Comparison of mechanical performance of different geotextiles manufactured from natural fibers of Syagrus. coronata (Mart.) Becc, Thypha domingensis and Juncus sp subjected to natural biodegradation.

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Abstract

The objective of this study was to evaluate the mechanical performance of geotextiles made from natural fibers of *Syagrus coronata* (Mart.) Becc., *Thypha domingensis*, and *Juncus* sp. The geotextiles were treated with waterproofing resin and exposed to biodegradation for 120 days to understand their stress and strain behavior. The geotextiles was treated with colorless wood waterproofing resin by Hydronorth® to make it less permeable, delay the degradation process, and consequently increase the material's resistance to climatic variables. Subsequently, the geotextiles was subjected to natural degradation on slopes covering an area of 10m². Samples of the exposed material to the degradation processes were collected every 30 days. The findings reveal that the examined fibers, following treatment with waterproofing resin, exhibit the capability for extended utilization in the field, with Thypha fiber outperforming the other tested fibers. These results hold significant potential for the incorporation of natural fibers in endeavours related to environmental conservation.

1. Introduction

The increased use of petroleum-based polymers has raised concerns about the significant amount of solid waste that they generate. Geotextiles made by synthetic fibers, which are widely used in several fields of engineering, are one of the contributors to this problem. Estimates suggest that around 1.5 billion square meters of geotextiles are used annually [1]. Geotextiles are favored due to their cost-benefit relationship and a wide range of applications, including mechanical, hydraulic, and biological functions [2, 3].

Most of the geotextiles are made from non-degradable materials, such as Polypropylene (PP), Polyethylene Terephthalate (PET), and Polyethylene (PE), which pollute the environment [4]. There is a growing interest in finding sustainable alternatives, such as natural fibers or biodegradable polymers, which can replace non-biodegradable materials in up to 50% of all engineering applications [5]. The growing demand for more sustainable solutions and the reduction of environmental pollution has led to an increase in research on biodegradable geotextiles based on natural bioengineering [6]. In this context, natural fibers, which have been used since the beginning of civilization in clothing, crafts, and cords, emerging as a promising alternative.

Initially, the natural fibers obtained from plants were part of people's daily lives [7]. As time passed, advances in technology brought new methods and synthetic fibers, resulting in an increase in production. Soil bioengineering or geotextile are important components to be considered when attempting to recover degraded areas. The natural geotextiles made from *Syagrus coronata* (Mart.) Becc., *Thypha domingensis*, and *Juncus* sp. fibers offer an ecological alternative to traditional synthetic fibers because they originate from renewable and biodegradable natural resources.

The natural geotextiles, with high resistance to traction and deformation, are ideal for stabilization and erosion control. Natural fibers derived from plant sources have several benefits when compared to synthetic fibers. These benefits include low density, accessibility, impact resistance, flexibility, less abrasiveness, health safety, a sustainable production process, emission reduction, recyclability, controlled degradability, and carbon neutrality [8, 9]. They can be used in combination with other materials (for example, inert materials and synthetic fibers in smaller proportions) to protect shorelines, preventing the sliding of already eroded surfaces [10] or on roads to stabilize the asphalt structure [11]. Additionally, the use of natural geotextiles helps to preserve local biodiversity, allowing the environment to regenerate more quickly and sustainably.

Natural geotextiles are a versatile means for the recovery and reinforcement of degraded areas. They are in high demand due to the numerous benefits and various uses of these materials [12]. These materials are primarily used to restore soils, control plant growth, prevent erosion, stabilize slopes, prevent watercourse flooding, and improve water quality. Because they are naturally biodegradable, geotextiles produced from natural fibers are not affected by humidity [13], temperature changes, soil pH, or the activities of microorganisms and animals, and they can resist pressure with different compression patterns [14].

Although geotextiles made of vegetal fibers are durable and can be applied in various contexts, natural fibers present limitations, such as water absorption and lower stability and durability [15]. The absorption of moisture and the presence of microorganisms accelerate the degradation of materials [16].

