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How Effective Are Palm-Fiber-Based Erosion Control Blankets (ECB) against Natural Rainfall?

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Abstract: Rainfall-induced soil erosion is a significant environmental issue that can lead to soil degradation and loss of vegetation. The estimated global annual loss increased by 2.5% over 11 years, from 35 billion tons in 2001 to 35.9 billion tons in 2012, mainly due to spatial changes. Indonesia is predicted to be among the largest and most intensively eroded regions among countries with higher soil erosion, regarded as hot-spots higher than 20 Mg yr^{-1} ha^{-1}. Due to climate change, natural rainfall patterns in the tropical regions have been subject to change, with a lower number of rainy days and increased intensity of precipitation. Such changes trigger more soil erosion due to heavier rainfall kicking up dried soil particles that are exposed in the bare embankments. Unfortunately, there is no prevention available in developing countries due to the lack of availability and high prices of mitigation techniques such as terraces and covering areas with geotextiles or blankets. Erosion control blankets (ECBs) have emerged as a potential solution to mitigate soil erosion. This research article aims to evaluate the effectiveness of sugar-palm-fiber-based ECB in reducing soil erosion caused by natural rainfall. The study investigates the effectiveness of sugar-palm-based ECB in protecting against erosion at the designated embankment. During the three months of typical rainy seasons (February to April 2023), total eroded mass (kg) was collected and measured from two adjacent microplots (10 m^2 each), one covered with ECB and the other one left as uncovered soil (bare soil). The results indicate that eroded mass is proportional to rainfall, with coefficients of 0.4 and 0.04 for bare soil and ECB-covered embankments, respectively. The total soil loss recorded during the monitoring period was 154.6 kg and 16.7 kg for bare and ECB-covered soil, respectively. The significantly high efficiency of the up to 90% reduction in soil losses was achieved by covering the slope with sugar-palm-fiber-based ECB. The reason for this may be attributed to the intrinsic surface properties of sugar palm fiber ropes and the soil characteristics of the plot area. Sugar palm (*Arenga pinnata*) fiber has higher lignocellulosic contents that produce a perfect combination of strong mechanical properties (higher tensile strength and young modulus) and a higher resistance to weathering processes. Although the cost of production of handmade sugar-palm-fiber-based ECB is now as high as 4 EUR, further reductions in cost production can be achieved by introducing machinery. Compared to typical ECBs which have smaller openings, sugar-palm-based ECB has larger openings that allow for vegetation to grow and provide it with a lower density. As such, we recommend improvements in the quality of palm-fiber-based ECB via the introduction of further automation in the production process, so that the price can be reduced in line with other commercially available natural fibers such as jute and coir.

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1. Introduction

Rainfall-induced soil erosion is a major issue that can lead to ecosystem deterioration and the loss of fertile topsoil [1]. The soil particles may move and be carried off slopes during periods of intense precipitation. This process frequently occurs around mountainous or hilly terrain, artificial roads, and embankments. Global annual soil loss due to erosion was estimated to amount to more than 75 billion tons [2], which was later revised to 35.9 billion tons [3,4]. Cropland expansion was found to be a potential factor driving the increase in erosion. The southeast Asian countries with the least developed economies are predicted to have suffered the highest increases in soil erosion. Indonesia is listed among them, with its soil erosion hotspot reaching 20 Mg (tons) ha^{-1} yr^{-1}, spanning 0.076 million km^2 (5% of the country) [3].

The impact of the high soil erosion in Indonesia has been reported elsewhere in Jakarta [5]; Dieng, Central Java [6]; and Lake Limboto, Gorontalo Province [7]. The latter is a notable example, due to the rapid shrinkage of Lake Limboto in Gorontalo Province caused by approximately 3.3 million cubic meters of eroded sediments from 23 inlet rivers being deposited into the lake over 14 years [8]. The Alo-pohu River is the most eroded river, losing approximately 190 tons ha^{-1} yr^{-1} [9]. High soil erosion has also been reported in the largest river catchment area of Bone River in Bone Bolango regency, Gorontalo province, that brings sediment to Gorontalo city. High levels of erosion may pose risks to the development of the city, bringing threats of natural disasters such as floods and landslides that degrade environmental quality, leading to soil deposition on the river estuary and nearby Pantai Indah beach [10,11].

Therefore, erosion control is needed in order to reduce the amount of eroded materials, with the prevention of further degradation being a compulsory facet of Sustainable Development Goal (SDG) number 15 [12]. To achieve this, researchers have developed certain procedures that can be categorized as soil treatments, known as erosion control blankets (ECBs): geotextiles or geosynthetics which cover the soil's surface. By providing temporary cover and stabilizing the soil surface, erosion control blankets have been designated as a viable remedy to reduce erosion [13].

Most ECBs are produced from plastic fibers (e.g., polypropylene), commercially available materials with a lifespan of 10–20 years [14]. Hybrid ECB mats made from coconut fibers intertwined with layers of polypropylene are also commercially available [14]. Commercially available natural-fiber-based ECBs, such as those made from jute and coir, demonstrated their effectiveness in reducing soil erosion [15]. Additionally, the 100% biodegradability of natural-fiber-based geotextiles and their adherence to the soils have made them preferable to others [16].

