fig. 3(c2)) and for biochar-compost-ECB-ruzi (Fig. 3(c3)), the benefit of prolonging the incubation time is not so clearly seen. Still, utilizing the ECB with biochar/compost leads to a considerable decrease in erosion depth as compared to bare soil in both cases. It is thus clear that a greater emphasis should be placed on utilizing the ECB for biochar-soil amendment in slopes rather than solely extending the incubation time. It is acknowledged that the ruzi grass used in this study was only 10 days old, and its root reinforcement effect was likely not yet established. However, this early stage of plant establishment is critical, and the ECB can play a pivotal role in erosion control during this period, when the plant roots are not yet effective.

3.6 Erodibility-coefficient (k_d) and critical shear stress (τ_c) of BAS

The erodibility coefficient (k_d) and critical shear stress (τ_c) of BAS, for all treatments, were calculated using Equation 3 as follows;

$$\varepsilon_r = k_d(\tau_o - \tau_c)^a \tag{3}$$

;where ε_r is the rate of erosion (m/s), k_d is the erodibility coefficient (m^3/N.s), τ_o is the developed boundary shear stress (Pa), τ_c is the critical shear stress (Pa), and a is an empirical exponent assumed to be unity as indicated in a number of previous studies [32, 41]. The procedure described by [22, 69] was followed for the calculation of τ_c and k_d.

