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Resistance of *Syagrus coronata* fibers in waterproof-coated natural geotextiles under environmental degradation

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Introduction: Soil mass instability on steep slopes presents significant challenges for erosion control and soil stabilization, requiring the development of biodegradable geotextile alternatives. This study aimed to evaluate the resistance of geotextiles produced from *Syagrus coronata* (Mart.) Becc. fibers, treated with waterproofing resin, subjected to the effects of exposure to degradation under environmental conditions.

Methods: Geotextile samples were exposed to solar radiation, rain, wind, and soil microorganisms; mechanical behavior was assessed via tensile strength and static puncture tests, supplemented by scanning electron microscopy. Statistical analyses, including ANOVA-RM and regression models, were applied to discern the effects of exposure time and resin treatments on the fibers' performance.

Results and discussion: Key findings indicate that a single-layer resin treatment significantly prolongs the mechanical viability of the fibers over 120 days, maintaining higher ultimate tensile strength compared to untreated or double-layer-treated fibers. Although double-layer resin provided an initially higher tensile resistance, it accelerated structural failures beyond 90 days, while untreated fibers were nonviable after 60 days. These results highlight a trade-off between stiffness and durability, evidencing that a single-layer resin application delivers an optimal balance of mechanical resilience and flexibility. These findings suggest that a single-layer resin treatment provides a balance between durability and mechanical performance, making it a suitable choice for eco-friendly geotextile applications. Properly treated *Syagrus coronata* fibers emerge as an economical and sustainable alternative for geotextiles, offering greater durability and contributing to improving slope stabilization and erosion control in environmental conditions of recovery and revegetation of degraded areas.

KEYWORDS

soil bioengineering, natural geotextiles, erosion control, ouricuri, environmental degradation and protection

Introduction

Soil erosion is one of the biggest environmental challenges, leading to depletion of arable lands, water pollution, and sedimentation in rivers and reservoirs (Owens, 2020). This process initiates with the decomposition of soil aggregates due to the impact of rainfall or hydration processes, followed by the deposition of disaggregated particles within soil pores, initiating the transport of sediments (Han et al., 2019; Wang et al., 2021). Soil, being a finite and very important resource for various human activities such as food production, is strongly linked on the environmental sustainability discussion, requiring solutions to conserve natural resources and improve vegetation cover for soil protection (Hajitaheriha et al., 2021).

Soil bioengineering emerges as a sustainable solution, particularly with emphasis on soil and water conservation (Giupponi et al., 2019; Holanda et al., 2021; Mickovski and Waterlot, 2021; Preti et al., 2022). It involves the integration of inert materials such as iron, rocks, and geotextiles with living structures like vegetation (Cislaghi et al., 2017) gaining importance in erosion control along riverbanks and slopes (Maxwald et al., 2020). This study builds on previous research by exploring *Syagrus coronata* natural fiber's geotextil, addressing gaps in durability under environmental conditions (Holanda et al., 2021).

Within soil bioengineering strategies, geotextiles serve as erosion obstacle, offering immediate protection against slope erosion (Ardila et al., 2021; Tanasă et al., 2022; Wu et al., 2021). Their application facilitates rapid erosion control by improving slope stability and promoting swift vegetation growth (Broda et al., 2018; Fuggini et al., 2016; Saha et al., 2012). Geotextiles, as noted by Yan et al. (2018), foster vegetation growth, creating an environment that intercepts precipitation and reduces splashing, thus effectively managing soil erosion.

Geotextiles can be manufactured from synthetic, natural, or hybrid materials (Bassyouni, 2018; Likitlersuang et al., 2020; Nsiah and Schaaf, 2019), serving as surface protection against raindrop impact (splash effect) and reducing surface runoff velocity.

Thus, the incorporation of natural fibers into geotextile production offers a cost-effective alternative to their synthetic counterparts. Due to their widespread availability and low processing costs, geotextiles composed of natural fibers present an economically viable solution for soil stabilization, particularly in richness regions in such plant materials.

In addition, natural fibers demonstrate predictable durability, which makes them suitable for agricultural applications where adherence to typical crop planting cycles is important. This ensures continued effectiveness throughout planting cycles, avoiding potential disruption of mechanized farming processes caused by persistent fiber residues in the soil (Guerreiro Filho et al., 2010).

Recent research has increasingly explored the use of natural geotextiles in soil stabilization and erosion control, particularly because natural fibers can be chemically treated to enhance mechanical performance and improve their durability. For instance, Jaswal and Sinha (2022a) investigated the performance of coir geotextiles treated with different chemical solutions and demonstrated how surface treatments can significantly affect tensile strength and service life under varying load conditions. Their follow-up study (Jaswal and Vivek, 2023) further indicated that reinforcing unpaved road models with treated coir geotextiles can markedly enhance bearing capacity and reduce surface deformation. Similarly, Vivek Dutta and Kumari (2020), Vivek Dutta and Parti (2020), and Vivek Dutta and Parti (2019) evaluated the interface properties of sand/clay–coir geotextile systems and examined how chemical modifications influence tensile behavior and the overall performance of unpaved roads. These works collectively underscore the potential of natural fibers, not only in mitigating erosion but also in improving the structural integrity of road subgrades.