1.1. Mechanical Properties of Sugar Palm Fibers

The mechanical characteristics of sugar palm fibers are a key factor in determining the effectiveness of ECBs. Understanding how the sugar-palm-based ECB performs in wet environments requires in-depth knowledge of these characteristics, with extensive studies on the mechanical properties of sugar palm fibers having recently been undertaken [17,18], including investigations into the tensile strength of sugar palm ropes and nets [19]. The mechanical strength superiority of sugar palm fibers can be attributed to their higher lignocellulosic content compared to other natural fibers [20].

Natural lignocellulosic fibers are categorized as engineering materials due to their combination of tensile strength and density. Lignocellulosic content refers to the presence of lignin, cellulose, and hemicellulose in plant-based fibers. These components play a crucial role in determining the mechanical properties of fibers. Lignin provides rigidity and hydrophobicity to the cell wall, contributing to the overall strength of the fiber. Cellulose, on the other hand, offers tensile strength and stiffness, while hemicellulose acts as a matrix that binds cellulose microfibrils together, enhancing the overall structural integrity of the fiber [21,22].

For instance, research by Petroudy (2017) [23] demonstrated that the presence of lignin in fibers significantly influences their tensile strength and modulus. Additionally, the work of Chanliaud et al. (2002) [24] highlighted the role of cellulose in enhancing the mechanical properties of natural fibers. Furthermore, comparative studies have been conducted to evaluate the mechanical strength of fibers with varying lignocellulosic contents. For example, a study by Suryanto et al. (2014)[25], comparing the mechanical properties of different natural fibers, found that fibers with a higher lignocellulosic content exhibited superior mechanical strength compared to those with a lower lignocellulosic content. Table 1 shows a comparison of key aspects related to mechanical strength and the chemical compositions of several common natural fibers used in erosion control or soil stabilization. Coir (coconut fiber) and jute have shown excellent engineering characteristics that can be used to not only improve soil conditions, but also to provide immense benefits to the natural environment. The higher lignin concentration (up to 45%) of coir makes it among the most resistant natural fibers to biodegradation. A higher tensile strength (100–800 MPa) enables all the listed natural fibers to be employed for geotechnical purposes. The advantage of sugar palm compared to other fibers is that it has a combination of a relatively higher tensile strength (220–286 MPa), minimal elongation (2.2%), and a moderate and uniform size/density.

Table 1. Mechanical and chemical properties of common natural fibers used in geotechnical applications [19,20,22,26,27].

Key Aspects	**Natural Fibers**					
Mechanical Properties	**Coir**	**Hemp**	**Jute**	**Sisal**	**Buriti**	**Sugar Palm**
Diameter (μm)	90–500	33	10–85	180–470		240–370
Density (kg/m^3)	870–1520	1140–1500	1100–1500	700–1450	630–1120	1160
Tensile strength (MPa)	100–225	270–920	250–860	280–750	129–254	222–286
Young modulus (GPa)	3–6	30–70	10–30	9–56	22–32	4–12
Elongation at break (%)	15–50	240–370	222–286	4–12	2.3–3.1	2.2–6.1
Chemical (%)						
Cellulose	32–51	67–78	56–71	57–71	65–71	43.88
Hemi-cellulose	29–35	5.5–16.1	29–35	16		7.24
Lignin	31–35	2.2–3.7	11–24	11	21–27	33.24
Water absorption	95–180	8–9	12–105	56–230	9.1	8.36

1.2. Properties of Common ECBs

Erosion Control Blankets (ECB) made from natural fibers have been studied by researchers for many years (see Table 2). Sugar-palm fiber-based ECB was found to be the lightest ECB, with a weight density of 0.29 kg/m^2, which is 75% and 60% lighter than coir mat 40 and jute mats, respectively. The combination of large openings and a long lifespan (more than 5 years) make it suitable for growing plants such as maize or grasses, which is confirmed in RIHN Newsletter [28].

Table 2. Properties of commercially available ECB, reported by several researchers [19,28].

Dimensions and Properties	Natural Fibers					
	Borassus	Buriti	Jute *	Coir *	Water Hyacinth	Sugar Palm
Mat thickness (mm)	20	10	6	9	6.96	6
Strip thickness (mm)	22.5	12.5	6	9	7.0	7.5
Density (kg/m^2)	1.091	0.413	0.5	0.4	0.854	0.29
Percentage of open area	22.9	55.8	70–75	65	58.78	77.44
Mesh size (mm)	50 × 50	40 × 40	11 × 18	-	30 × 30	50 × 50
Lifespan (yr.)	NA	NA	Up to 1	4–6	NA	>5

* Coir mat 40 is a commercially available product. See the following link: https://www.erosioncontrol-products.com/erosioncontrolmats.html (accessed on 14 February 2024); NA: Not Available.

Natural geotextiles can also be made by individuals, including small groups of farmers or artisanal gold miners [29]. The production of natural-fiber-based geotextiles by individuals or small-scale industries was estimated to cost around 3.0 EUR per m^2 for Buriti fibers [16], which is considerably costlier than Borassus mats, at 0.3 EUR per m^2 [30]. These, however, are midrange compared to commercial coir and jute geotextiles, which are priced at 0.69 EUR per m^2 [31]. Handmade geotextiles such as those produced from sugar palm by groups of gold miners could cost around 4.0 EUR per m^2 [19].

