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Valorization of Banana Pseudo-Stem Waste as Biodegradable Geotextiles for Soil Conservation

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ABSTRACT

Soil erosion is a major challenge on sloping agricultural land because it removes fertile topsoil and reduces long-term productivity. Banana pseudo-stem (BPS) sheaths are abundant agricultural residues with fiber characteristics that may support their use as biodegradable surface covers. This study evaluated handwoven BPS geotextiles fabricated from 1.0, 1.5, and 2.0 cm strips under a fixed 9% slope and 75 mm h⁻¹ simulated rainfall. The novel contribution is the controlled comparison of strip width within the same BPS material and over-under woven configuration, thereby linking a fabrication variable to runoff, sediment yield, and net cover efficiency. The experiment followed a Completely Randomized Design with four treatments and three replications. BPS 1 (1.0 cm strips) achieved the highest net cover efficiency (94.74%), followed by BPS 2 (88.76%) and BPS 3 (85.77%). BPS 1 also produced the lowest sediment yield (15.91 g m⁻² h⁻¹), compared with 299.24 g m⁻² h⁻¹ for bare soil. Thus, under the tested laboratory condition, narrower strips formed a denser protective cover and provided greater erosion control. Field performance under other slopes, rainfall regimes, soil types, and longer exposure periods remains to be validated.

1. Introduction

Soil erosion remains a major concern for agricultural sustainability, particularly in sloping areas where the top layer of soil is easily removed by water, wind, or gravity [1]. In the Philippines, frequent tropical storms and monsoon rains make upland farms and vegetated slopes especially vulnerable. This often leads to the loss of nutrient-rich topsoil, which in turn reduces crop productivity and affects long-term soil health [2][3].

Bananas (*Musa spp.*) are among the most widely produced and traded fruits globally, with annual production exceeding 179 million tonnes. Major producers include India, China, Uganda, Indonesia,

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and the Philippines [4][5]. In the Philippines, banana plantations occupy large areas, many of which are located on gently to moderately sloping land. These conditions make them particularly prone to soil erosion [6]. At the same time, banana production generates a large volume of agricultural waste, especially banana pseudo-stems (BPS), which are often left unused after harvest [7][8].

Banana pseudo-stem sheaths are rich in fiber, with about 54.3% fiber content, and are known for their tensile strength, structural rigidity, and water absorption capacity [9][10]. Natural-fibre geotextile studies have reported erosion-control potential for materials such as bamboo, coir, jute, and composite banana-fibre/coir products [11][12][25]. However, the available studies have largely emphasized established fibre types or their general material and erosion-control performance. They provide limited evidence on minimally processed BPS sheaths woven as complete surface-cover mats, and they do not establish how BPS strip width within a constant weave influences runoff and sediment retention. Consequently, a configuration-specific basis for selecting BPS strip width remains lacking.

Using BPS as a geotextile may support the United Nations Sustainable Development Goals, particularly SDG 12 on responsible consumption and production through agricultural-residue utilization and SDG 15 on life on land through soil conservation [13][14]. BPS is locally available in banana-producing regions and is frequently underutilized [7][8]. Nevertheless, availability alone does not establish commercial feasibility; material collection, drying, fabrication labor, transport, installation, durability, maintenance, and replacement requirements must also be evaluated before large-scale adoption.

This study investigates BPS as a soil-conservation material by evaluating geotextiles made from strips 1.0, 1.5, and 2.0 cm wide. Specifically, it aims to (1) fabricate handwoven BPS geotextiles using a consistent over-under configuration, (2) determine how strip width affects surface runoff and sediment yield, and (3) assess net cover efficiency under a controlled 9% slope and 75 mm h⁻¹ simulated rainfall. The novelty lies in isolating strip width as a design variable within the same BPS material, mat dimensions, and weave, rather than in treating the 9% slope itself as novel. This controlled comparison provides preliminary configuration guidance for BPS mats, while the fixed slope and rainfall intensity define the study boundary and not the full range of anticipated field conditions.

