Comparative Analysis of Biodegradation Resistance in Natural Geotextile Fibers

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Abstract

This research provides a comprehensive analysis of the behavior of natural geotextile fibers - *Syagrus coronata*, *Typha domingensis*, and *Eleocharis sp.*, under environmental stressors over a period of 120 days. A total of 24 samples, measuring 7 cm in length, were selected for field exposure, comprising geotextile fibers derived from the cited species. Most samples underwent treatment with waterproofing resin at two concentrations: 0.324 mg/mL for a single layer (concentration A) and 0.648 mg/mL for a double layer (concentration B). Control samples were left untreated. Fracture analysis was conducted using digital processing of scanning electron microscopy images. The results revealed variable resistance to degradation, influenced by different treatments and exposure durations. Notably, *Typha domingensis* fibers treated with concentration B resin exhibited reduced cracking, attributable to their unique morphological and structural characteristics and their interaction with the protective resin, *Eleocharis* sp. fibers treated with a double layer (concentration B) demonstrated superior resistance to degradation compared to concentration A. On the other hand, no significant difference between treatments was observed in *Syagrus coronata* fibers, which nonetheless exhibited inherent resistance to degradation even without treatment. Typha domingensis fibers demonstrated superior physical performance compared to other fibers, which can be attributed to their inherent morphological and structural characteristics as well as their intrinsic composition. These findings underscore the importance of additives and protective treatments in enhancing the durability and resistance of geotextiles.

1. Introduction

The increasing concern for the environmental impact of human activities has spurred the exploration of sustainable alternatives in engineering. Natural geotextiles have emerged as a promising solution for soil stabilization and erosion control, offering a more sustainable option compared to synthetic geotextiles (Pandey et al., 2017). Natural fibers, derived from renewable sources, possess favorable mechanical properties and cost-effectiveness, making them suitable for various applications such as soil stabilization, erosion control, drainage systems, and reinforcement of asphalt and concrete (Ramzan et al., 2020; Prasad et al., 2023).

The utilization of natural geotextiles in conjunction with sustainable technologies has demonstrated significant advantages in soil protection, while also proving to be more economically viable than traditional engineering techniques (Li et al., 2020). Geotextiles provide direct protection against soil erosion, exhibit controlled degradation, and expedite the process of revegetation, minimizing erosion processes (Holanda et al., 2020).

Vegetable fibers used in geotextile production offer a favorable combination of mechanical and environmental properties (Kumar, 2018). These geotextiles present advantages like simplified implementation, compatibility with the surrounding landscape and environment, contributing to the preservation of local biodiversity (Dixon et al., 2016). Therefore, comprehensive studies on the durability of natural geotextiles, both in laboratory and field settings, are crucial to better recognize their properties and ensure successful slope and riverbank stabilization, promoting soil anchorage.

The selection of appropriate natural fibers for geotextile manufacturing is paramount in guaranteeing material efficiency and optimizing durability (Rocha et al., 2022). When selecting fibers, characteristics like tensile strength, modulus of elasticity, density, abrasion resistance, and processability must be taken into consideration (Croitoru and Roata, 2021).

While geotextiles made from vegetable fibers are viable and applicable in various situations, it is critical to acknowledge the limitations of natural fibers, including water absorption, reduced stability, and durability (Khalid et al., 2021). These factors can potentially compromise the integrity and functionality of the material over time. The biodegradation of geotextiles is influenced by several factors, including the chemical composition of the fibers, environmental conditions, and the presence of microorganisms (Prambauer et al., 2019).

The fungal action primarily drives the degradation of geotextiles, with bacteria playing a secondary role in the process (Karimah et al., 2021). In humid conditions, fungi exhibit high efficiency in breaking down natural fibers (Ahmed and Nizam, 2008). The interaction between lignocellulosic fibers and microorganisms follows a degradation pathway involving enzymatic oxidation, reduction, and hydrolysis (Lynd et al., 2017). Fungi excel in breaking down natural fibers under moist conditions (Goodell et al., 2020).

One significant consequence of enzymatic oxidation during biodegradation is the formation of fractures in natural fibers, leading to a reduction in mechanical strength and overall durability. This issue is particularly relevant as most natural fibers possess porous characteristics and an affinity for water due to the presence of hydrophilic groups in their structure (Qua et al., 2011).

The combination of porous features and fractures allows for moisture absorption, resulting in fiber swelling and weakening of the cell wall. This behavior further facilitates microbial attack, as microorganisms possess enzymatic systems capable of hydrolyzing carbohydrate polymers present in the fibers (Bissaro et al., 2018). In the context of natural geotextiles, durability refers to the material's ability to maintain integrity and performance over a given period, even when exposed to environmental agents (Li et al., 2020).

Untreated organic polymers are primarily degraded by fungi, with bacteria playing a secondary role (Numan et al., 2018). However, research indicates that this degradation pathway can be slowed down by applying protective treatments to fibers used in geotextile production, especially in the face of biodegradation (Ramesh, 2016).

Recent studies have investigated the mechanical damage inflicted on geotextiles, whether they are synthetic or natural fibers treated with protective compounds (Dias Filho et al., 2022). These studies have explored the actions of microorganisms and potential solutions to delay their detrimental effects, such as the development of hybrid geocomposites with enhanced mechanical strength and improved durability (Boopalan et al., 2013; Kikumoto et al., 2010).

Currently, the study of fractures in geotextile meshes relies on several classical methods that can be exhaustive, prone to sampling and measurement errors, or invasive and destructive, leading to subjective results or indirect measurements. In this regard, scanning electron microscopy (SEM) emerges as a valuable and efficient tool for analyzing geotextiles, providing detailed and precise information while minimizing the risk of errors and delivering faster results (Rezende et al., 2011).

Digital image processing has gained popularity in the field of natural engineering, finding applications in the inspection of species with biotechnical characteristics (Van Eeckhout et al., 2021), analysis of soil disturbances caused by agricultural equipment (Beraldo et al., 2014), and evaluation of root systems (Carvalho et al., 2020). Building upon this trend, the present study aims to explore the potential of these techniques in analyzing fractures in geotextile meshes. The accuracy and efficiency of these modern tools can prove immensely valuable in assessing the impact of natural biodegradation on natural fiber geotextiles.

A rigorous analysis of the cracking and durability of plant fibers in field conditions can yield valuable insights into their effectiveness and potential applications in soil bioengineering for slope stabilization. Therefore, this article aims to investigate the performance of grid-concentration geotextiles, made from natural fibers, under degradation caused by exposure to climatic agents in practical field conditions, focusing on the variation of fiber fissures.

2. Materials and Methods

2.1 Collection of Plants and Processing of samples

The selection of samples of *Syagrus coronata* (Mart.) Becc, *Thypha domingensis* and *Eleocharis* sp. was based on the mechanical properties and cellulose and lignin contents of each species reported in the literature. Leaves and sprouts from the plants were collected in two municipalities in the Lower São Francisco river, in the northeastern Brazil between 2020 and 2022.