Despite these advancements, the literature on natural geotextiles remains largely focused on, *Corchorus capsularis*, and other more conventional fibers, leaving significant gaps regarding the *durability, mechanical performance, and biodegradation profiles* of lesser-studied natural fibers. In particular, there is limited research on the use of *Syagrus coronata* (Mart.) Becc. fibers, which could present unique mechanical properties, cost advantages, and environmental benefits when appropriately treated for long-term geotextile applications. As pointed out by existing studies on coir, the selection of chemical or physical surface treatments is crucial to balance mechanical reinforcement, water repellency, and flexibility, a trade-off that directly impacts the long-term effectiveness of erosion control measures (Jaswal and Sinha, 2022b).

Therefore, with proper maintenance and treatment, natural fiber geotextiles can offer advantageous and sustainable solutions in soil bioengineering applications, especially within agricultural environments (Al-Rashed and Jabari, 2020; Ryu et al., 2005).

The main characteristics of vegetable fibers include their renewable origin, low density, and biodegradability (Sathees Kumar et al., 2021), combining favorable mechanical and environmental properties (Akbarimehr et al., 2020). Vivek Dutta and Parti (2019) indicated that vegetable fibers can reach the mechanical properties of composites in geosynthetics while minimizing environmental impacts compared to synthetic fibers.

However, there are limited options for natural fibers suitable for geotextile manufacturing (Kumar Patel and Singh, 2022; Sayida et al., 2020). One explanation for this lackness is the insufficient studies of natural fibers from a broader range of plant species, explained by the lack of knowledge on their tensile strength with waterproofing agents in field conditions, which could enhance resistance to climatic degradation.

Therefore, to improve the understanding of the durability of geotextiles using natural fibers, this study aimed to evaluate the resistance of geotextiles produced from *Syagrus coronata* (Mart.) Becc. fibers, treated with waterproofing resin, subjected to the effects of exposure to degradation under environmental.

Materials and methods

Plant collection and processing

The *Syagrus coronata* (Mart.) Becc. (Figure 1a) is an angiosperm valued for its attractive appearance and tolerance to various environmental conditions, such as salt and wind. Its fibers are used in handicrafts, while its fleshy endocarp fruit (Figure 1b) is also noteworthy. Is a nutritional source for various domestic animals throughout the year (Ribeiro et al., 2021). Additionally, the leaves of the ouricuri palm are used for household roofs and in local communities for various purposes. Overall, *Syagrus coronata* (Mart.) Becc. is recognized for its ornamental and utilitarian qualities. The

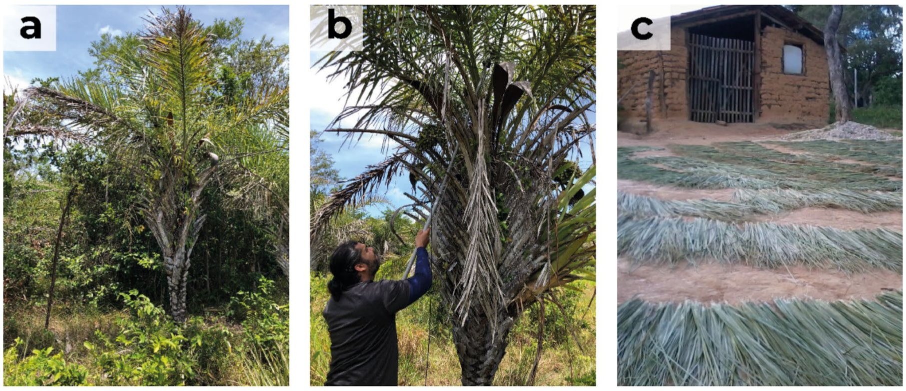

FIGURE 1
(a) *Syagrus coronata* (Mart.) Becc, **(b)** hand cutting of *Syagrus coronata* fibers at the petiole, 0.02 m above the sheath, ensuring plant regeneration and **(c)** shade drying of the collected fibers.

studied species were officially registered in Brazil's National System for the Management of Genetic Heritage and Associated Traditional Knowledge (*Sistema Nacional de Gestão do Patrimônio Genético e do Conhecimento Tradicional Associado*) under the registration code SisGen of A2B3842.

Geogrid manufacturing

The manufacturing geogrid made from *Syagrus coronata* fibers was conducted in four main stages, in order to produce a high-quality material with strong mechanical strength. The raw material was manually collected using smooth-bladed instruments to avoid damaging the fibers, with cuts made at the petiole, 2 cm above the sheath, to allow for plant regeneration (Figure 2b). After collection, the leaf blade fibers were subjected to drying in the shade in a ventilated environment (Figure 2c) for 6 days. This procedure was designed to reduce moisture and preserve the mechanical properties of the fibers.

After drying, the fibers were grouped into bundles with an average weight of 3 kg and stored in well-ventilated locations to prevent degradation prior to processing. This step was developed to maintain fiber uniformity and improve handling up to next stages.

The geotextile has a mass per unit area of 153.7 g/m^2, which falls within the typical range for nonwoven geotextiles, as outlined in ASTM D5261-10 (ASTM, 2018). Commonly corcialized nonwoven geotextile standards generally have a mass per unit area between 100 and 400 g/m^2, while woven geotextiles range from 100 to 300 g/m^2 (ASTM, 2018).