2. Methodology

2.1 Preparation and Fabrication of Banana Pseudo-Stem (BPS) Geotextile

Banana pseudo-stem sheaths were used as the primary material for fabricating the erosion control geotextiles. These were collected after harvesting Cardava banana (*Musa acuminata* × *balbisiana*) and manually stripped. The sheaths were then sun-dried for about 10 days to reduce moisture content and make them easier to handle during processing.

Once dried, the pseudo-stem sheaths were cut into strips with widths of 1.0 cm, 1.5 cm, and 2.0 cm, while maintaining a uniform length of 110 cm. The strips were cut using scissors, and their dimensions were checked with a ruler to ensure consistency.

The prepared strips were then woven by hand into mats using a simple over-under pattern, similar to traditional mat weaving. Each mat was made to fit the size of the erosion plots (110 cm × 20 cm). The time required for weaving varied depending on strip width, with narrower strips taking longer to assemble. On average, mats made from 1.0 cm strips (BPS 1) took about 2 hours to complete, while those made from 1.5 cm (BPS 2) and 2.0 cm strips (BPS 3) took approximately 1.5 hours and 1 hour, respectively. Care was taken to keep the weaving density as uniform as possible across all treatments.

2.1.1 Determination of Geotextile Physical Properties

The fabricated BPS geotextiles were characterized based on their thickness and mass per unit area. Thickness was measured at several points on each mat using a digital caliper, and all treatments showed an average thickness of about 3 mm.

To determine the mass per unit area, a representative sample measuring 12 × 10 cm was taken from each treatment. Each sample was weighed using a digital scale with a precision of 0.01 kg. The mass per unit area was then calculated and expressed in g m⁻². The resulting values were 156.00 for BPS 1, 187.20 for BPS 2, and 246.34 for BPS 3.

2.2 Design and Construction of Erosion Plot and Rainfall Simulator

2.2.1 Erosion Plot and Runoff Collector

Rectangular erosion plots were constructed using galvanized iron sheets measuring 110 cm × 20 cm × 12.7 cm (length × width × height), as shown in Figure 1. Each plot was fitted with runoff and sediment collectors at the downslope end to capture both flowing water and transported soil particles. All plots were set at a uniform slope of 9%, following the approach described by *Alewell et al.* [15].



Fig. 1. Constructed rainfall simulator, (A) Attached with erosion plots and (B) Shows the erosion and run-off collectors, cans set-up for during the rainfall simulator calibration.

2.2.2 Rainfall Simulator

A rainfall simulator (Figure 1) was used in this study, consisting of 24 copper misting nozzles connected by 1/4-inch barbed tees and tubing. The system was supplied with water at a constant pressure of 40 psi. The nozzles were mounted on a wooden frame positioned 1.83 m above the center

of the erosion plots, with a spacing of 0.15 m between each nozzle. The entire setup was supported by a wooden structure with a height of 2.50 m to maintain stability throughout the experiment.

The simulator was adjusted to produce a rainfall intensity of 75 mm h⁻¹, representing moderate to high erosive conditions commonly used in soil erosion studies [16–19]. Rainfall intensity was verified through volumetric collection over a known area and time.

To better describe the erosive potential of the simulated rainfall, its kinetic energy was also estimated. This was calculated using the empirical relationship $KE = 0.119 + 0.0873 \log_{10} I$ [20], where KE is expressed in MJ ha⁻¹ mm⁻¹ and I is the rainfall intensity in mm h⁻¹. At an intensity of 75 mm h⁻¹, the estimated kinetic energy was 0.283 MJ ha⁻¹ mm⁻¹. Over the 2-hour rainfall duration, equivalent to a total rainfall depth of 150 mm, the total kinetic energy applied in each run was approximately 42.45 MJ ha⁻¹. This estimate allows for comparison of the simulated rainfall's erosive force with values reported in related studies.