Several experiments were conducted using small-scale developed geotextiles from natural fibers (Buriti and Borassus) to reduce soil erosion almost two decades ago, mainly in the United Kingdom [16,30,32,33]. A group of researchers in Thailand also developed a natural fiber mat made from water hyacinth [34,35] and kenaf [36]. Recently, SRIREP researchers have promoted the use of geotextile mats made from sugar palm (Arenga pinnata) as ECBs and green curtains [29]. The advantages of sugar palm fibers compared to other natural fibers are described elsewhere[17,20,37–39]. Compared to synthetic fiber ECBs, natural-fiber-based ECBs are superior in terms of decelerating the initiation of runoff, reducing the runoff rates, and reducing total soil losses for moderate slopes [19]. The tested materials were sod and straw, but both are weak against weathering processes and usually used to feed livestock, making them not ideal materials to prevent erosion. Geotextile materials made from natural fibers have been employed as soil or sand reinforcements, and as erosion control blankets [22–24]. Natural-fiber-based geotextiles have advantages over synthetic fibers composed of plastic, such as a low cost and environmental friendliness [25,40]. Researchers have utilized a variety of natural fibers to control soil erosion, including coconuts, sisal, jute, cotton, hemp, flax, sugarcane bagasse, and wheat straw [25]. According to studies [18,37], the Arenga pinnata fibers have demonstrated favorable mechanical qualities for agricultural use.

However, due to economic restrictions, commercially available ECB mats were found to be unaffordable for most developing countries. As an alternative, such countries may turn to the use of abundant natural fibers that can be used to produce ECB mats or other products, such as green curtains [29]. Due to its affordability and accessibility, sugar-palm-fiber-based ECB can be considered a promising option for developing countries [19]. The efficiency of this specific ECB in preventing soil erosion brought on by rainfall, however, has not been thoroughly studied.

2. Materials and Methodology

2.1. Research Methodology

The research aims to assess the efficiency of sugar-palm-fiber-based ECB against natural rainfall-induced soil erosion, the event that contributed the most to reductions in the quality of the soil distributed along the hilly region of Indonesia. To investigate this, we used field experiments and measured natural rainfall at a location in close proximity to BMKG (where the rainfall data were recorded). The ECB was prepared according to a tested ECB model described in a previous article [41], while the method of measuring soil mass was an improvement of adopted techniques [34,41,42]. The research methodology used in this research is mainly adopted from field studies conducted in Europe [15,42] and Thailand [34,35], with some modification, mainly in terms of ECB preparation and eroded soil collection techniques. The use of natural rainfall for a longer duration is unique, and this decision was made in order to resolve the fluctuations in rainfall due to climate change, which mainly occur in tropical regions.

The overall research flow is summarized in Figure 1. The research began by searching for a suitable location for the experiment, before coordinating and gathering assistance to collect rainfall data from BMKG, as well as asking the local government for permission to conduct an experiment at a specific location in their administrative jurisdiction. Once the location and timeframe were defined, we started making the ECB net, embankment preparations, and erosion map drawings. Once these three tasks were completed, we placed the ECB on the embankment and installed the erosion measuring equipment. Over the course of three months of precipitation (February to April 2023) we monitored the erosion events, collecting the eroded masses (mainly soil) and measuring them. After three months, the weather became dry again; we then focused on preparing the report for the students and writing the manuscript for publication.

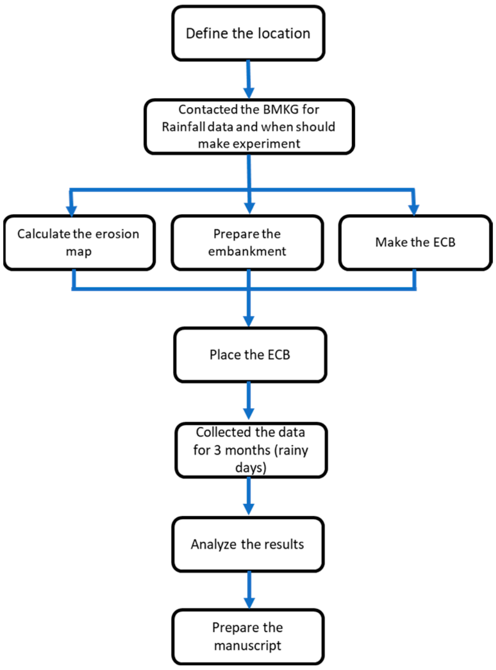


Figure 1. Flow chart of research activities on efficiency of erosion control blanket.

2.2. Sugar Palm Fiber Net ECBs

Sugar palm fibers can be made into ropes (with an average diameter of 0.6 cm) (see Figure 2a,b), which are then woven into patterns to form nets. In this study, nets with mesh size dimensions of 5 cm × 5 cm (opening size of 3.8 cm × 3.8 cm) were selected to investigate the performance of the material. The ECB was prepared from sugar palm fibers using a knot type of 5 m in length and 1 m in width, as shown in Figure 2. The average mass per unit area and thickness of the woven sugar palm nets was 0.29 kg m^{-2} and 0.6 cm, respectively. The average weight of the woven sugar palm net and its thickness was 0.29 kg m^{-2} and 0.75 ± 0.04 cm, respectively.

(**a**) (**b**)

(**c**) (**d**)

Figure 2. A sugar-palm-fiber-based net being prepared from previously manufactured (**a**) sugar palm fiber ropes with a diameter of 6 mm (**b**), woven on top of a nailed wooden frame (**c**); (**d**) the completed product.

2.3. Embankment Preparation

The experiment was carried out on a test embankment built in Ulanta village in Bone Bolango regency's Suwawa district, Indonesia (0°33′27.1″ N 123°08′55.7″ E) (see Figure 3). The study location is among the erosion-prone areas suffering from severe erosion on the GIS-based map recently produced by Olii, M.R., et al. [43]. The location is separate from any trees that may affect the results of the experiment. Looking at the topographic map, the slope at the location has a vulnerable value ranging from 5 to 8% (mostly flat). The topsoil is categorized as eutric cambisols (FAO/UNESCO classification) [44].