Typha domingensis, is a perennial angiosperm plant found in humid zones within the genus Typha, of the family Typhaceae (Hegazy et al., 2011). It can be found in various regions around the world, including the Americas, Europe, Africa, and Asia (Greenhouse et al., 2012). This highly adaptable and fast-growing plant is often found in marshy areas and along the streambanks, lakes, and rivers, and is more tolerant of water depth and salinity than other Typha species (Grace, 1989; Hotchkiss, 1949). The plant can grow up to 5 meters tall and is known for its distinctive cylindrical stems of brown flowers surrounded by green leaves (Les, 2020). The leaves of *Typha domingensis* are long and flat with a cylindrical stem, used as materials for roofing, making baskets, and mats.

Besides its ornamental and utilitarian value, *Typha domingensis* is also important for its role in humid zone ecosystems. It acts as a filter, removing excess nutrients and pollutants from the water (Deguenon et al., 2022). Generally, *Typha domingensis* is a valuable species with a wide range of uses and ecological benefits. The formal identification of the plant material *Typha domingensis* was made by Dr. Maria Luiza Silveira de Carvalho, who is professor of Botany at Biology Institute-UFBA.

Syagrus coronata (Mart.) Becc., an angiosperm (monocotyledonous) belonging to the Arecaceae botanical family commonly known as "licuri palm", is a species of perennial palm native to South America. Easily propagated (Gonçalves et al., 202), in Brazil it is commonly found in the dry and arid regions of the Caatinga biome, extended from the north of Minas Gerais state, occupying the entire eastern and central portion of Bahia state, to the south of Pernambuco state, also encompassing the states of Sergipe and Alagoas in northeastern Brazil (Drumond et al., 2007). The tree is known for its fronds resembling feathers, which can grow from 2 to 3 meters in length, distributed in a spiral along the length of the stem, and its crown can reach a diameter of up to 10 meters (Lima 2019). It presents small, yellowish flowers arranged in panicle-type inflorescences, protected by a large leathery peduncular bract (Lorenzi et al.,2004).

Syagrus coronata (Mart.) Becc. is a plant with multiple uses due to its attractive appearance and tolerance to various environmental conditions, such as salt and wind. Its fibers are also used in handicrafts, and its abundant, ovoid, and fleshy endoderm fruit serve as a nutritional source for various domestic animals, as they flower throughout the year (Bagaldo et al., 2019; Ribeiro Daza et al., 2021). In addition, the leaves of the licuri palm are used for roofs and palm trees in local communities. In general, *Syagrus coronata* is a versatile and valuable species, widely appreciated for its ornamental and utilitarian qualities. The formal identification of the plant material *Syagrus coronata (Mart.) Becc.* was made by Msc. Mariana Macário, specialist in Arecaceae and doctoral student in the Post-Graduation Program in Botany/UEFS.

Eleocharis sp., is an angiosperm with flowers belonging to the botanical family Juncaceae, commonly known as *Eleocharis*. This genus is widely distributed throughout the world and is found in a variety of habitats, including swamps, meadows, and pastures (López-Juambeltz et al., 2020). This species is known for its tall, green, or reddish stems, which can reach a height of 1.5 meters (Xia et al., 2020). Thus, they are flexible and have a cylindrical shape. The leaves are narrow and flat and are arranged along the stem in a spiral pattern (Tackholm, 1974).

The *Eleocharis* sp. flowers are small and discreet. They are arranged in dense clumps along the stem and are typically green or brown in color. *Eleocharis* sp. is a valuable species for many uses, including erosion control, habitat creation, and wet zone restoration (Snogerup, 1978). It is also commonly used as a landscaping plant, as well as material for making baskets, vases, and other items. Tackholm and Drar (1974) mention that the production of *Eleocharis* sp. mats was described by Abu Hanifa (895 AD) and Ibn El- Beitar (1248 AD), with Cairo being the main center of the ancient mat industry.

In ancient times in Egypt, the roots of *Eleocharis* were used in the manufacture of writing instruments, sandals, and baskets. *Eleocharis* sp. is a resistant, versatile, and attractive species that has a wide range of uses and ecological benefits (El-Shamy et al., 2015). The formal identification of the plant material *Eleocharis* sp. was made by Dr. Ana Paula do Nascimento Prata, who is professor of Agronomy at Universidade Federal de Alagoas - UFAL.

Voucher samples were kept in the Herbarium of the Universidade Federal de Sergipe (ASE), São Cristóvão-SE, Brazil. After classification and botanical registration, the samples of the three species were taken to the laboratory for drying, stretching, and fiber separation using two geotextiles.

The collection of wild plants specimens in Brazil requires mandatory licenses and must follow the standard procedures recommended by the National System of Management of Genetic Heritage and Associated Traditional Knowledge "SisGen" (Freitas et al., 2021). This collection was carried out under the registration code SisGen A2B3842.

2.2 Field experiment implementation

The geotextiles used in this study were produced in a previous phase of research conducted by the Laboratory of Erosion and Sedimentation – LABES/UFS, using fibers from *Syagrus coronata*, *Thypha domingensis*, and *Eleocharis* sp. To enhance the durability of these natural geotextiles, they were coated with a colorless wood resin, specifically the waterproofing product from the Hydronorth® brand (Fig. 1a).

This coating process aimed to reduce permeability and delay degradation, thereby increasing the material's resistance to climatic factors. To ensure extensive coverage, the waterproofing resin was applied to both sides of the geotextiles. The geotextiles underwent the following treatments: a) Geotextile without waterproofing resin (control), b) Geotextile treated with a single layer of waterproofing resin at concentration A (0.324 mg/mL^{-1}), and c) Geotextiles treated with two layers of waterproofing resin at concentration B (0.648 mg/mL^{-1}).

The experimental testing to evaluate the impact of climate factors on the geotextiles was conducted on a 14 m^2 slope consisting of Quartzipsamments. The test site was situated on the Campus of the Universidade Federal de Sergipe (UFS) in São Cristóvão, state of Sergipe, northeastern Brazil (coordinates 10°55'47.2"S 37°06'12.6"W) (Fig. 1b).

For the assessment of biodegradation agents, five samples were collected from the central region of the geotextile during each scheduled collection over a maximum exposure period of 120 days (four months). These samples were exclusively selected from geotextiles displaying varying degrees of resistance or integrity. The collection process included four distinct time intervals: T_0 (0 days), T_1 (30 days), T_2 (60 days), T_3 (90 days), and T_4 (120 days).

Subsequently, the collected samples were delivered to the Microbiology Laboratory of the UFS for fungi identification. The identification process followed the methodology outlined by Giovannetti et al. (1980).

2.3 X-Ray Diffraction (XRD)

Estimates of crystalline and amorphous cellulose were obtained using the X-ray diffraction technique (XRD) performed at temperature, in order to contribute to a detailed understanding of these biopolymers used to manufacture geotextiles. This methodological approach allows an in-depth and rigorous analysis of the crystalline structures inherent in cellulose and lignin, thus increasing the understanding of these vital structural components in plant biochemistry (Romruen et al. 2022). To determine the amorphous content (lignin and hemicellulose) and cellulose, analyzes were carried out following the methodology of Rowell et al. (1997). The procedure consists of first grinding the fibers in a knife mill and then sieving them through a 16-mesh sieve. After that, the material is immersed in 1:1 cyclohexane/ethanol for 48 hours and then immersed in water for 6 hours, for the extraction of the nonpolar and polar soluble components, respectively. The material is then dried in an oven at a temperature of 105°C ± 5°C for 4 hours e.g. finally, the DRX analyzes were performed in triplicate. The identification of the crystalline phases present in the fibers was performed using the X-ray diffraction technique. The analysis was conducted using a Rigaku diffractometer, operating with a copper tube at 40 kV and 20 mA. Sweeping was performed on the 2θ scale, with a range of 5° to 55° and a sweep speed of 0.5°/min.