Rainfall uniformity was evaluated using Christiansen's Uniformity Coefficient (CU). A total of 40 collection cans were randomly distributed across the plot area during testing. The simulator achieved a CU value of 87.05%, which falls within the acceptable range for uniform rainfall distribution [17][21]. The CU was computed using Eq. (1) [16][17].

$$CU = 100 \left(1.0 - \frac{\sum |z - m|}{\sum z} \right) \quad (1)$$

where:

CU= coefficient of uniformity, %

z = individual observation at each sample point from uniformity test, mL

$|z - m|$ = total absolute value of deviations from average amount of water measured in all accumulation containers, mL

$m = \frac{\sum z}{n}$ = mean depth of observations, mL

n = number of observations.

2.3 Soil Sampling, Characterization, and Preparation

The soil texture used in this study was a clay loam soil gathered in an unmanaged cornfield in Purok 2, Poblacion, Carmen, Cotabato, Philippines. The soil texture was determined through a field sampling. The soil sample was collected in random location in the area by simply traveling 20 steps from the first point to the next sampling spot creating a zigzag pattern. The spade was used to make a "V" shaped cut into the soil in a depth of 15 cm in each soil was taken. The percent sand, silt, and clay particle were determined using the sieve method and soil texture was classified using the USDA Soil Texture Triangle. The initial properties of the soil were determined before sampling, with a bulk density of 1.25 g cm⁻³ and a moisture content of about 12% (wet basis) which is the normal condition of clay loam soils in the field.

Additionally, around 500 kg of soil was acquired in the field to be used in this study. The soil was prepared according to the procedures presented by Khan *et al.* [22] and Abrantes *et al.* [23]. Collected soil was then dried under the sun over a period of 24 hours, sieved using a 4 mm mesh and mixed thoroughly to achieve uniformity.

2.4 Experimental Design and Setup

The experiment followed a Completely Randomized Design (CRD) with four treatments, as presented in Table 1, and each treatment was replicated three times. Because only one rainfall simulator was available, the runs were conducted sequentially. To minimize variability, all trials were carried out under controlled conditions, particularly with respect to temperature and wind. Fresh soil was used for each run, and treatments were randomly reassigned to the erosion plots to avoid any bias.

Table 1

Treatment applied in this study with the nomenclature identified for the use on the discussion with its description.

Treatment	Nomenclature	Description
I	Control	Bare soil (no BPS geotextile)
II	BPS 1	Mat made from 1.0 cm BPS strips
III	BPS 2	Mat made from 1.5 cm BPS strips
IV	BPS 3	Mat made from 2.0 cm BPS strips

The BPS geotextiles were carefully placed over the soil surface based on the assigned treatments, ensuring even coverage across each plot.

The experiment made use of locally available materials, including the constructed erosion plots, rainfall simulator, runoff collectors, water reservoir, and pump system. For each run, 25 kg of prepared soil was placed into the erosion plot, spread evenly, and then compacted using a wooden block until a uniform depth of 10 cm was achieved.

2.5 Data Collection and Measurements

2.5.1 Surface Run-off Determination and Collection

Prior to rainfall simulation, soil in each erosion plot was saturated with water. Then, a fine cloth was used to cover the inlet of the runoff collector to trap sediments. The rainfall was then applied continuously at a rate of 75 mm h⁻¹ over a period of 2 hours.

The runoff samples were collected at 15 minutes and 30 minutes intervals in the first and second hours respectively, following the method of Torillo [24]. Collected runoff was stored in labeled polyethylene collection bags. Collected sediments were dried in the oven at 105°C until the constant weight was achieved, defined as less than 1% variation between successive measurements.

2.6.2 Sediment Concentration, Sediment Yield, and Net Efficiency

The sediment concentration, sediment yield and net cover efficiency were calculated using Eq. (2), Eq. (3) and Eq. (4) adapted from Valle *et al.* [12].

$$\text{Sediment Concentration} = \frac{m_{\text{dry,covered}}}{V} \quad (2)$$

where:

$m_{\text{dry,covered}}$ = dry weight of sediments in runoff from covered slope

V = volume of the covered slope runoff

$$\text{Sediment yield} = \frac{m_{\text{dry}}}{\text{Surface area} \times \text{Time}} \quad (3)$$

where:

m_{dry} = dry weight of sediments taken after oven-drying the residue of runoff collector's filter until moisture content is not more than 5%.