The embankment length measured 5 m and forms an angle 60 degrees from the horizontal plane. The embankment was prepared as illustrated in Figure 4 by flattening the surface and clearing the vegetation with conventional tools, removing the gully. The sloping surface meets the upper surface, which is covered with grass and is bounded by walls with the surrounding and undulated terrain forming an ideal setting for the experiment location. We used pandanus leave mats (called "*Amongo*" in the local language) to protect the water from the top, left and right sides, and placed them at the bottom side of the embankment. The *Amongo* mat placed at the bottom was used to capture the soil particles that were eroded from the embankment.

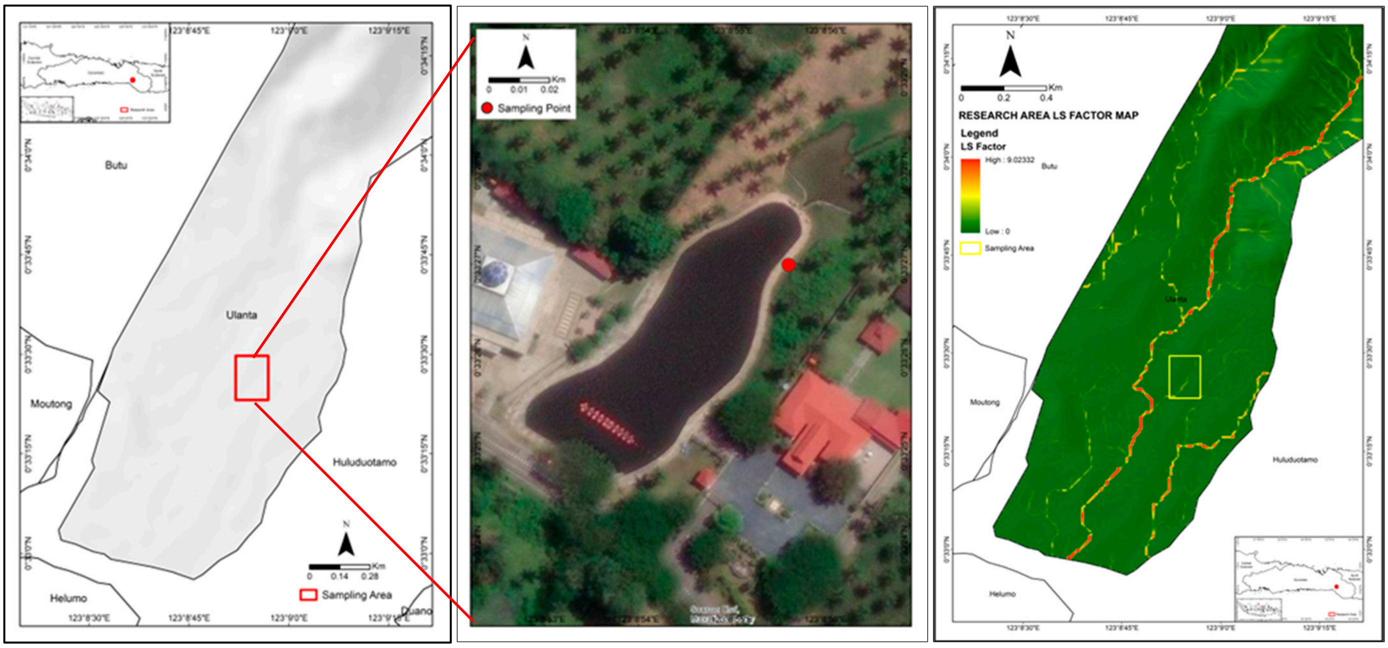


Figure 3. Study location in Taman Taqwa, of Bone Bolango regency, Gorontalo Province, Indonesia (**left panel**). The location is clear from tree cover (**center panel**). The LS factors at the location are low, as shown in the map (**right panel**).

Figure 4. Preparation of embankment and installation of the sugar palm fiber net.

2.4. Evaluation of Erosion Control Practices

To evaluate the effectiveness of erosion management techniques, researchers have conducted field experiments, as demonstrated in previous studies [15,35,42,45–48][15,34,42,45–49]. This strategy offers a controlled setting for evaluating sugar-palm-fiber-based ECBs' resistance to rainfall and comparing these results with other erosion control techniques. In the upper and lateral borders of the soil-defined plots, metal plates were installed. To collect sediments carried by runoff during rains, a metal gutter was placed in front of each plot. An adjustable cover kept the gutter safe and enabled the collection of the captured fragments of eroded earth. A plastic hose was linked to the metal tube welded in the gutter's front edge to carry runoff water and sediments to a plastic tank located downslope (Figure 5). This passive control strategy, as explained above, has been used for many years; for better results, one could propose semi-active control and adaptive control [50,51].

The sediments were stored in the lab until gravity began to deposit the sediments. Following the removal of the clean water, the sediments were weighed, and the eroded sediments were analyzed. After three months of rain from natural sources, the technique was carried out on both sides of the embankment. The use of natural rain instead of artificial rain is common for a field experiment on erosion control performances, as reported by researchers [42,52].