2.4 SEM Methodology

Fracture analysis was conducted using the histogram of images obtained through Scanning Electron Microscopy (SEM). SEM is a microscopy technique utilized for characterizing and analyzing the microstructure of samples, generating high-resolution three-dimensional images that provide insights into the material's chemical composition. This technique enables the identification of the sample's structure, morphology, chemical elements, and surface topography (Mahltig et al., 2022).

The histogram of an image represents the statistical distribution of gray levels present in the image. It graphically displays the number of pixels corresponding to each gray level. By examining the histogram visually, valuable information regarding image quality, such as contrast levels and average brightness, can be obtained. It helps in identifying whether the image exhibits a uniform distribution of tones or if certain gray bands predominate.

The analysis provides insights into the location and extent of fractures that occurred in both the treated and untreated fiber samples during the 120-day exposure period. To convert crack levels into pixel intensity levels, the images underwent local thresholding employing the Minimum method proposed by Prewitt & Mendelsohn (2006). This method involves iterative smoothing using a moving average with a window size of 3 until only two local maxima remain, where the threshold limit "t" satisfies $yt - 1 > yt < = yt + 1$. The analyses were performed using the ImageJ software (Schneider et al., 2012).

For SEM analysis, the samples were gold-metalized using a Cressington metallizer from the manufacturer Kurt J. Lesker 108. Images were captured using the HITACHI TM 3000 equipment under a vacuum and electron beam of 15 kV. The darkest damaged areas were selected based on thresholding. The following adjustments were applied to generate the histogram: a histogram scale of 255 (8 bits of memory), and

50x magnification, enabling the visualization of the morphological surface of fibers exposed to climatic factors for 30, 60, 90, and 120 days, respectively.

2.5 Statistical analysis

To evaluate the temporal evolution of biodegradation among various treatments and fibers over the specified interval (T_1 – 1st day to T_4 – 120th day), a factorial analysis of variance (ANOVA) was conducted, considering multiple measurements. The primary objective of this analysis was to monitor the activity of biodegradation agents over time and examine the influence of applying the waterproofing resin. Data normality was assessed using the Kolmogorov-Smirnov (KS) and Shapiro-Wilk (SW) residual tests (Shapiro and Wilk, 1965; Kolmogorov, 2008), while the assumption of variance homogeneity was evaluated using the Levene test (Barker and Shaw, 2015).

For automated fracture identification and diameter measurement in the sample images, the publicly available software ImageJ was employed. These measurements served as parameters for assessing fiber degradation. Upon confirming a statistically significant difference among the groups identified through the analysis of variance ($p < 0.05$), post hoc comparisons were conducted. To examine the interaction effects of fiber, resin application, and exposure time, post hoc analyses were performed using Hochberg's GT2 test at a 5% significance level, considering the overall homogeneity of the samples.

The effects of the discrepancy between initial natural degradability and natural degradability after 120 days of exposure were analyzed using the Bonferroni test (Pereira et al., 2015) with a significance level of 5%. Effect sizes were measured using Eta squared (η^2) and Cohen's *d* for the mean difference test (ΔM) (Cohen, 2013). Effect sizes quantify the strength of the relationship between an independent variable (IV) and a dependent variable (DV). In this study, the effect size obtained by the DV indicates the impact of the geotextile treatment compared to the control treatments (T_1 and without waterproofing resin).

To enhance the reliability of the results and account for deviations from normality in the sample distribution and differences in group sizes, bootstrapping procedures were implemented. These procedures help mitigate potential biases and increase the robustness of the findings.

3. Results

3.1 DRX Analysis

The X-ray diffraction pattern of the three analyzed fibers is shown in Fig. 2. The X-ray diffraction analysis (XRD) results from the three fibers showing two prominent diffraction peaks at $2\theta = 11.65°$ and 22.20 °, 11.69° and 22.14°, 11.71° and 21.54° for *Eleocharis* sp., *Typha domingensis* and *Syagrus cononata* respectively. The presence of these peaks suggests that the fibers have a specific crystalline structure, with crystalline planes corresponding to these diffraction angles. Unlike *Eleocharis* sp. and *Typha domingensis*, *Syagrus cononata* showed a greater intensity in the 002 plane (corresponding to 2θ of

21.54°) than in the 101 plane (2θ = 11.71°), indicating that there is a greater concentration of crystalline structures of cellulose in their composition than amorphous structures (lignin and hemicellulose).

3.2 Analyzes SEM

The analysis of residual data distribution revealed that only the *Syagrus cononata* fiber treatment exposed for 30 days without resin application (concentration A) exhibited a normal distribution, as indicated by the Kolmogorov-Smirnov test (KS = 0.466, $p < 0.052$) and the Shapiro-Wilk test (SW = 0.821, $p < 0.031$). The Levene's test confirmed the homogeneity of variance across all groups. To address the violation of assumptions in the analysis of variance, 1,000 resamplings were performed, and a 95% confidence interval was calculated for mean differences using the BCa method (Haukoos et al., 2005).

The overall results of the ANOVA demonstrated statistically significant differences in the number of fractures over the 120-day experiment for the three fibers without resin treatment ($F (4, 113) = 6.403$, $p < 0.000$; $\eta^2 = 0.255$). Additionally, there were significant differences observed for fibers treated with concentration A, although the effect size was relatively low ($F (4, 24) = 3.672$, $p < 0.011$; $\eta^2 = 0.329$) when compared. No statistically significant differences were observed among the three fibers treated with concentration B protection after 120 days of exposure ($F (4, 24) = 2.213$, $p < 0.092$; $\eta^2 = 0.234$).

Upon analyzing the post hoc test results, it is evident that among the three fibers examined and treated with the protective resin, *Typha domingensis* treated with concentration B exhibited the lowest frequency of fracture occurrence by the conclusion of the 120-day natural degradation period (N = 31.97). The SEM images of *Typha domingensis* (Fig. 3) revealed an improved fiber-matrix interfacial adhesion and morphology of the surface after the application of the waterproofing resin.

In the comparison between *Typha domingensis* fibers treated with concentration B and untreated fibers of the same species after 120 days of exposure, a significant performance improvement was observed. There was an approximate increase of 350.6% in performance ($\Delta M = -112.10$ N, BCa 95% [52.34–171.87], $p = 0.006$, Cohen's $d = 5.212$). However, when analyzing the number of fractures in *Typha domingensis* fibers over 120 days, with and without the application of waterproofing resin, no statistically significant differences were found (Table 1).