The fibers were defibrated to approximately 4 mm in diameter to ensure uniformity in geogrid weaving and mechanical performance, optimizing structural integrity and load distribution. Although variations in initial leaf properties, such as water content and fiber density, may occur, the defibration process naturally homogenizes the fiber dimensions by separating individual strands and eliminating irregularities. This method ensures consistent mechanical properties, as fiber thickness directly influences tensile strength and flexibility (Holanda et al., 2008). While this study did not focus on the impact of initial leaf uniformity, prior research indicates that post-processing techniques, including drying and mechanical refinement, play a more significant role in determining fiber consistency than the initial state of the raw material.

FIGURE 2
(a) Handcrafted loom used for weaving *Syagrus coronata* fibers into a geogrid and **(b)** application of a double layer of waterproof coating using a high-pressure spray system to improve durability and environmental resistance.

The manufacturing was carried out using wooden molds measuring 1 m^2 (Figure 2a), made by pins spaced 25 mm apart, which reflect the geogrid mesh spacing (25 mm) (Figure 2b), adjusted to evaluate the material's behavior under natural degradation. The fibers were initially arranged around the mold to form the base structure and then woven perpendicularly to create a grid pattern. Knots were applied at the intersection points to enhance the material's strength.

In order to reach durability, these natural geotextiles were treated with a waterproofing spray, utilizing a colorless wood resin of the Hydronorth® brand (Figure 2b). The wood resin utilized in this study is a Hydronorth® acrylic-based protective finish, formulated for waterproofing and preserving porous surfaces. Its chemical composition primarily includes acrylic polymers dispersed in either a solvent or water-based carrier, along with stabilizing additives to enhance ultraviolet (UV) resistance and microbial protection (Hydronorth, 2019). The objective of this treatment was to reduce permeability, delay degradation, and therefore increase resistance to climatic variables.

TABLE 1 Mean physical and mechanical properties of *Syagrus coronata* fiber geotextile.

Property	Mean value
Extension at max. load (mm)	6.33
Tensile deformation (%)	3.33
Load at rupture (N)	9.43
Tensile strength (N/mm)	3.14
Stiffness, J_sec (N/mm)	92.98
Rupture stress (N/mm)	1.34

Each geotextile sample received a uniform spray application of resin (Hydronorth®) with an estimated coverage of 0.0932 mL/m^2 per layer. The resin was applied in a single-pass spray technique, ensuring uniform distribution across the fibers. The treated samples were then allowed to air dry for 24 h before exposure to environmental conditions.

For the double-layer treatment, the same amount of resin per layer was applied as for the single-layer treatment, with a 24-h interval between applications to allow for adequate drying and better penetration of the resin. This process ensured that the second layer remained uniform.

The geotextiles were then randomly organized in the following treatments: (a) geotextile without waterproofing resin (control); (b) geotextile treated with a single layer of waterproofing resin; and (c) geotextile treated with two layers of waterproofing resin.

These treatments allowed reducing permeability, delaying degradation, and increasing resistance under climatic variables. Both sides of the geogrids were resin coated to ensure complete coverage. The Table 1 summarizes the mean physical and mechanical properties of the *Syagrus coronata* fiber geotextile from five test repetitions. The fibers exhibited an average extension at maximum load of 6.33 mm (3.33% strain) and a mean load at rupture of 9.43 N. The average tensile strength (based on the cross-sectional diameter of 3 mm) was 3.14 N/mm, with a mean stiffness (J_sec) of 92.98 N/mm and a rupture stress of approximately 1.34 N/mm. By comparison, commercially used coir and jute geotextiles (Vivek Shafi Mir and Sehgal, 2022a), often report tensile strengths in the ranges of 2–6 N/mm (coir) and 3–8 N/mm (jute).

Implementation of experiments

The experimental tests took place on a 14 m^2 slope area with Typic Quartzipsamment soil on the campus of the Universidade Federal de Sergipe (UFS), located in the municipality of São Cristóvão, Sergipe state, northeastern Brazil (coordinates 10°55'47.2"S 37°06'12.6"W). Geotextiles made from *Syagrus coronata* (Mart.) Becc, were exposed to environmental variables such as solar radiation, wind, rain, and soil microorganisms (Figure 3).

The geotextiles underwent natural degradation on the slope, with five collected samples at each scheduled time point from the central part of the geotextile during a maximum exposure period of 4 months. Four sample collections were conducted at different time intervals: T_0 (0 days), T_1 (30 days), T_2 (60 days), T_3 (90 days), and T_4 (120 days), representing the maximum period in which the geotextiles retained sufficient integrity for resistance tests. The selected exposure durations

FIGURE 3
(a) *Syagrus coronata* geotextiles exposed on a slope during sample collection and **(b)** detailed view of the geotextile.

(30, 60, 90, and 120 days) were based on previous studies evaluating biodegradation rates of natural fiber geotextiles under environmental conditions (Fontes et al., 2021). These time intervals allow for progressive analysis of mechanical deterioration, simulating real-world degradation patterns over short to medium-term field applications.