The efficiency of ECB was calculated using the formula expressed in Equation (1), where w_c and w_{uc} are the dry weight of eroded mass (kg) from ECB-covered and uncovered embankments (bare soil) [53]. The highest value of 100% means that the ECB perfectly protects soil erosion. The values may differ depending on several parameters, such as the ECB's material properties (including the opening dimensions, type, and dimension of fibers), nature of the embankment (soil characteristics and inclination of embankment), and precipitation intensity (mm/h).

$$Erosion\ resistance\ ratio = \frac{(w_{uc} - w_c)}{w_{uc}} \times 100\% \quad (1)$$

The field experiment carried out by RIHN in Figure 6 shows that sugar palm fiber nets are more effective than plastic-fiber-based nets because they allow vegetation to grow freely thanks to their larger openings [28].

(**a**) (**b**)

Figure 5. Design of field experiment on bare-soil plot (**a**) and ECB-covered plot (**b**); metal plate borders are installed to avoid eroded soils from falling outside the designed collectors placed below.

(**a**)

(**b**)

Figure 6. Application of the sugar palm fiber net (**a**) and a common synthetic net on (**b**) the embankment near the front of the main entrance of the RIHN building.

2.5. GIS Hazard Map

A rainfall map of the study location was created using Climate Hazards Group InfraRed Precipitation with Station (CHIRPS), produced in collaboration with scientists at the USGS Earth Resources Observation and Science (EROS) Center, to deliver complete, reliable, up-to-date data sets for a number of early warning objectives, like trend analysis and seasonal drought monitoring [54](Climate Hazard Center, n.d.). The elevation of the location was measured using the Digital Elevation Model (DEM) from DEMNAS of Badan Geospasial Indonesia [55]. For a wide range of agricultural, conservation, mining, construction, and forestry applications, the Revised Universal Soil Loss Equation (RUSLE) [56,57] forecasts long-term, average annual erosion by water. Considering the location's conditions (rainfall and elevation), the RUSLE method was utilized to construct the hazard map/erosion map. The RUSLE method was also used by researchers to determine the estimated amount of erosion [43,57–59].

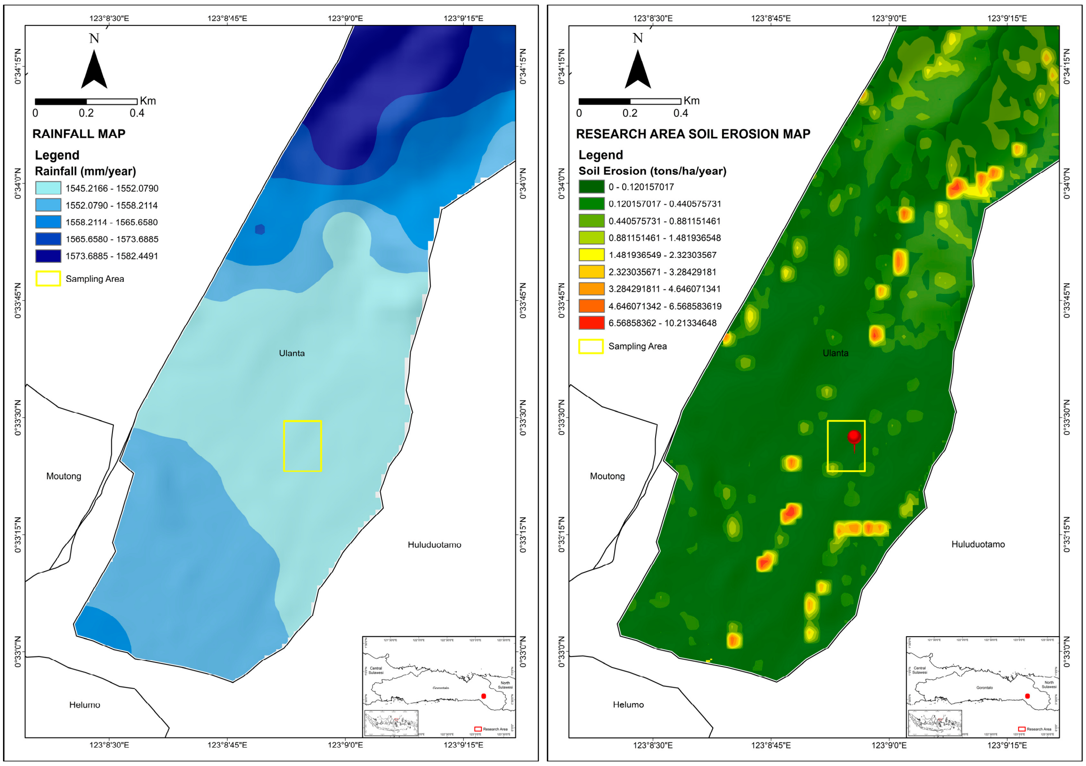
3. Results and Discussion

3.1. Precipitation and Erosion Map of the Location

The annual precipitation predicted using CHIRPS (shown in Figure 6a) indicates that the location has low levels of precipitation, which makes it suitable for the experiment, since higher precipitation is correlated with higher kinetic energy, which may have an impact on topsoil particles. The combination of precipitation, topography and soil properties contributed to the soil erosion map shown in Figure 7b. The data of the soil erosion map show that the location has significantly lower levels of potential soil erosion, which could mean that the erosion may only originate from the embankment.