Table 1
Fractures analysis of *Typha domingensis* fibers during 120 days of natural degradation exposure.

time Treatment	Exposure	Average	Mean Difference (IJ)	95% CI for mean difference Bottom	Higher	follow bonf	Cohens'd
30 days	Without waterproofing resin	48.984	--	--	--	--	--
	Concentration A	68.086	--	--	--	--	--
	Concentration B	59.893	--	--	--	--	--
60 days	Without waterproofing resin	51.799	-2.815	-129.109	123.479	1.000	0.112
	Concentration A	51.779	16.307	-109.988	142.601	1.000	0.555
	Concentration B	63.269	-3.376	-129.670	122.918	1.000	0.110
90 days	Without waterproofing resin	36.466	12.518	-113.777	138.812	1.000	0.434
	Concentration A	138.048	-69.963	-196.257	56.332	1.000	2.380
	Concentration B	127.489	-67.596	-193.891	58.698	1.000	2.300
120 days	Without waterproofing resin	144.077	-95.093	-221.388	31.201	0.298	3.237
	Concentration A	149.174	-25.755	-152.050	100.539	1.000	0.880
	Concentration B	31.972	27.921	-98.374	154.215	1.000	0.950

* *The mean difference is statistically significant at a significance level of 0.05.*

The analysis of the results obtained for *Typha domingensis* fibers, subjected to two concentrations of protective resin treatments, demonstrates a statistically significant variation in fracture occurrence after 120 days of exposure to natural degradation.

Similarly, when evaluating *Eleocharis* sp. fibers treated with two concentrations of protective resin, a significant variation in fracture occurrence after 120 days of exposure is observed ($\Delta M = 118.67$ N, BCa 95% [93.86–143.47], $p < 0.001$, Cohen's $d = 13.286$). Treatment B shows a significantly lower incidence of fractures compared to the other treatment, with a difference of 305.9% (N = 38,804).

Furthermore, when considering the time variable, no statistically significant differences are observed in the geotextile fibers made from both treated and untreated *Eleocharis* sp. fibers (Table 2).

Table 2
Fracture analysis of *Eleocharis* sp. fibers treated with protective resin during 120 days of exposure to natural degradation.

Treatment	Exposure time		Average	Mean Difference (IJ)	95% CI for mean difference		follow bonf	Cohens'd
					Bottom	Higher		
	30 days	Concentration A	74.304	- -	- -	- -	- -	- -
		Concentration B	41,991	- -	- -	- -	- -	- -
	60 days	Concentration A	123,280	-48,976	-300,530	202,578	1,000	1,070
		Concentration B	67,981	-25,990	-326,654	274,675	1,000	0.480
	90 days	Concentration A	76,530	-2,227	-253,781	249,327	1,000	0.050
		Concentration B	90,650	-48,659	-349,323	252,006	1,000	0.890
	120 days	Concentration A	157,477	-83,174	-334,728	168,380	0.430	1,820
		Concentration B	38,804	3,187	-297,478	303,851	0.344	0.060

** The mean difference is statistically significant at a significance level of 0.05.*

Table 3
Fissures formation in *Syagrus coronate* fibers during 120 days of natural degradation exposure.

time Treatment	Exposure	Average	Mean Difference (IJ)	95% CI for mean difference		follow bonf	Cohens'd
				Bottom	Higher		
30 days	Without waterproofing resin	46.338	--	--	--	--	--
	Concentration A	66.462	--	--	--	--	--
	Concentration B	46.340	--	--	--	--	--
60 days	Without waterproofing resin	89.028	-42.691	-153.550	30.500	0.462	0.878
	Concentration A	18.578	47.884	17.824	86.284	0.050	3.297
	Concentration B	89.030	-42.690	-149.770	22.931	0.465	0.855
90 days	Without waterproofing resin	125.563	-79.225	-124.658	-38.068	0.039	3.557
	Concentration A	128.802	-62.339	-197.267	71.726	0.480	0.831
	Concentration B	125.567	-79.226	-121.082	-38.236	0.043	3.551
120 days	Without waterproofing resin	--	--	--	--	--	--
	Concentration A	107.558	-41.096	-133.418	42.735	0.428	0.953
	Concentration B	353.200	-306.860	-761.490	-43.185	0.314	1.372

** The mean difference is statistically significant at a significance level of 0.05.*

Figure 4 displays the morphological analysis *of Eleocharis* sp. fiber geotextile under SEM, aimed at assessing its resistance to degradation by environmental agents. The cellular structure of *Eleocharis* sp. fiber contributes to its distinctive qualities, rendering it a promising material for various applications, including bioengineering (Zhou et al., 2020). Nonetheless, preserving these unique characteristics, notably its resistance to degradation, is essential to ensure the feasibility of its applications. Hence, the incorporation of protective additives becomes imperative.

Regarding *Syagrus coronata* fiber treated with concentration B (Fig. 5b), a higher number of fractures is observed after 120 days of exposure (N = 353.20). However, there is no statistically significant difference when compared to the concentration A treatment during the equivalent period, with an average of 107.55

fractures (ΔM = – 245.65 N, BCa 95% [– 477.59–386.27], p = 0.341, Cohen's *d* = 1.08). Conversely, untreated *Syagrus coronata* fibers demonstrate lower susceptibility to natural degradation, but only for a duration of up to 90 days of exposure.

The effects of treatments on *Syagrus coronata* fibers were evaluated during 120 days of natural degradation exposure. The analysis results indicate that both the single-layer resin treatment (concentration A) and the double-layer resin treatment (concentration B) produced similar outcomes. No statistically significant differences were observed when comparing these treatments to the initial phase of the T_0 experiment.

These findings suggest that the resin treatment, combined with the inherent resilience and degradation-resistant components present in *Syagrus coronata* fibers, contribute to the absence of significant differences between concentration A and concentration B treatments.

In a study conducted by Carneiro et al. (2017), which examined the degradation behavior of geotextiles using scanning electron microscopy, it was observed that exposure of these materials to the external environment resulted in damage caused by natural exposure to ultraviolet radiation.

4. Discussion

The obtained results from the analysis of three natural fibers - *Syagrus coronata*, *Typha domingensis* and *Eleocharis* sp., submitted to different treatments and exposed to natural degradation over 120 days, provide important information about the behavior of these fibers under these conditions. The results show the potential of these fibers as raw material for making natural geotextiles, as mentioned by Haukos et al. (2005) Gowthaman et al. (2018) and Addis et al. (2022) on the behavior of natural fibers when subjected to environmental stressors.

The application of treatments with protective resin on the fibers under study has shown to have an impact on their resistance to natural degradation. Analysis of variance (ANOVA) showed statistically significant differences in the number of fractures over the 120-day experiment for the three fibers without resin treatment.

The data suggest that the treatments with one and two layers of waterproofing resin present significant lower losses in the deformability of the geotextile compared to the untreated geotextile. This behavior is similar to that observed by Matheus et al. (2004) with manufactured-type natural geotextiles.

This behavior indicates a slower process of structural alteration due to the loss of lignin and alteration of the degree of crystallinity of the cellulose in the treated samples. However, it is important to note that although protective resin treatments were effective in increasing fiber durability, they did not completely eliminate the occurrence of cracking (Sumi et al. 2018). However, although these treatments can significantly improve the performance of natural fibers under environmental stressors, they cannot completely eliminate the inherent vulnerabilities of these fibers to such stressors (Pelzer et al. 2015).