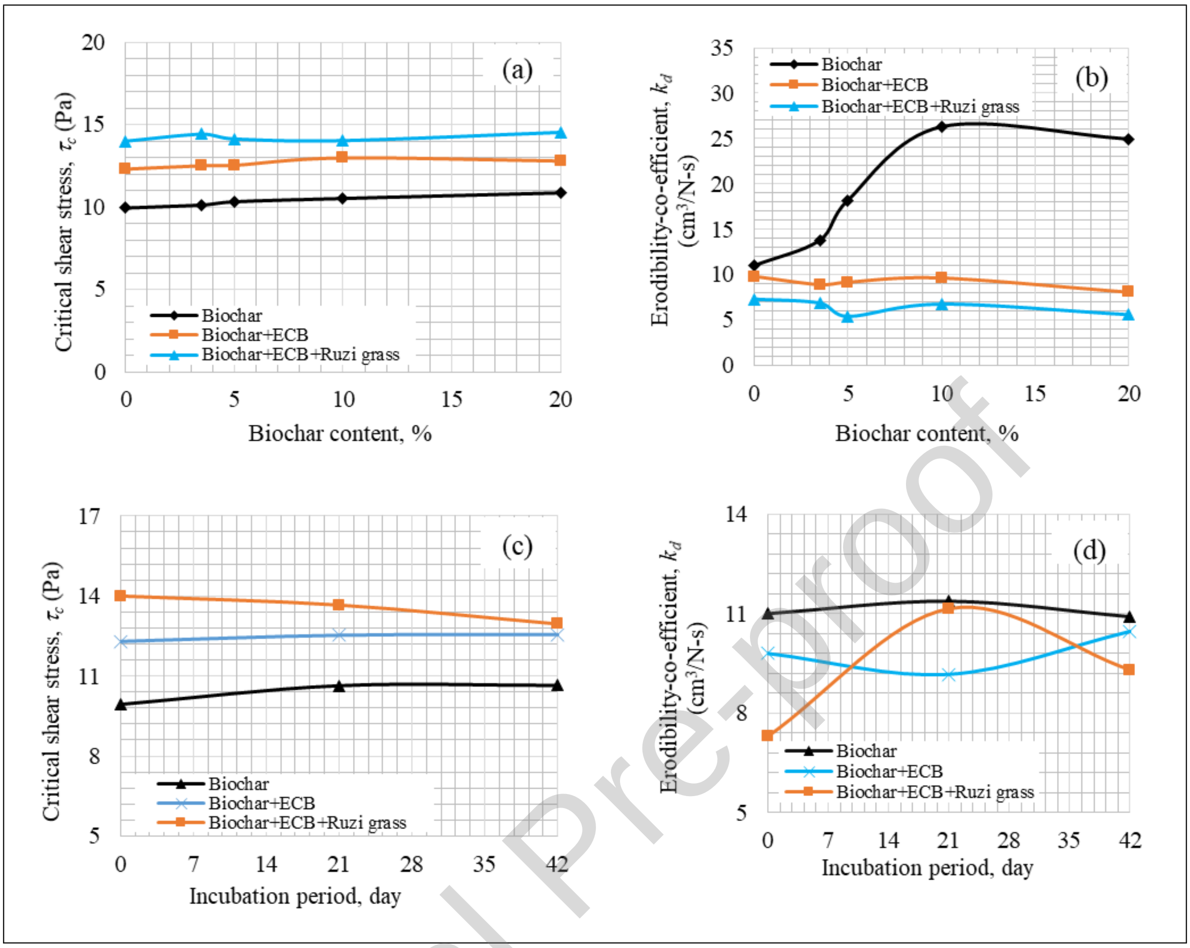

Fig. 4. Erodibility-coefficient (k_d) and critical shear stress (τ_c) of BAS: (a) critical shear stress vs biochar content; (b) erodibility-coefficient vs biochar; (c) critical shear stress vs incubation period; (d) erodibility-coefficient vs incubation period.

Fig. 4 illustrates the relationship between critical shear stress (τ_c) and the erodibility coefficient (k_d) for both soil and BAS under various treatments. The bare soil is indicated as BAS with zero % biochar content, serving as a baseline that exhibits high erosion rates, low critical shear stress and its susceptibility to erosion. As shown in Fig. 4(a), the critical shear stress (τ_c) increases very slightly with biochar content, for all three different treatments: Biochar, Biochar+ECB, and Biochar+ECB+Ruzi grass. The BAS alone without ECB demonstrated the lowest shear stress values being around 10 Pa, regardless of the biochar content. The Biochar+ECB treatment exhibited slightly higher shear stress values of around 12-13 Pa. The Biochar+ECB+Ruzi grass treatment demonstrated the highest shear stress values, ranging from approximately 13 to 16 Pa.

Fig. 4(b) displays the relationship between biochar content (%) and the erodibility coefficient (k_d). The Biochar treatment showed a significant increase in the erodibility coefficient with increasing biochar content, rising from around 10 $cm^3/N{\cdot}s$ at 0% biochar to approximately 25 $cm^3/N{\cdot}s$ at 20% biochar. It is evident that the soil becomes more erodible as biochar content increases when used without ECB. This again suggests that biochar may not be a standalone solution for erosion prevention. It must be used in conjunction with other erosion control measures. Conversely, the Biochar+ECB treatment demonstrated a stable erodibility coefficient, maintaining values between 9 and 11 $cm^3/N{\cdot}s$. The Biochar+ECB+Ruzi grass treatment showed the lowest and most stable erodibility coefficients, ranging from about 6 to 8 $cm^3/N{\cdot}s$, indicating that this combination provided the best resistance to erosion regardless of biochar content.

Fig. 4(c) illustrates the change in the critical shear stress (τ_c) over an incubation period of 21 and 42 days of BAS with biochar and compost. The critical shear stress was slightly above 10 Pa and showed a gradual increase, stabilizing at around 11 Pa by the end of the incubation period. The Biochar+Compost+ECB treatment maintained a stable critical shear stress of approximately 12–13 Pa throughout the 42 days. The Biochar+Compost+ECB+Ruzi grass treatment initially had the highest shear stress at around 14 Pa but showed a slight decrease over the incubation period, ending just above 13 Pa. This indicates that although the combination of ECB and Ruzi grass initially enhanced the soil's shear stress, a minor decline occurred over time, potentially due to biochemical influences on the ECB. Similarly, as shown in Fig. 4(d), the erodibility coefficient remained consistent over the incubation period for the Biochar+Compost treatment, while fluctuations were observed in the ECB and Ruzi grass treatments. The underlying causes of these variations are unclear and warrant further investigation.