The intact and degraded samples were submitted to mechanical testing to evaluate their performance. For the unconfined tensile test, fiber samples were prepared with a total length of 200 mm and a useful length of 100 mm, in agreement with NBR ISO 103109:2013 (ABNT, 2013). The samples were subjected to static punching tests, following NBR ISO 12236 (ANBT, 2013) guidelines, using a 15 cm diameter. The geogrid was strategically positioned in the soil surface, facilitating fiber samples removal for tensile testing (Figure 3). This placement minimized the risk of fiber damage during extraction by reducing the need for excavation or excessive handling, thereby preserving the integrity of the material for accurate testing. For each treatment, five replicates were extracted to ensure reliability and statistical results robustness.

The mechanical properties data are necessary to understand the geotextiles performance in stabilizing slopes, where they experience traction, compression, and flexion. This study measured key mechanical resistance parameters, including rupture, stiffness, and toughness (Stokes et al., 2004). Unconfined tensile strength tests were performed at the UFS Materials Engineering Laboratory using a universal testing machine (EMIC, Model DL) with a maximum capacity of 300 kN.

The grip-grip distance was 100 mm, with the deformation speed fixed at 20 mm/min. Steel claws with grooved internal faces secured the geotextiles in the universal testing machine to improve adherence and prevent displacement during the traction force application. Throughout the testing process, the tests generated curves that illustrate breaking strength (αmax), breaking deformation (ε), and secant stiffness (Jsec). Figure 4 illustrates the tensile tests performed on *Syagrus coronata* (Mart.) Becc.

These punching tests followed the ISO 12236 specifications: Geotextiles – Determination of static puncture resistance – CBR-type piston test NBR ISO 12236 (ANBT, 2013), with the only variation being the sample size, which adhered to Mini-CBR test specifications (50 mm in diameter).

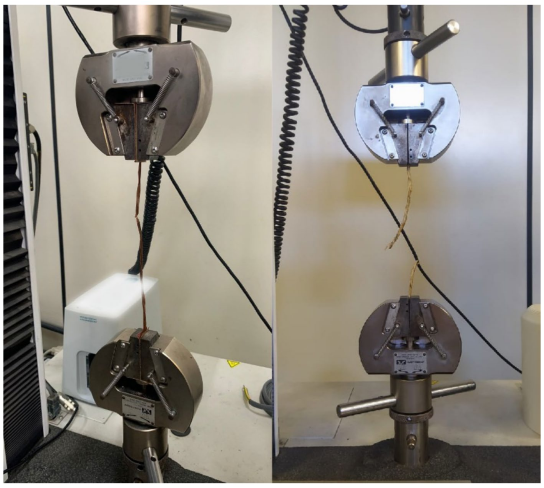

FIGURE 4
Tensile testing of *Syagrus coronata* (Mart.) Becc fibers.

The samples were cut to a diameter of 70 mm and firmly secured between the rings of a cylindrical support with an internal diameter of 50 mm. A 17 mm diameter punch was attached to the test machine to ensure its centralized and perpendicular alignment relative to the sample. The punch descended at a rate of 50 mm/min, while the machine applied the punching force.

Statistical analysis

The statistical evaluation was carried out to analyze how treatments and environmental exposure time influenced the mechanical properties of the *Syagrus coronata* geotextile. Two primary methods were applied: repeated measures analysis of variance (ANOVA-RM) and regression analysis. These analyses examined the effect of fiber exposure to environmental conditions on tensile strength (T1 to T4, corresponding to 1–120 days) and the application of waterproofing resin on the mechanical strength of the fibers.

The fixed (independent) variables (IVs) in this study were the applied treatments, specifically the presence or absence of waterproofing resin and the environmental exposure duration (30, 60, 90, and 120 days). These factors were systematically controlled and manipulated to assess their impact on the geotextile's structural integrity. The free (dependent) variables (DVs) were the mechanical properties of the geotextile, including tensile strength, puncture resistance, and deformation, which were measured across different treatment conditions.

Interaction effects between exposure time and waterproofing resin application were explored to identify statistically significant trends, with effect sizes calculated using Cohen's D to quantify the practical significance of the findings. The Bonferroni test was applied to maintain rigorous error control in multiple comparisons. To evaluate the influence of treatments in relation to control conditions, Eta squared (η^2) and Cohen's D were used as indicators of the magnitude of treatment effects. The mean difference (ΔM) test provided quantitative insights into variations between treatment groups, highlighting the significance of observed differences. To ensure the reliability of the statistical analyses, data normality was assessed using the Kolmogorov–Smirnov (KS) and Shapiro–Wilk (SW) tests, while Levene's test confirmed homogeneity of variances, a critical assumption for ANOVA-RM. In cases where sphericity was violated, Mauchly's test determined the need for adjustments, and Greenhouse–Geisser or Huynh-Feldt corrections were applied accordingly. Bootstrapping (1,000 resamplings with a 95% bias-corrected and accelerated (BCa) confidence interval) was implemented to enhance the robustness of the findings by mitigating potential biases and addressing distributional skewness.

All statistical tests were conducted at a significance level of $p = 0.05$. Regression analyses were used to evaluate the relationship between waterproofing treatments and the durability of mechanical resistance, while independent sample *t*-tests were performed to compare treatment groups, identifying statistically significant differences among the analyzed variables. These methodological approaches ensured a comprehensive assessment of the effects of waterproofing resin application and exposure duration on the mechanical behavior of the natural fiber geotextile.