Still, the data indicate that the application of waterproofing resin effectively preserves the morphology of the fibers for the observed period of 120 days, as shown by the images of scanning electron microscopy (SEM) and by the absence of strong damage or fractures in their surfaces. These results agree with the findings of Carneiro et al. (2017), who observed damage caused by natural exposure to ultraviolet radiation in geotextiles exposed to the external environment.

The resistance to fiber degradation is influenced by multiple factors, including the chemical composition of the parent material and the applied treatments (Rizal et al., 2018). X-ray diffraction analysis (XRD) of the analyzed fibers revealed the presence of diffraction peaks characteristic of cellulose, indicating that approximately 48.3% of the *Eleocharis* sp. is composed of crystalline regions, while the remainder is composed of amorphous regions.

The diffraction peaks at 2θ = 22.20°, 22.14° and 21.54° presented in *Eleocharis sp*, *Typha domingensis* and *Syagrus cononata*, respectively, are close to the typical value for the diffraction peak (0 0 2) of cellulose I, which is the most common form of cellulose in natural plants. This peak is due to spacing between adjacent cellulose chains in the crystal plane (0 0 2). Diffraction peaks at 2θ = 11.65°, 11.69°, 11.71°, on the other hand, are less common in plant fibers but could be due to a different form of cellulose or a secondary crystalline structure.

Cellulose, being a semi-crystalline material, does not have a completely ordered structure (Hebert and Muller 1974). This is reflected in the diffractograms, which display broad peaks rather than the narrow, well-defined diffraction lines that you would expect from a fully crystalline material. In addition, the fibers in question were produced from different sources, variations in the intensities and configurations of these peaks are observed. These differences can be attributed to variations in the crystalline and amorphous structure of cellulose in different sources (Davidson et al. 2004).

The X-ray diffraction peaks for the three fibers indicate the presence of cellulose I and II. The presence of both peaks suggests that the fiber contains a mixture of cellulose I and II, which is common in many natural materials (Hermans and Weidinger 1948). Among the samples, *Syagrus cononata* was the fiber with the highest concentration of cellulose II among the others, as it was the only one to have a peak in the region of 21.54° significantly higher than in the region of 11.71°, indicating a higher index of crystallinity.

The presence of lignin in natural fibers provides an initial defense against degradation agents (Sarasini et al., 2013). Fibers from natural geotextiles naturally present reductions in cellulosic compounds, mostly due to the increase in depolymerization when subjected to exposure to high temperatures, such as in semi-arid and tropical regions as were developed in this study.

Regarding this behavior Pérez et al. (2002) also observed a similar degradation pattern in treated and untreated natural Sisal fibers when subjected to biodegradation. The researchers observed that the degradation starts with hemicelluloses and amorphous cellulose in the initial phase. The ester linkages in lignin are also hydrolyzed mainly during the initial phase of biodegradation and that the application of protective measures before natural exposure delays the hydrolysis of the compounds (Jeffries 1990).

Each polymer is degraded by a variety of microorganisms that produce a set of enzymes that work synergistically. In this sense, the use of protective resin in *Eleocharis* sp. may have played an important role in increasing its durability by delaying the actions of degrading agents.

When observing the data of *Eleocharis* sp. These reveals that B concentration treatment significantly improves fracture toughness after 120 days of natural degradation, exhibiting a remarkable 75.36% reduction in observed fractures compared to untreated fibers. These findings are consistent with the findings of Samir et al. (2022), emphasizing the importance of resin treatments to increase moisture resistance and attenuate the inherent hydrophobic behavior of natural fibers.

Regarding to *Syagrus coronata* fibers, the treatment with concentration A shows a resistance to cracking compared to the treatment with concentration B, although this difference is not statistically significant. Similar findings were reported by Franco et al. (2022) in their study on geotextiles made of polyester treated with UV stabilizers. They observed that fibers without the stabilizing treatment showed signs of degradation at a faster rate than those with the stabilizing treatment. However, the untreated *Syagrus coronata* fibers showed less susceptibility to natural degradation, but only for a period of up to 90 days of exposure, similar to what was observed by Roopan et al. (2015) using fibers from *Cocos nucifera.*

Another factor is the action of the microbial population over the initial 30–45 days of biodegradation with the latency phase in the growth of the microbial population. The subsequent increase in microbial population continuing over a period of up to 90 days possibly corresponds to population growth triggered by increased exposure of fibers and their lignocellulosic constituents as nutrients (Saha et al. 2015).

Fibers from *Typha domingensis* also demonstrated a significant improvement in performance when treated with concentration B compared to untreated fibers of the same species after 120 days of exposure. These fibers had a juxtaposed and agglutinated structure, with a rigid appearance and surface roughness. There was an approximate 350.6% increase in performance. This indicates that the *Typha domingensis* fiber treated with concentration B showed the best performance, with less degradation over the 120 days of exposure.

The application of two layers of waterproofing resin may also have reduced the effective temperature in the fibers due to the reduction in the direct contact of the fibers with the heated soil during the exposure time. Das et al. (2013) also observed that the amount of lignin present in *Cocos nucifera* fibers reduces the α max by 6% when exposed to 1 h of heating at 180°C, while studying Jute fibers (*Corchorus capsularis*) Khan et al. (2012) observed that fibers exposed to degradation lose 10% of α max when exposed to 170°C in 1h. Notably, as the time of exposure to the sun increases, there is also an increase in creep deformations and a decrease in elastic stiffness in non-woven geotextiles. This is particularly important, since the preservation of the fiber morphology is crucial for its application in several fields, and submitted in different regions, including those with a tropical climate.

Our results also highlight the importance of considering the inherent morphological and structural characteristics of fiber species when evaluating their performance under environmental stressors. For example, *Typha domingensis* fibers demonstrated superior physical performance compared to other fibers, which can be attributed to their inherent morphological and structural characteristics as well as their intrinsic composition. This finding underscores the importance of selecting the appropriate fiber species for specific applications.

However, it is important to consider the broader implications of these treatments. The process of transforming selective synthetics into mineralization products involves a series of intermediate biochemical steps to achieve degradation (Gao and Gu 2021). In this sense, the use of intermediate products can be more toxic than the initial compounds in some cases (Gu 2016). Therefore, chemical modification of the parent compounds is not always a preferred strategy in pollutant management and remediation (Gu 2020). Emphasizing the need for careful consideration and complete assessment of the possible environmental impacts of these treatments, regarding quantity, concentration and level of application.

It is important to point out that the analyzed fibers in this work, all of them originate from the same geographic region, considered non-invasive. This means that they come from plants that are native to the regions in which they are grown and do not pose a threat to local ecosystems (Valone and Weyers 2019). This is an important aspect, as the use of invasive plants for fiber production can have negative environmental impacts, including changing habitats and reducing its biodiversity.

5. Conclusions

The findings of this study provide evidence supporting the effectiveness of protective resin application on geotextiles made from *Syagrus coronata*, *Typha domingensis*, and *Eleocharis* sp. in enhancing their resistance to natural degradation after 120 days of exposure period, mostly related to the utilization of concentration B treatment (two layers of waterproofing resin) resulted in improved durability.