Surface area = computed area of erosion plot

Time = time from the start to shut off of rainfall simulation

$$\text{Net cover efficiency} = \frac{m_{\text{dry,un covered}} - m_{\text{dry,covered}}}{m_{\text{dry,uncovered}}} \quad (4)$$

where:

Net cover efficiency = performance efficiency of BPS geotextile, %

$m_{\text{dry,uncovered}}$ = dry weight of the sediments from the uncovered slope

$m_{\text{dry,covered}}$ = dry weight of the sediments from the covered slope

2.6 Statistical Analysis

Analysis of data was done by Analysis of Variance (ANOVA) on a Completely Randomized Design to establish significant differences between treatments. All the statistical tests were performed at a 1% level of significance ($\alpha = 0.01$) using STAR (Statistical Tool for Agricultural Research) software. When significant differences were detected, Tukey's Honestly Significant Difference (HSD) test was applied for post hoc comparison of treatment means.

3. Results

3.1 Surface Run-off and Sediment Yield

The BPS geotextile treatments had a significant impact on the surface runoff and erosion sediment yield of the erosion plots under 75 mm h⁻¹ simulated rainfall (Tables 2 and 3) at 9% slope. Statistical analysis indicated that treatment and rainfall duration and the interaction between the two had a very significant effect on runoff and sediment transport ($p \leq 0.01$).

Table 2

Effect of banana pseudo-stem (BPS) geotextile strip width on surface runoff under simulated rainfall (75 mm h⁻¹)

Treatment**	Run-off Collected (L)					
	Time (seconds)**					
	15	30	45	60	90	120
Control	2.42 ^{Ad}	5.51 ^{Ac}	6.59 ^{Ac}	7.46 ^{Ac}	13.56 ^{Ab}	22.08 ^{Aa}
BPS 1	0.00 ^{Ba}	0.12 ^{Ca}	0.17 ^{Ca}	0.38 ^{Ca}	0.75 ^{Da}	1.19 ^{Da}
BPS 2	0.00 ^{Bd}	1.61 ^{BCcd}	2.47 ^{Bc}	3.11 ^{Bbc}	5.25 ^{Cab}	7.31 ^{Ca}
BPS 3	0.00 ^{Bc}	2.19 ^{Cbc}	2.33 ^{Bb}	3.31 ^{Bb}	7.44 ^{Ba}	7.31 ^{Ba}

Note: ** highly significant at p value of 0.01 in terms of run-off

Means followed by the same uppercase letter within a column are not significantly different among treatments, while means followed by the same lowercase letter within a row are not significantly different across sampling times, based on Tukey's HSD test at $p \leq 0.01$. The interaction between treatment and rainfall duration was found to be highly significant.

Table 3

Total runoff, sediment yield, and runoff sediment concentration of erosion plots under BPS geotextile treatments during simulated rainfall (75 mm h⁻¹)

TREATMENTS	Total Run-off (L)	Mass of soil collected (g)	Run-off sediments concentrations (g L ⁻¹)	Sediment yield (g m ⁻² hr ⁻¹) **
Control	57.61	131.67	2.29	299.24 ^a
BPS 1	2.59	7.00	2.70	15.91 ^c
BPS 2	19.75	14.33	0.73	32.58 ^d
BPS 3	22.58	18.33	0.81	41.67 ^b

Note: ** highly significant at p value of 0.01 in terms of sediment yield

Means followed by the same lowercase letter within a column are not significantly different among treatments based on Tukey's HSD test at $p \leq 0.01$.