Daily precipitation during the monitoring period from February 1st to April 30th is shown in Figure 8, which describes the characteristics of a tropical rainforest climate where rainfall occurs between December and March, according to the Koppen–Geiger classification of climate [60]. Despite this, the total number of rainy days during the monitoring period was less than the 5-year average (2019–2023). The number of rainy days with precipitation > 10 mm/h during the monitoring period amounted to 10—around two times higher than the 5-year average. The shifts in precipitation patterns in tropical regions are predominantly caused by a permanent El Nino-like response in the eastern pacific zonal shifts over the maritime continent and South America [61,62].

This high precipitation is correlated with higher kinetic energy, which may detach soil particles from bare soil. The relationship between kinetic energy (KE) and precipitation intensity has been described elsewhere [63,64], and can be mathematically determined using the universal power law proposed by Shin, S.S. et al. [65] Erosion is also related to the number of days with precipitation > 9 mm, with two such days being recorded during the early monitoring period. Furthermore, from days 50–55 (around the end of March), there was a high accumulation of precipitation and three days with precipitation >9mm. The two events may have some consequences for eroded soil particles.



(**a**) (**b**)

Figure 7. Precipitation (mm yr^{-1}) map (**a**) and soil erosion (tons ha^{-1} yr^{-1}) map of the location area (**b**).

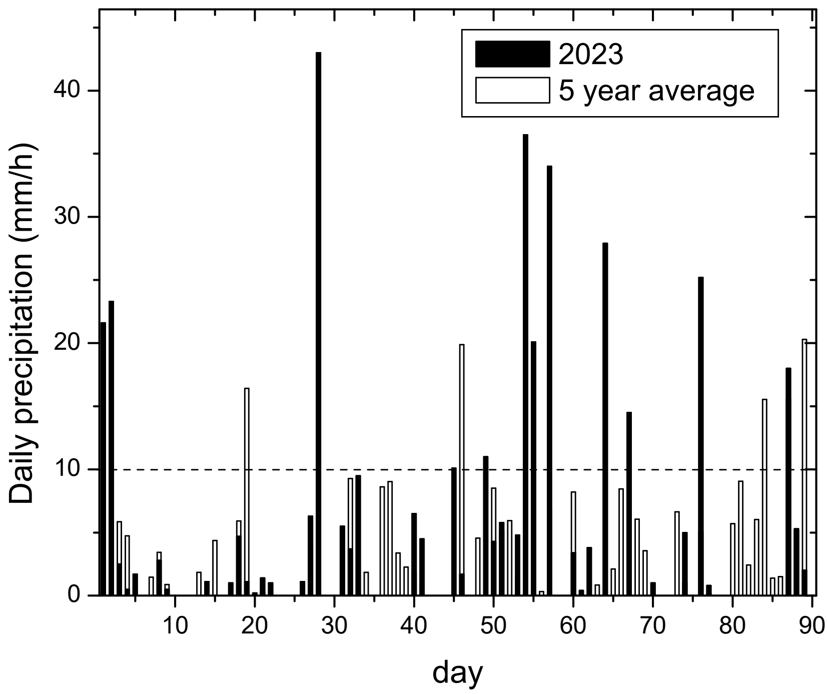


Figure 8. Rainfall events at the location around the embankment (data provided by BMKG); number of days with precipitation > 10 mm during monitoring period is 10, which is 2 times higher than the 5-year average.

3.2. ECB Effects on Soil Erosion

Over the course of three months, a total of 13 erosion events took place, most likely attributable to the 371.9 mm of cumulative rainfall seen in Figure 9. This is a significantly lower quantity than the 424 mm observed during the regular three months of precipitation (February–March). The normal precipitation throughout the months from February to April was subtracted from the daily average of five years of data, spanning from 2019 to 2023. The lower levels of precipitation during the recording period were understood to signal the onset of the El Nino pattern and the weakening of the La Nina trend[66]. The projection of the large shift in precipitation patterns was quantitively and directly linked to global greenhouse emissions by researchers [67].

Soil erosion events that occurred during the monitoring period at the embankment with and without ECB covers are shown in Table 3. The total amount of soil loss at the embankment was 154.6 kg without ECB covers and 16.7 kg with ECB covers. The two days with the highest amounts of rainfall that caused erosion were 28 February 2023 (20 kg) and 30 March 2023 (40 kg). The cumulative amount of precipitation between each successive event was 54.1 mm and 95.4 mm, respectively. The precipitation that incurred the most erosive event recorded a daily peak of 36.5 mm and 3 days with more than 9 mm of rainfall, while the second most erosive event occurred with 43 mm and 1 day with over 9 mm.