Typha domingensis fibers treated with concentration B resin exhibited a lower incidence of cracking, which can be attributed to the favorable morphological and structural characteristics of this plant species and its effective interaction with the applied protective resin.

Syagrus coronata fibers did not exhibit significant differences between the two resin treatment concentrations. Nevertheless, when untreated, they displayed inherent resistance to natural degradation, and the fibers treated with concentration A resin exhibited superior performance.

Regarding morphological aspects, the micrographs revealed satisfactory adhesion between the fibers and resin, as well as a uniform dispersion and distribution of the resin application across all fibers.

The use of SEM techniques in conjunction with digital image processing has provided more precise and reliable results regarding the degradation behavior of natural fibers used as raw materials for geotextile production. These results hold particular relevance due to the abundant availability of natural fibers domestically and the increasing global demand for sustainable and environmentally friendly alternatives.

Declarations

Declaration of competing interest

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

Data Availability

Sequences of images showcasing damage and cracks, captured at various time points and under different magnifications, will be provided in a forthcoming specialized publication.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.17632/jjf8yv7vch.1.

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Figures

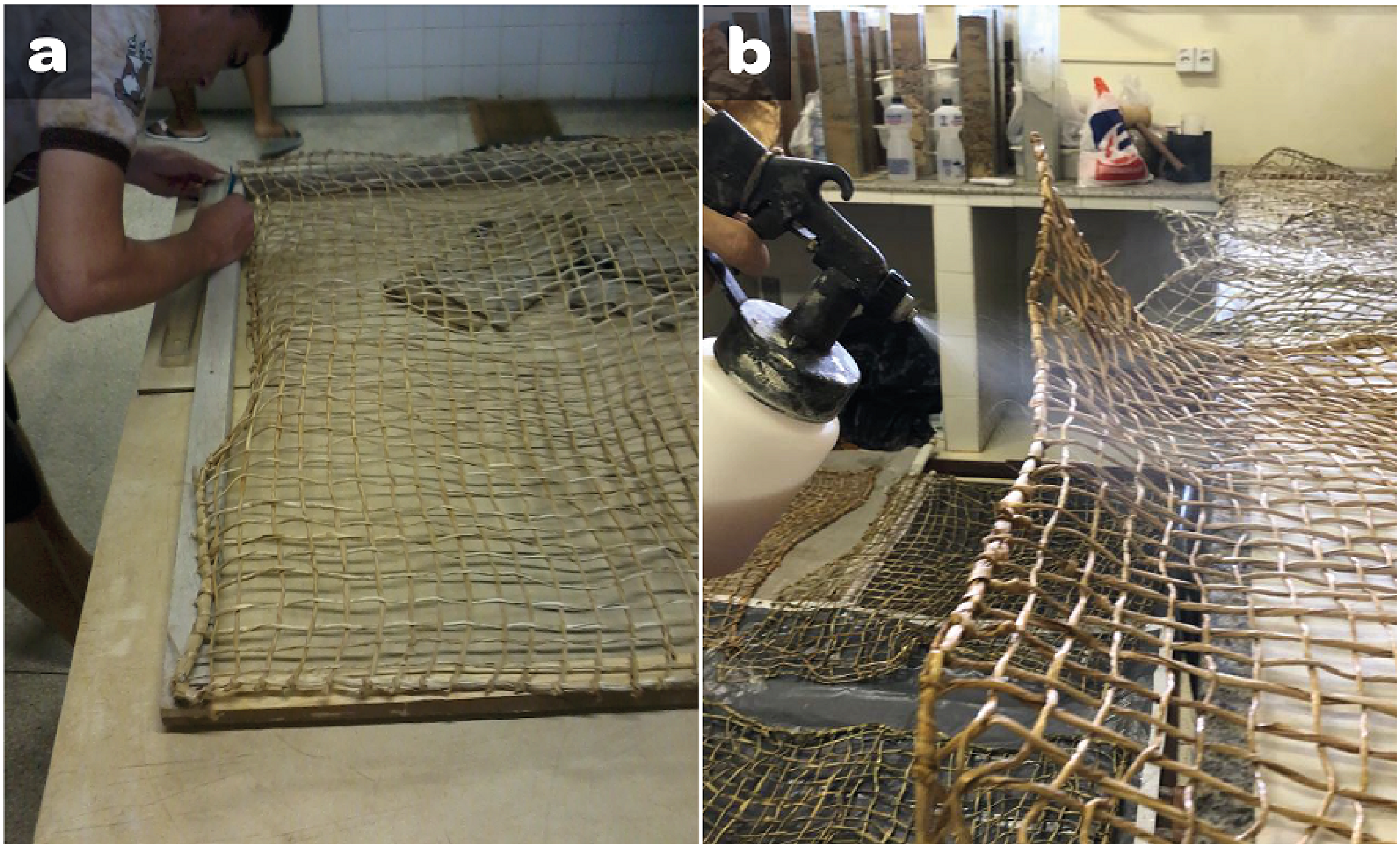

Figure 1

(a) Geotextiles manufactured using fibers from *Syagrus coronata*, *Thypha domingensis*, and *Eleocharis* sp. coated with a protective resin. (b) Geotextiles subjected to exposure on a slope.