The control plots (uncovered soil) produced the highest total runoff (57.61 L) during the 2-hour rainfall simulation and the highest sediment yield (299.24 g m⁻² h⁻¹). In contrast, all BPS-covered plots reduced runoff and sediment yield under the tested 9% slope and 75 mm h⁻¹ rainfall condition. These findings demonstrate erosion-control performance relative to bare clay loam soil in the controlled experiment, but they should not be interpreted as proof of equivalent performance under untested field conditions.

BPS 1 (1.0 cm strips) had the lowest total runoff (2.59 L) and sediment yield (15.91 g m⁻² h⁻¹), suggesting that narrower strips produced more continuous surface coverage and greater resistance to overland flow. Although its runoff sediment concentration (2.70 g L⁻¹) was slightly higher than that of the control (2.29 g L⁻¹), the greatly reduced runoff volume resulted in a much lower total transported sediment mass. BPS 2 (1.5 cm strips) and BPS 3 (2.0 cm strips) also reduced sediment yield relative to the control (32.58 and 41.67 g m⁻² h⁻¹, respectively), but they were less effective than BPS 1, plausibly because the wider strips formed larger openings through which water and sediment could move.

Runoff generally increased with rainfall duration in all treatments (Table 2), consistent with progressive soil wetting and declining capacity to store additional water. However, runoff and sediment transport remained lower in the BPS-covered plots than in the bare-soil control. The results indicate that the mats restricted overland flow and retained detached particles under the tested conditions; infiltration was not measured directly and therefore should not be inferred as the sole mechanism.

The performance of the BPS mats may be explained by three related mechanisms: interception of raindrop impact, increased surface roughness that slows overland flow, and physical retention of detached soil particles. A literature-based comparison provides preliminary context: BPS 1 sediment yield (15.91 g m⁻² h⁻¹) was numerically lower than the 17.13 g m⁻² h⁻¹ reported for a banana-fibre and coconut-coir geotextile by Hernandez et al. [25], and the net cover efficiencies of the BPS treatments exceeded the 74.7% reported for a *Bambusa blumeana* geotextile by Valle et al. [12]. These values were obtained in different studies with potentially different soils, slopes, rainfall characteristics, mat properties, and test procedures; therefore, they are contextual benchmarks rather than evidence that BPS outperforms coir, jute, bamboo, or commercial rolled erosion-control products.

Within the tested BPS configuration, strip width was therefore an important fabrication variable: the 1.0 cm strips produced the lowest runoff and sediment yield and the highest net cover efficiency. A direct benchmark using commercial geotextiles and established natural fibres under identical experimental conditions is still required to determine relative technical and practical advantage.

3.2 Net Cover Efficiency of BPS Geotextiles in Controlling Soil Erosion

The net cover efficiency of produced BPS geotextiles was assessed to measure their efficiency in controlling erosion and sediment transport (Table 4). The statistical analysis result showed that there is a significant difference between treatments ($p \leq 0.01$) which supports the notion that strip width affects the performance of the BPS mats. BPS 1 (1.0 cm strips) had the highest net cover efficiency of 94.74%, BPS 2 (1.5 cm strips) had 88.76% and BPS 3 (2.0 cm strips) had 85.77%. These findings suggest that finer strips offer a greater continuous cover of the soil surface, which increases the retention of sediments and minimizes the detachment of soil on 9% slopes.

Table 4

Net cover efficiency (%) of banana pseudo-stem (BPS) geotextiles with different strip widths under simulated rainfall (75 mm h⁻¹)

Treatments	Net Cover Efficiency (%)				Standard Deviation
	Replications			Average*	
	I	II	III		
BPS 1	94.38	94.35	95.5	94.74 ^a	0.66
BPS 2	91.88	87.9	86.49	88.76 ^b	2.80
BPS 3	89.38	81.45	86.49	85.77 ^b	4.01

Note: * means significant at p value of 0.01 in terms of average net efficiency

Means followed by the same lowercase letter within a column are not significantly different among treatments based on Tukey's HSD test at $p \leq 0.01$.