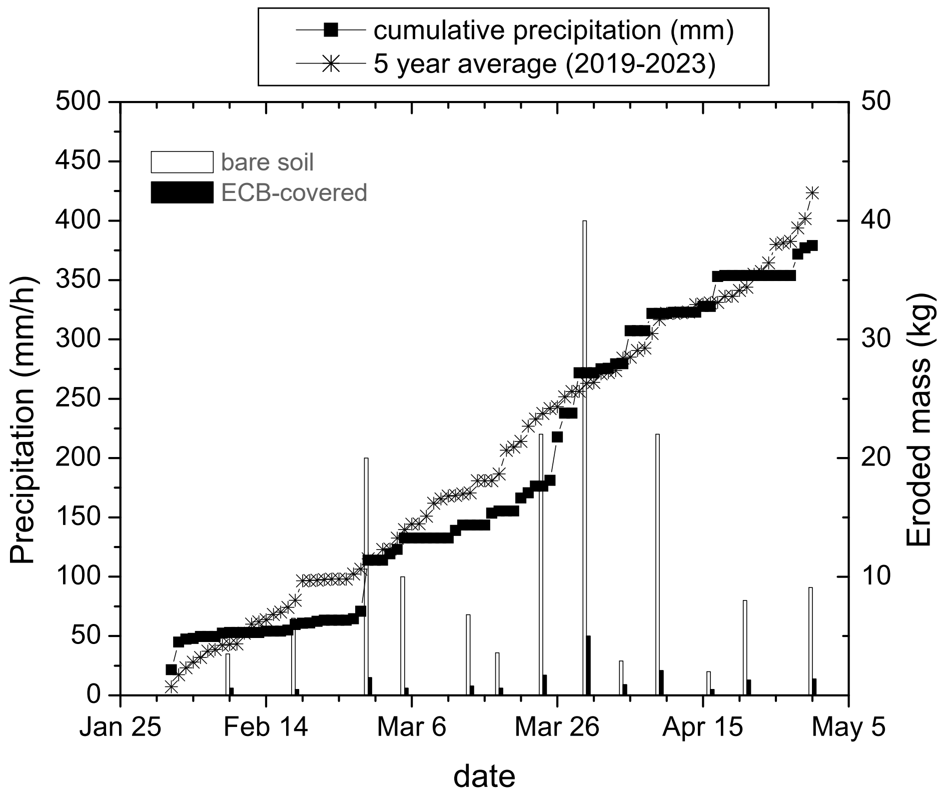


Figure 9. Cumulative precipitation during erosion monitoring period as compared with 5-year average (2019–2023). During the monitoring period, 13 erosion events occurred, with total amounts shown as bars (white for bare soil and black for ECB-covered soil).

The monitoring period's cumulative precipitation totals and dates for soil erosion incidents at the embankment with and without ECB coverings are displayed in Table 3. At the part of the embankment without an ECB cover, 154.6 kg of total soil loss was recorded, while 16.7 kg was measured at the slope with an ECB cover. It can therefore be inferred that the almost 10:1 ratio of comparative soil losses demonstrates the efficiency of palm-sugar-based ECB in preventing erosion. The three days that experienced the most erosion caused by rainfall were 30 March 2023 (40 kg), 24 March 2023 (22 kg), and 9 April 2023 (22 kg). Between these three episodes, there was a total of 95.4 mm, 21.1 mm, and 54.1 mm of precipitation, respectively. The amount of precipitation that triggered the majority of the erosive events peaked daily at 36.5 mm, and had three days with more than 9 mm rainfall, followed by the second most erosive event, with 27.9 mm precipitation and two days over 9 mm. The erosive event of 24 March 2023 (22 kg) was triggered by a total of 21.1 mm precipitation, which is only half of that recorded on 9 April 2023, despite its causing the same amount of total soil erosion.

Table 3. Erosion events, cumulative precipitation between adjacent events, and soil losses measured at the embankments with and without ECB covers.

Erosion Event	**Precipitation Characteristics**			**Soil Loss (kg)**	
Date	**P [1]**	**P Peak [2]**	**NDP [3]**	**Bare Soil**	**ECB**
9 February 2023	52.9	23.6	2	3.5	0.6
18 February 2023	6.8	4.7	0	6.5	0.5
28 February 2023	54.1	43	1	20	1.5
5 March 2023	18.7	9.5	1	10	0.6
14 March 2023	11	6.5	0	6.8	0.8
18 March 2023	11.8	10.1	1	3.6	0.6
24 March 2023	21.1	5.8	0	22	1.7
30 March 2023	95.4	36.5	3	40	5.0
4 April 2023	7.6	3.8	0	2.9	0.9
9 April 2023	41.6	27.9	2	22	2.1
16 April 2023	6	5	0	2	0.5
21 April 2023	26	25.2	1	8	1.3
30 April 2023	25.3	18	1	9.1	1.4
TOTAL	379.1			154.6	16.7

[1] P—total event precipitation; [2] P peak—maximum daily precipitation; [3] NDP 9 mm—number of days with 9 mm precipitation or more.

3.3. *Efficiency of ECB*

The efficiency of ECB during the monitoring period was calculated to be 89.2% using the data in Table 1 and Equation 1, much higher than the wooden block covered with jute net, as reported by Chen et al. [53]. The higher efficiency of the sugar palm ECB may relate to the intrinsic properties of sugar palm ropes and the properties of the soil.

Furthermore, we measured the approximate eroded mass data using linear regressions to gain an understanding of the eroded mass from slopes with and without ECB cover, and plotted these against the rainfall data, as shown in Figure 10. The rate of eroded mass from the bare soils was about 0.4 kg mm^{-1}, roughly 10 times higher than the 0.04 kg mm^{-1} recorded on the covered slope. Soil losses of about 2 kg mm^{-1} from the bare soil of the embankment (3V:4H) were reported by researchers [35]. For the bare soil plot, the large deviation of the eroded soil data from linear regression, found between ranges of 20–60 mm precipitation, may be attributed to the effects of rainfall patterns, as reported by Mohamadi and Kavian [68]. In addition to rainfall intensity, the precipitation's duration and kinetic energy also play a role in erosion [69].