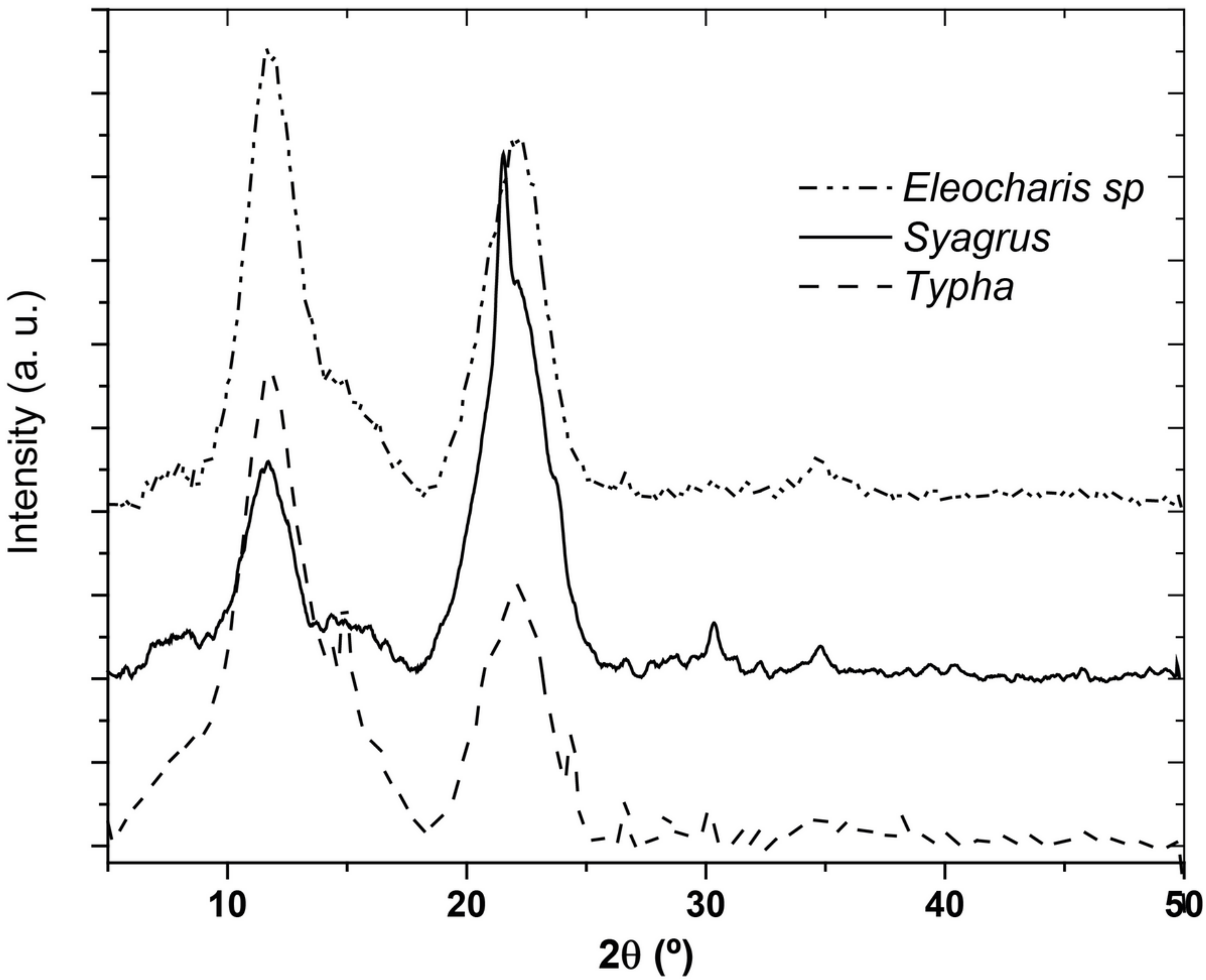

Figure 2

X-ray diffractogram of *Eleocharis* sp. fiber, *Syagrus cononata* and *Typha domingensis*.

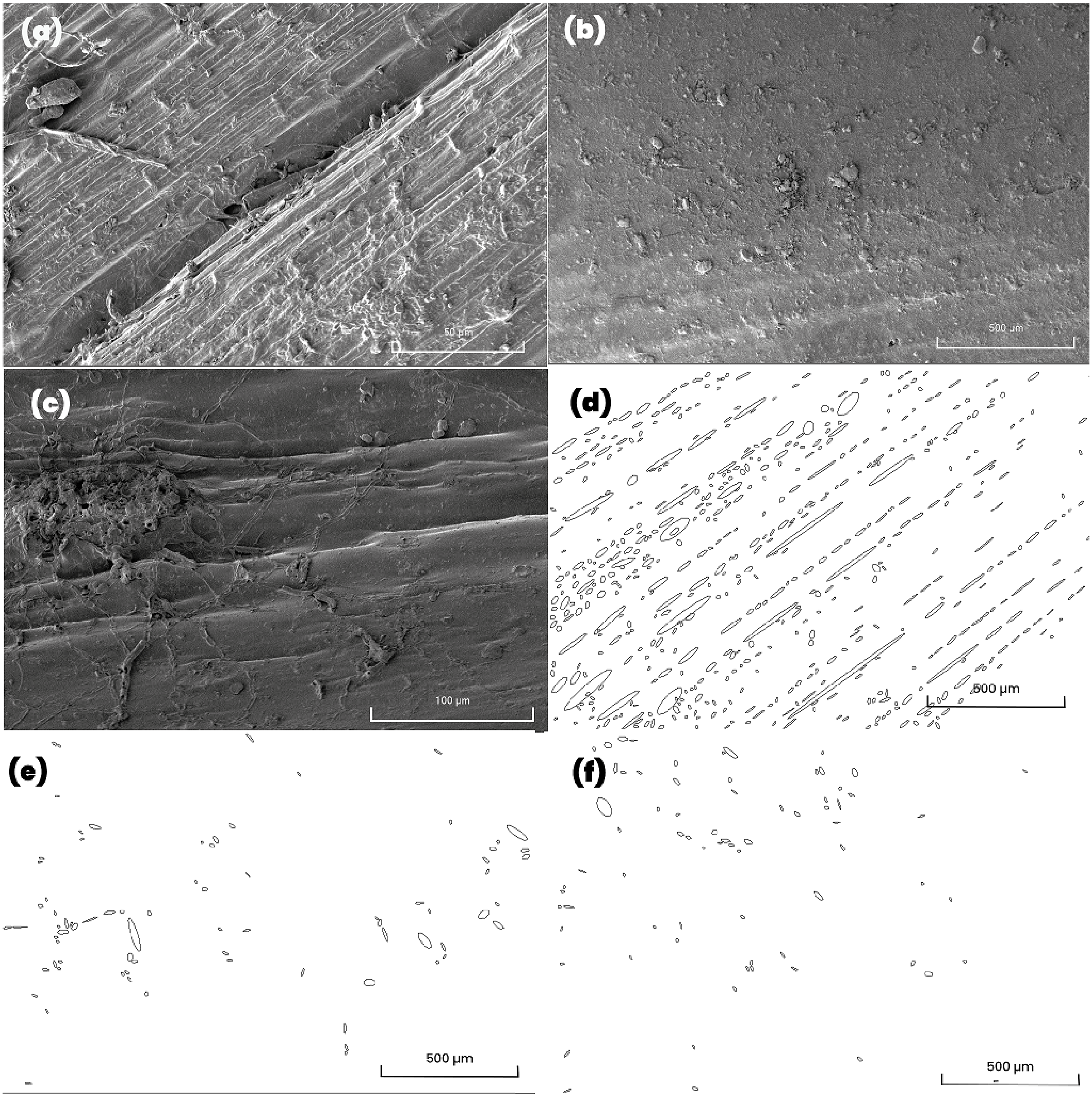

Figure 3

SEM images after 120 days of *Typha domingensis* exposure: (a) Untreated fiber, (b) Fiber treated with concentration A, (c) Fiber treated with concentration B, (d) Fissure markings on untreated fibers, (e) Crack markings on concentration A fiber, and (f) Fiber crack markings on concentration B fibers.