Overall, this study highlights a key insight for practical applications: using biochar alone does not enhance the erosion resistance of silty sand and may even have adverse effects, as demonstrated by the jet erosion test. A novel recommendation from our findings is that to maximize the benefits of biochar as a soil amendment for erosion control, it should be combined with erosion control blankets (ECB) and vegetation, such as ruzi grass. However, it is important to note that these observations are specific to silty sand and may not be directly applicable to other soil types, such as clays. Further research is necessary to evaluate the broader applicability of these findings across different soil types.

The critical shear stress values obtained from the erosion tests can serve as a guideline for understanding the effects of biochar and erosion control blankets (ECB) on erosion resistance. However, the severity of erosion expected in the field would also depend on various factors, such as flow velocity, duration, slope gradient, and site-specific conditions. A potential approach to defining threshold levels for in-situ erosion severity could involve criteria similar to those proposed by Briaud et al. [16]. This approach will be further explored in our future studies.

4. Conclusions

In this study, the erosion resistance of corn-cob biochar soil amendment was investigated on a tropical silty sand at varying biochar concentrations ranging from 0% (bare soil) to 20% by weight, using the submerged jet erosion test. A total of 32 submerged jet tests were conducted to examine the influence of various factors on the erosion resistance including soil unit weight, biochar content, the use of erosion control blanket (ECB), ruzi grass and biochar/compost incubation period. The effect of biochar on basic properties of the soil, namely, Atterberg's limits, shear strength, and thermal conductivity were also studied. Based on the experimental results, the following conclusions can be reached.

1. **Effect of biochar on the fundamental properties of tropical silty sand:** As the biochar content increases from 0% (bare soil) to 20%, the liquid limit (LL), plastic limit (PL), and shrinkage limit (SL) tend to increase by 8–10%. This suggests that biochar-amended soil (BAS) can retain more water than bare soil without a significant loss of strength. However, the plasticity index (PI) shows a fluctuating trend with the addition of biochar. The highly porous nature of biochar also leads to an increase in optimal moisture content and a reduction in maximum dry unit weight in compaction tests.
2. **Mechanical and thermal behaviour of BAS**: At the lower normal stresses (<45 kPa), which represents the shallow depth of soil cover on slopes, the addition of biochar has minimal influence on the shear strength of BAS. However, a subtle decrease in shear resistance was noted in biochar-treated samples under higher confining pressures ($\sigma_v \geq 80$ kPa), possibly due to particle crushing. This leads to the overall decrease in angle of friction and an increase in cohesion with higher biochar content. With increasing biochar content from zero to 20%, the thermal conductivity of BAS reduced from 2.10 W/(m·K) to 0.58 W/(m·K).

3. **Erosion resistance of corn-cob biochar as a soil amendment:** Mixing biochar alone with soil increases soil erosion, as indicated by an increase in the erodibility coefficient of BAS from 11 to 25 cm³/N-s, while the critical shear stress remains relatively unchanged. However, when biochar is fixed at 5% and soil dry density increases from 13 to 19 kN/m³, erosion is reduced by 4% to 16%. The introduction of an erosion control blanket (ECB) significantly decreases erosion. When biochar is combined with ECB and ruzi grass, erosion is reduced by 34% to 38%, with the critical shear stress increasing from 10 to 14 Pa and the erodibility coefficient decreasing from 11 to 7 cm³/N-s. Similar results were observed after 21 and 42 days of incubation when biochar was combined with compost, ECB, and ruzi grass. The benefit of extending the incubation time remains unclear for the combination of biochar-compost with ECB, indicating the need for further investigation.

Data Availability Statement: Data for the formal analysis are presented in the article. Raw data are available upon request from the corresponding author.

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Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Tananop Muanlhao, Monir Hossain, Surat Semmad and Apiniti Jotisankasa. The first draft of the manuscript was written by Monir Hossain and

Apiniti Jotisankasa. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declaration of interests

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

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Apiniti Jotisankasa reports equipment, drugs, or supplies was provided by Japan International Cooperation Agency. Apiniti Jotisankasa reports a relationship with Green Ground Solutions, co Ltd that includes: board membership and equity or stocks. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.