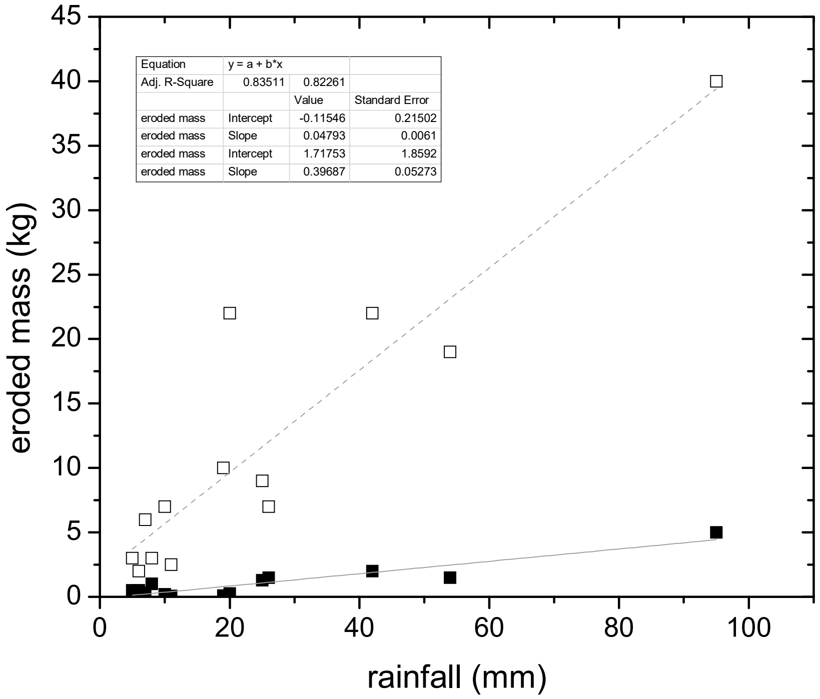


Figure 10. Graph of eroded mass from the slope covered with (filled squares) and without (open squares) ECB, plotted against rainfall data. The full line and dashed lines indicate the linear regression of the eroded mass vs. rainfall data with and without ECB respectively.

4. Discussion

Regarding the mitigation of erosion, the sugar-palm-fiber-based ECB was deemed to be more effective than other types of ECB. Using woven water hyacinth covers over bare soil reduced soil loss by 70%, but in our investigation, we discovered that ECB covers made from sugar palm fibers reduced soil loss by over 90%. The soil loss may experience further reductions should naturally growing grass or planted seeds grow inside the openings, which were intentionally made larger (48 mm × 48 mm) than that of common ECBs [34,35]. Higher reductions in soil erosion via the application of natural-fiber-based mats or blankets have been reported in other studies [15,16].

However, with regard to the sustainability of natural ECBs, a shorter lifetime was reported, leading to their alternative name of Limited-Lifetime Geotextiles [34]. Compared to synthetic ECBs, which have a lifetime of about 10–20 years, the commercially available ECB, consisting of coconut fibers intertwined with polypropylene, has a lifetime of about 12–18 months [14]. On the other hand, the strength of sugar palm fibers could offer higher resistance than other natural fibers, where the tensile strength of aging fibers is reduced by half after 10 years [20]. Sugar-palm-fiber-based ECB's mechanical properties allow it to last for up to an estimate of 20 years because sugar palm fibers have a greater lignin concentration of over 30% compared to other natural fibers [70,71].

Therefore, we may propose the use of sugar palm fiber nets as an alternative solution for reducing soil erosion at embankments, while also introducing a new industry for rural communities. This new industry can be described as a sustainable one and may deter communities from participating in extractive industries such as artisanal gold mining, which lead to degradation of the environment and human health [72,73]. The sugar palm fiber industry is one of the many emerging industries (*Karawo*, *Amongo*, sorghum and geotourism) that have been developed in tandem with the so-called Transdisciplinary Communities of Practice (TDCOP) [74].

5. Conclusions

This research proposes the use of sugar-palm-fiber-based ECBs to reduce soil erosion and improve slope stabilization. This type of ECB allows for both the prevention of soil particle slips and the subsequent support of vegetation growth. An embankment with a 4 m width and 5 m length was prepared for the purposes of this study. Over the course of three months (from February to April 2023), the erosion and slope stability were monitored under natural rainfall. The total soil erosion for the bare slope reached 154.6 kg, compared to 16.7 kg at the slope with an ECB cover. The daily soil erosion recorded at both slopes was caused by heavy rainfall of 95.4 mm, resulting in 40 kg and 5 kg of erosion, for bare and ECB-covered soil, respectively. The amount of soil erosion and eventual erosion is proportionally correlated with the cumulative precipitation in mm. The gradients of correlation were 0.4 kg mm^{-1} and 0.04 kg mm^{-1} for the bare and ECB-covered slopes respectively. We found that sugar palm ECBs showed significantly higher efficiency (90%) in preventing soil erosion, strong mechanical properties (such as tensile strength and Young modulus) of ropes and nets, and strong resistance to weathering processes, making it suitable for use as an environmentally friendly method for reducing soil erosion in Indonesia. Therefore, it is important to expand the use of palm-fiber-based ECB to reduce soil erosion in Indonesia, while at the same time providing a form of sustainable development for local communities. Sugar palm production centers could not only produce sugar palm for alcohols, but also sugar palm fiber products, such as ropes, nets, and brooms. To implement this vision, we collaborated with rural communities on the edge of the Nantu Conservation Forest of Gorontalo regency, training them to produce high-quality sugar palm fiber products such as brooms and nets. The limitations of the current study can be found in the fact that the research was only applied to specific embankments that have no relation to agricultural activities. This should be addressed by the further research that has already began in the agricultural areas of corn plantations in the Gorontalo province. The number of plots will also be increased in order to assess the effects of agricultural activities (tillage, non-tillage, and crop age).

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