Results and discussion

Ultimate tensile strength (σu)

As observed in Figure 5, the ultimate tensile strength (σu) of the geogrid fiber significantly increased with the addition of resin. An analysis of σu data revealed significant differences in tensile strength for both samples without resin [$F(1.488; 23.880) = 65.664$, $p < 0.001$, $\eta^2 = 0.891$] and with resin [$F(1.488, 23.880) = 48.200$, $p < 0.040$]. The substantial effect size for the non-resin samples indicates a strong relationship between the exposure period to biodegradation and the decline in rupture stress, while the results for resin-treated samples suggest a similar, though less pronounced, trend. The substantial effect size indicates a strong relationship between the exposure period to biodegradation and the decline in rupture stress.

The comparison between the geotextile fibers of *Syagrus coronata*, with or without waterproofing resin layer, over 120 days showed remakable differences in the ultimate tensile strength of the fibers. At the end of the exposure period, only the fibers treated with a single layer of resin remained viable, with an average maximum tensile strength of 0.964 N/m. This difference was statistically significant when compared to the initial sample, with a mean difference of 4.274 N/m. The untreated fibers (without resin) did not tolerate exposure to degradation beyond 60 days, with the average tensile strength recorded at this point being σu = 1.312 N/m^2 (Table 2). This represents a statistically significant reduction close to 63.2% in tensile strength compared to the initial value of 3.569 N/m^2 ($p = 0.033$). The progressive loss of tensile strength observed in untreated fibers beyond 60 days can be partially attributed to microbial colonization, which accelerates the enzymatic degradation of cellulose and hemicellulose. Studies have shown that fungi and bacteria present in soil environments facilitate hydrolysis of natural fibers, leading to a reduction in mechanical integrity (Jeon, 2016; Desai and Kant, 2016).

Treated fibers with a single layer of resin exhibited a more rapid loss of tensile strength, with a reduction of 73.45% over the same period (ΔM = 3.849 N/m). The rapid loss in tensile strength in treated fibers may be attributed to the formation of a rigid barrier that initially

TABLE 2 Ultimate tensile strength h of fibers over a 120-day period of exposure to natural degradation in the field.

Exposure time	Treatment	Mean	Mean difference (ΔM)	95% CI for mean difference		*Sig.*
				Bottom	Highest	
0 day	Without waterproofing resin	3.569		–	–	–
	Single layer	5.238	–	–	–	–
	Double layer	5.088	–	–	–	–
30 days	Without waterproofing resin	1.563	2.006	−1.102	5.114	0.539
	Single layer	3.696	1.542	−1.566	4.651	0.874
	Double layer	5.761	−0.674	−3.782	2.435	0.745
60 days	Without waterproofing resin	1.312	2.257*	0.126	4.389	0.033
	Single layer	1.390	3.849*	1.718	5.980	<0.001
	Double layer	1.977	3.111*	0.979	5.242	0.002
90 days	Without	–	–	–	–	–
	Single layer	1.360	3.878*	1.904	5.852	<0.001
	Double layer	1.548	3.539*	1.565	5.514	<0.001
120 days	Without waterproofing resin	–	–	–	–	–
	Single layer	0.964	4.274*	2.486	6.062	<0.001
	Double layer	–	–	–	–	–

*The mean difference is significant at a 0.05 level.

enhances strength but later traps moisture and accelerates degradation. This phenomenon aligns with findings from Akter et al. (2020) on jute-based geotextiles. Research has shown that jute geotextiles buried in soil completely lost their strength within a period of two and a half months due to biodegradation (Ghosh et al., 2019). In addition, prolonged exposure to sunlight can result in progressive loss of strength of natural fibers (Thomas and Hridayanathan, 2006).

Similarly, fibers treated with two layers of resin experienced a 61.14% reduction in tensile strength (ΔM = 3.111 N/m). Despite the faster initial degradation, fibers treated with a single layer of resin remained viable throughout the entire experimental period of 120 days, with an average tensile strength of $\sigma u = 4.274\ N/m^2$ at the end of the experiment. In contrast, untreated fibers and those treated with two layers of resin were no longer viable beyond 60 and 90 days, respectively (Figure 5). Furthermore, repeated exposure to rain likely contributed to fiber weakening, as wet-dry cycles induce swelling and contraction, generating internal stresses that exacerbate mechanical deterioration. This phenomenon has been observed in other natural fiber-based geotextiles, where prolonged exposure to fluctuating humidity conditions accelerates material fatigue (Chun et al., 2023).

Natural geotextile fibers are recognized to present a decrease in their ultimate tensile strength (σu) due to increased depolymerization at elevated temperatures (Joseph et al., 2002), often present in semi-arid and tropical regions. The application of two layers of waterproofing resin may have reduced the effective temperature affecting the fibers by minimizing direct contact with heated soil during exposure (Yin, 2017; Zhang, 2014). Also, Das and Banerjee (2013) observed a 6% reduction in σu when the *Cocos nucifera* fibers were exposed to 1 h of heating at 180°C, while Khan (2012) noted a 10% reduction in σu when the jute fibers (*Corchorus capsularis*) were exposed to 170°C for 1 h. As temperatures rise, there is typically a corresponding increase in creep strains and a decrease in elastic stiffness in non-woven geotextiles.