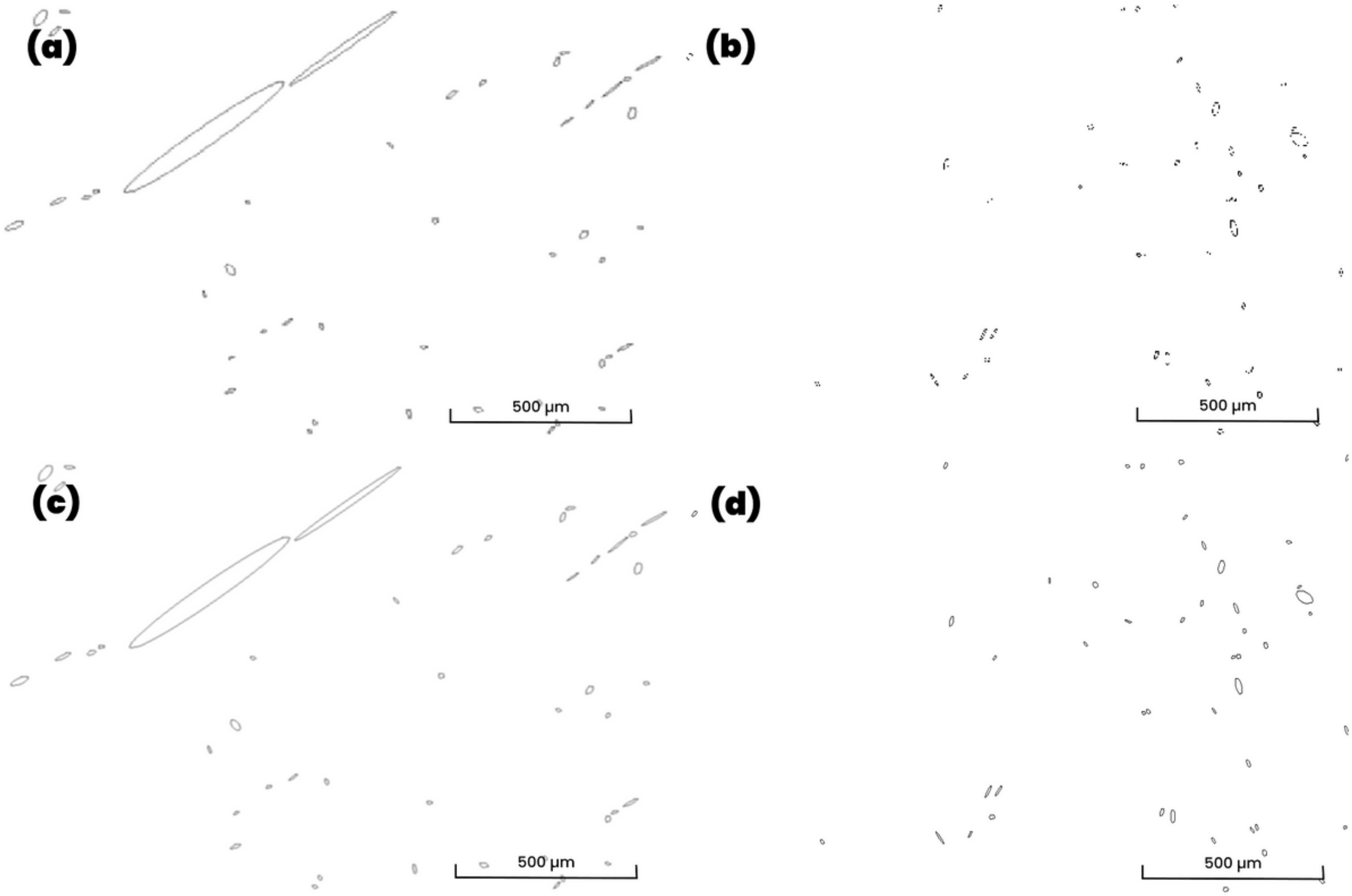

Figure 4

SEM images of *Eleocharis* sp. fiber: (a) Fracture markings in treatment concentration A fiber, and (b) Fracture markings in treatment concentration B fiber.

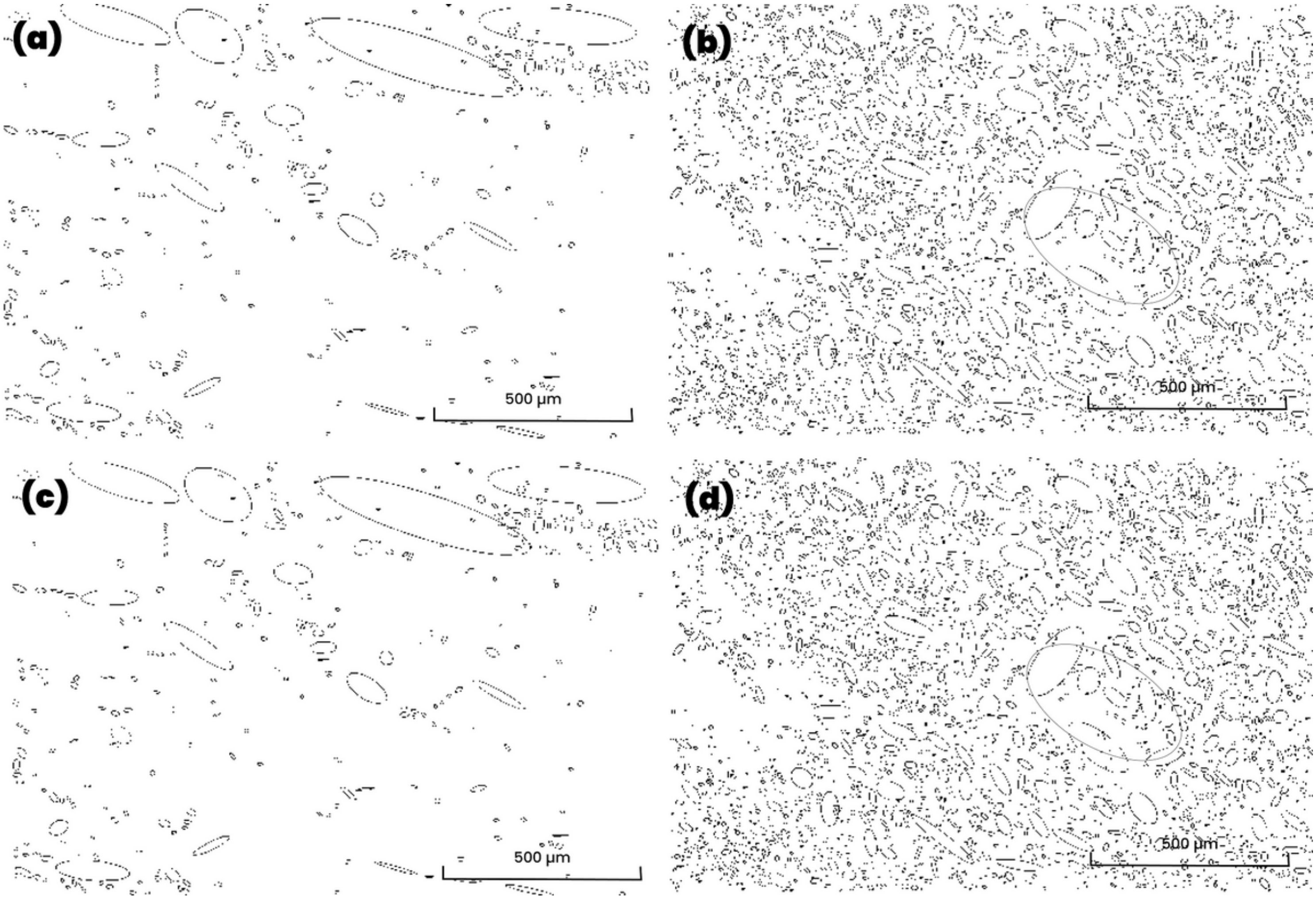

Figure 5

SEM images of *Syagrus coronata* fiber: (a) Fissure marks in concentration A fiber, and (b) Fissure marks in concentration B fiber.

Supplementary Files

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