Net cover efficiency was calculated from the difference between the dry sediment mass from uncovered and covered plots, expressed as a percentage of the uncovered sediment mass. BPS 1 had the highest efficiency, consistent with its low runoff and sediment yield. BPS 2 and BPS 3 also protected the soil but had lower mean efficiencies than BPS 1, which may be associated with the larger openings created by wider strips.

The BPS treatments had higher net cover efficiency than the 74.7% reported for *Bambusa blumeana* geotextile by Valle et al. [12]. However, because this was not a side-by-side comparison, differences in experimental conditions prevent a definitive ranking of materials. The present findings support BPS as a promising biodegradable erosion-control material and identify 1.0 cm as the best strip width among those tested, but claims of lower cost or superior performance over commercial, coir, jute, or bamboo geotextiles require controlled benchmarking and economic analysis.

3.3 Practical Feasibility and Study Limitations

The fabrication procedure used simple tools and locally obtainable BPS sheaths: the material was manually stripped, sun-dried for approximately 10 days, cut with scissors, and handwoven. However, the recorded weaving times show a substantial labor requirement. For a 110 cm × 20 cm mat (0.22 m²), fabrication required approximately 2.0 h for BPS 1, 1.5 h for BPS 2, and 1.0 h for BPS 3, equivalent to about 9.09, 6.82, and 4.55 labor-hours m⁻², respectively. Thus, the superior erosion control of BPS 1 is accompanied by the greatest manual fabrication demand. Local production near banana farms could reduce raw-material hauling, but dried mats would still require bundling, storage in dry conditions, transportation to the site, anchoring or fastening during installation, inspection after intense storms, and replacement as the fibres degrade. Mechanized strip cutting and weaving,

standardized mat density and anchorage, and decentralized production should be investigated as possible routes to scalability. Because the study did not quantify raw-material collection, drying space, labor cost, transport cost, installation time, service life, maintenance frequency, or end-of-life management, it cannot yet establish total cost or commercial feasibility.

Several experimental limitations also constrain interpretation. Each treatment had three replications, and the experiment used one small plot size (110 cm × 20 cm), one slope gradient (9%), one rainfall intensity (75 mm h⁻¹), one 2-hour rainfall duration, one clay loam soil, and a controlled rainfall-simulator setting. Natural field conditions include variable slope gradients and lengths, antecedent moisture, soil heterogeneity, vegetation, repeated wetting and drying, wind, changing rainfall intensity and drop-size distribution, ultraviolet exposure, biological degradation, and installation disturbances. Accordingly, the reported runoff, sediment yield, and net cover efficiency represent comparative performance only within the tested condition and should not be generalized as absolute field-scale rates. Future studies should increase replication; test multiple slope gradients, rainfall intensities and durations, soil types, and initial moisture conditions; compare BPS directly with coir, jute, and commercial geotextiles; measure hydraulic properties, tensile strength, degradation, anchorage, and service life; and conduct field-scale, multi-season trials coupled with life-cycle and techno-economic assessment.

4. Conclusions

Under a 9% slope and 75 mm h⁻¹ simulated rainfall, all three handwoven BPS geotextiles reduced runoff and sediment yield relative to bare clay loam soil. BPS 1 (1.0 cm strips) performed best among the tested configurations, with total runoff of 2.59 L, sediment yield of 15.91 g m⁻² h⁻¹, and net cover efficiency of 94.74%. The results support the study's specific novelty: within a constant BPS material and over-under weave, narrowing the strips improved protective surface coverage and erosion control.

These findings are preliminary and condition-specific. With only three replications, a single small plot size, one slope gradient, one rainfall intensity and duration, one soil type, and a controlled setting, the study does not establish field-scale performance, durability, cost-effectiveness, or superiority over coir, jute, or commercial geotextiles. Future research should conduct direct material benchmarking and larger, longer field trials across multiple slopes, rainfall regimes, and soils, while quantifying mechanical durability, biodegradation, installation and maintenance requirements, production cost, transport, and scalability.

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Conflict of Interest Statement

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