In addition to microbial and moisture-induced degradation, exposure to UV radiation played a significant role in fiber deterioration. UV-induced photodegradation affects the structural integrity of natural fibers by breaking down cellulose and lignin, causing embrittlement and reduced tensile strength. Studies on coir and jute geotextiles confirm that prolonged exposure to solar radiation accelerates material fatigue and surface cracking (Mahzan et al., 2017).

The results of the T-Student test revealed a significant difference between the two groups of fibers treated with different layers of waterproofing resin. Specifically, fibers treated with two resin layers displayed a statistically higher maximum tensile strength ($\sigma u = 1.977\ N/m^2$, $\Delta M = 3.111\ N/m^2$) compared to those treated with a single layer ($\sigma u = 1.390\ N/m^2$, $\Delta M = 3.849\ N/m^2$) at the 60-day exposure mark. These differences were statistically significant, as the single-layer treatment resulted in a greater mean difference ($\Delta M = 3.849$, $p < 0.001$), while the two-layer treatment also demonstrated a significant mean difference ($\Delta M = 3.111$, $p = 0.002$).

The t-statistic value [$F(12) = -2.327$, $p < 0.05$] shows that the differences in tensile strength between the two treatments are statistically significant at the 60-day mark. Furthermore, the single-layer resin treatment-maintained viability until the end of the 120-day experiment, with an average tensile strength of $\sigma u = 0.964\ N/m^2$ and a statistically significant mean difference of $\Delta M = 4.274$ ($p < 0.001$) compared to untreated fibers. In contrast, fibers with two resin layers were no longer viable after 90 days.

Furthermore, the effect size, measured by Cohen's D, was calculated as 0.620, suggesting a moderate intensity of statistical significance for the observed differences in tensile strength between the two treatment groups. This indicates that, while the application of two layers of resin initially provided higher resistance, the single-layer treatment ensured longer-term durability and mechanical performance, particularly clear over the extended field exposure period.

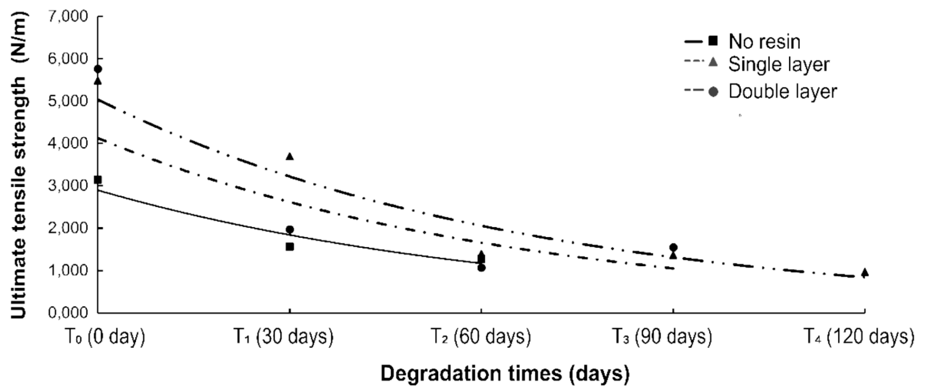

FIGURE 5
Tensile strength at breakage of *Syagrus coronata* fiber with an average diameter of 4 mm under field degradation for up to 120 days of exposure.

Overall, these results indicate that the number of waterproofing resin layers applied to fibers has an important impact on their tensile strength. Although treatment with a single resin layer enhances flexibility, allowing the material to absorb stresses without premature failures while maintaining protection against the effects of natural degradation. This aligns with previous studies on natural fiber composites, which suggest that moderate reinforcement can improve mechanical performance without compromising adaptability (Nurazzi et al., 2021).

However, adding two resin layers to geogrid fibers creates a structurally stiffer material, increasing susceptibility to cracks and failures due to accumulated stresses, especially under challenging environmental conditions. These findings align with previous studies reporting that stiffer materials, although initially more resistant, may experience faster structural failures under repetitive loads (Idrees et al., 2021).

This trend is particularly relevant for real-world applications such as road embankments and slope stabilization, where flexibility and durability are critical for long-term performance (Vivek Shafi Mir and Sehgal, 2022b). The results suggest that optimizing resin coatings is crucial to balancing strength and resilience in geotextile applications, preventing premature failures in challenging environmental conditions.

Also, the presence of two resin layers may form a dense barrier that, while initially and temporarily more resistant, promotes the retention of moisture and heat within the material. These factors can accelerate chemical and structural degradation processes over time, as observed in geotextiles treated with various resins (Akter et al., 2020). Additionally, such differences can be explained by load distribution and adhesion properties. Previous studies suggest that the sequence of layers and the interaction between fibers and the matrix significantly influence the strength and durability of hybrid composites (Kumar and Saha, 2022).

Tensile deformation (ε)

In the statistical analysis of fiber tensile deformation, only treatment T2, which involved a 60-day exposure with a single application of waterproofing resin, deviated from the normal distribution. This deviation was confirmed by the Kolmogorov–Smirnov (KS = 0.405, $p < 0.007$) and Shapiro–Wilk (SW = 0.680, $p < 0.006$) tests, indicating statistical significance. Levene's test validated the homogeneity of variance between the studied groups, supporting the application of ANOVA-RM.

ANOVA-RM revealed statistically significant differences in rupture deformation between different levels of deformation during the 120-day experimental period [$F(2.139; 21.561) = 9.764$, $p < 0.001$; $\eta^2 = 0.550$]. These results indicate variations in tensile strength related to time and treatment, with approximately 55% of the variability in tensile strength explained by differences in deformation levels over time, as indicated by the η^2 value.

The tensile deformation behavior of *Syagrus coronata* fibers (Figure 6) indicates that the application of two resin layers leads to a reduction in tensile strength at maximum load. This effect can be attributed to the increased stiffness imparted by the additional resin coating, which amplifies localized stress concentrations and accelerates degradation under environmental exposure (Soltan and Li, 2018). Furthermore, the denser resin layer may contribute to moisture and heat entrapment, which may further compromise fiber integrity by promoting hydrolytic and thermal degradation mechanisms (Wysokowski, 2021). These findings suggest that although resin application improves short-term mechanical performance, excessive layering may lead to long-term structural weakening due to accumulated internal stresses.

Composites exposed to UV radiation cycles and varying periods of rainfall experience significant degradation in their (Table 3) mechanical properties, particularly in deformation resistance. This effect is more found in materials without additive protection, as increased exposure to heat accelerates chemical degradation and weakens the fiber-matrix interface (Hamdan et al., 2019). Cunha et al. (2021) showed that such conditions lead to substantial losses in tensile properties, underscoring the need for solutions such as chemical additives, including resin, to mitigate these effects.

While increasing resin thickness improves protection against environmental factors such as moisture and UV exposure, and it simultaneously alters the mechanical behavior of the fibers, reducing their capacity for deformation under tensile loads (Table 2). Thicker resin layers promote benefits by enhancing the resistance of the fiber-matrix system to environmental degradation, including microfissures and delamination caused by cyclic stresses and thermal fluctuations. However, this increased stiffness also concentrates stress, which can accelerate localized failure under dynamic loading

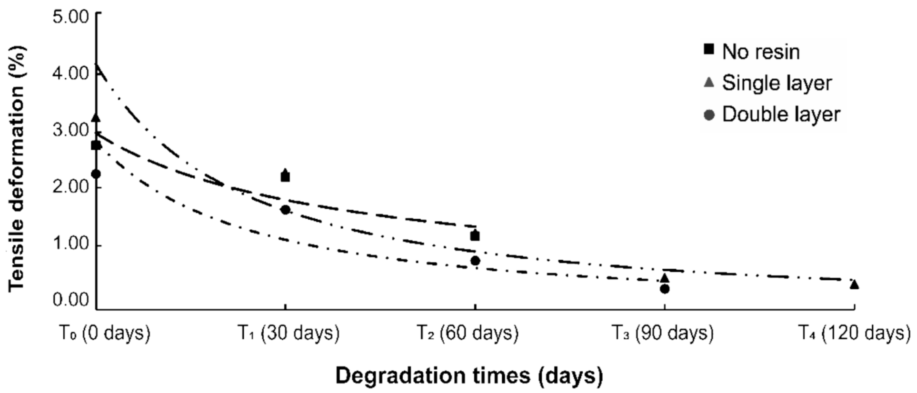

FIGURE 6
Rupture strain of the studied fiber over degradation time in the field.

TABLE 3 Tensile to deformation of *Syagrus coronata* fiber during 120-day exposure to natural degradation in the field.

Exposure time	Treatment	Mean (%)	Mean Difference (ΔM)	95% CI for mean difference		*sig.*
				Bottom	Highest	
0 day	Without waterproofing resin	3.30%	–	–	–	–
	Single layer	3.89%	–	–	–	–
	Double layer	2.75%	–	–	–	–
30 days	Without waterproofing resin	2.68%	0.68%	−1.9%	3.2%	1.000
	Single layer	2.77%	1.12%	−1.6%	3.5%	1.000
	Double layer	2.03%	0.72%	−2.1%	3.4%	1.000
60 days	Without waterproofing resin	1.49%	1.81%*	0.1%	3.7%	0.036
	Single layer	1.53%	2.36%*	0.4%	4.0%	< 0.000
	Double layer	1.04%	1.71%*	−0.1%	3.8%	0.069
90 days	Without	–	–	–	–	–
	Single layer	0.63%	3.26%*	2.1%	4.5%	1.000
	Double layer	0.43%	2.32%*	1.1%	3.7%	< 0.000
120 days	Without waterproofing resin	–	–	–	–	–
	Single layer	0.52%	3.77%*	2.3%	4.4%	< 0.000
	Double layer	–	–	–	–	–

*The mean difference is significant at a 0.05 level.

conditions, particularly in applications where high strain capacity is. These observations suggest that while the resin serves as a protective barrier, its mechanical influence on the composite structure must be carefully tailored to the application (Gao et al., 2022).

Accordingly, while the application of waterproofing resin strongly benefits the durability and mechanical performance of *Syagrus coronata* based geotextiles, the inherent trade-offs highlight a different approach need to resin thickness and composition, matching the material's characteristics with the specific demands of its use.

Static puncture resistance

The static puncture resistance obtained from the experiment is presented in Figure 7. ANOVA-RM revealed significant differences in static puncture resistance across degradation levels over time [$F(3.224, 230) = 49.329$, $p < 0.001$]. The large effect size ($\eta^2 = 0.925$) indicates that variations in degradation levels had an important impact on puncture resistance. As shown in Figure 7, the puncture resistance behavior of the fibers demonstrates that untreated fibers exhibited low initial performance, achieving a resistance of 6.47 N/m at 90 days before failing.

However, the application of waterproofing resin increased fiber rigidity, but paradoxically decreased resistance to diverging forces due to enhanced cohesion. Valentin et al. (2021) observed similar increases in stiffness in geotextiles as a result of long-term exposure to the weather. Resin application may also contribute to fiber shrinkage during weathering, reducing fiber plasticity. Both one-and two-layer resin treatments showed significantly lower responses (approximately 200%) than untreated fibers within the initial 90-day period. Interestingly, no significant differences emerged between resin treatments after 30 days, suggesting stabilization benefits and

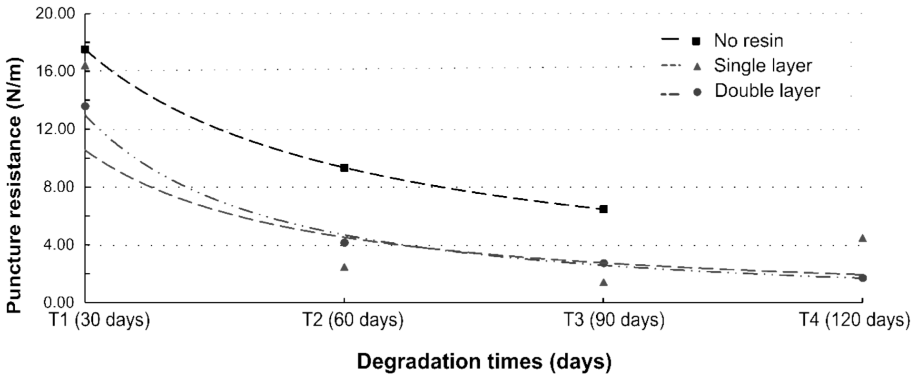

FIGURE 7
Static puncture resistance of the *Syagrus coronata* fiber over time.

indicating an optimal level of resin application beyond which additional layers do not add benefits.

On the other hand, the application of waterproofing resin led to an increase in the rigidity of the fiber, which paradoxically resulted in a decrease in resistance to divergent forces. This result was evident in the treatment with one-and two-layer resins, as shown in Figure 7, where the responses were significantly lower than untreated fibers within the initial 90-day period. Interestingly, no significant differences were observed between resin treatments after 30 days, suggesting that the benefits of resin application stabilized over time. This indicates that there may be an optimal level of resin application beyond which additional layers do not provide additional benefits.

This behavior aligns with findings in previous studies on natural fiber composites, where excessive resin application can lead to higher stiffness but reduced flexibility, ultimately compromising the material's ability to absorb stress without premature failure (Sujon et al., 2020). The initial reduction in mechanical resistance observed in resin-treated fibers may be attributed to localized stress concentrations at the fiber-resin interface, which can accelerate the formation of microcracks under tensile loads (Yamamoto et al., 2019).

Moreover, the stabilization observed after 30 days suggests that the resin's protective benefits reach a threshold, after which additional layers do not further enhance mechanical durability. This could be due to the saturation of resin penetration, where further applications primarily increase the surface density rather than improving the fiber-matrix bonding. Similar trends have been reported in hybrid composite materials, where excessive matrix reinforcement leads to brittleness and reduced impact resistance (Yang et al., 2020).

These findings stress the importance of waterproofing resin in improving puncture resistance, although with diminishing returns. This underscores the need for consideration of resin proportion to balance cost effectiveness with geotextile quality maintenance. These observations resonate with prior studies, such as Leon et al. (2016), affirming practical relevance in geotextile engineering.

Conclusion

The *Syagrus coronata* natural fibers, despite their inherent susceptibility to degradation under prolonged environmental exposure, demonstrated enhanced mechanical performance when treated with waterproofing resins. This study confirmed that resin application increased resistance to maximum load and static puncture, although at the cost of reduced flexibility and tensile strength under divergent forces.

Treated fibers exhibited greater resistance to maximum load and static puncture, although with a reduction in flexibility and tensile strength under divergent forces. This balance between advantages and limitations underscores the importance of carefully tailoring resin application to meet the specific demands of each engineering project.

The use of waterproofing resin, particularly a single-layer application, as an additive proved to be an effective strategy for extending the lifespan and performance of the materials, offering an approach that combines functionality, cost-effectiveness, and sustainability within the context of soil bioengineering.

These findings highlight the need to optimize resin application to balance durability and mechanical adaptability, ensuring the material's effectiveness for engineering applications.

Observed performance trends suggest that resin treatment helps mitigate the effects of environmental stressors on fiber integrity.

Notwithstanding these findings, certain limitations should be acknowledged. This study was conducted under specific regional climatic conditions over a four-month period, which may limit the generalizability of the results.

Future research involving longer exposure times and diverse environmental settings is essential to validate and broaden these findings for varied soil bioengineering applications.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

FH: Conceptualization, Writing – original draft, Writing – review & editing, Investigation. LS: Writing – original draft, Writing – review & editing, Formal analysis, Methodology. EMS: Writing – original draft, Writing – review & editing. AP: Writing – original draft, Writing – review & editing. JS: Writing – review & editing. EGS: Writing – original draft. CF: Writing – review & editing. RA: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.

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