Despite the multiplicity of geotextiles made from natural fibers that are not yet present on the market, the notion of using biopolymers as protective solutions for such purposes remains relatively unexplored [17, 18]. In general, natural fibers have porous characteristics and inherent attraction to water due to the presence of hydrophilic groups in their structure [19]. This association with the humidity results in swelling of the fibers and weakening of the cell wall, facilitating microbial attack [20]. The microorganisms possess enzymatic systems capable of hydrolyzing the carbohydrate polymers in the fibers into digestible units [21].

Therefore, humidity can be better controlled by supplementing the fibers with inorganic composts [22] We observe that geotextiles made by natural fibers and treated with sodium hydroxide present a higher support rate in sandy soil alone than in silty soil, both for flooded and non-flooded conditions for the treated geotextiles, to the detriment of untreated geotextiles, demonstrating their effectiveness. The natural fibers must be treated with protective substances. A probable factor is that the natural fibers, being cellulosic, are vulnerable to degradation by micro and macroorganisms, including bacteria and fungi when not treated with protective materials [23, 24]. The degradation of natural polymers are carried out mainly by fungi, with bacteria acting as secondary degrading agents [25]. Under humid conditions, the fungi is highly efficient in degrading natural fibers [26, 27].

Lignocellulosic fibers with microbes follow a degradation pathway involving enzymatic oxidation, reduction, and hydrolysis [28, 29]. It has been demonstrated that this pathway can be hindered by previous protective treatment processes on the fibers that will be used in making geotextiles exposed to biodegradation [21, 30]. In geosynthetics, supplementary additives are used to avoid degradation in long-term uses, helping the fibers remain in place for a longer time [31], thus producing different types of natural-based geocomposites.

In general, a geocomposite is formed by two main components: the matrix and the reinforcement [32]. Geotextiles made of natural fibers, although lightweight, do not offer the required rigidity, resistance, and dimensional stability for structural and load-bearing applications. Therefore, they are often blended with synthetic fibers that have high resistance and rigidity or subjected to chemical treatments [33].

Little has been studied regarding the use of protective additives in geotextiles made with natural fibers to increase their durability in the field. Although these additives can delay degradation, decomposition still occurs over long-term exposure [34]. To understand the effects of supplementary composts, it is necessary to verify geotextile quality factors, such as durability, through both field and laboratory tests. This understanding can help improve fiber-composite interactions and aid in the stabilization of slopes and potential forest recovery [35].

Analysis of the mechanical behaviors of traction and deformation can be useful in understand the relative influences on the durability and performance of natural fibers treated after exposure in the field [36]. It should be considered that each type of seed can obtain different results for each type of fiber from the application of a protective material [37].

As the properties and mechanical behavior of each type of fiber are different, the objective of this work is to evaluate the performance of geotextiles made from *Syagrus coronata* (Mart.) Becc., *Thypha domingensis*, and *Juncus* sp. fibers, treated with waterproofing resin.

2. Material and Methods

2.1 Collection of Plants and Processing of samples

The selection of samples of *Syagrus coronata* (Mart.) Becc, *Thypha domingensis* and *Juncus* 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 from two municipalities in the Baixo São Francisco region of northeastern Brazil between 2019 and 2020.

Typha domingensis, is a perennial angiosperm plant found in humid zones within the genus Typha, of the family Typhaceae [38]. It can be found in various regions around the world, including the Americas, Europe, Africa, and Asia [39]. This highly adaptable and fast-growing plant is often found in marshy areas and along the banks of streams, lakes, and rivers, [40] and is more tolerant of water depth and salinity than other Typha species [41]. The plant can grow up to 5 meters tall and is known for its distinctive cylindrical stems of brown flowers surrounded by green leaves [42]. The leaves of *Typha domingensis* are long and flat with a cylindrical stems, and they are used in various ways, including 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 [43]. Generally, *Typha domingensis* is a valuable species with a wide range of uses and ecological benefits.

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 [44], in Brazil it is commonly found in the dry and arid regions of the Caatinga biome, with a distribution area that extends from the north of Minas Gerais, occupying the entire eastern and central portion of Bahia, to the south of Pernambuco, also encompassing the states of Sergipe and Alagoas in northeastern Brazil [45]. 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 [46]. It presents small, yellowish flowers arranged in panicle-type inflorescences, protected by a large leathery peduncular bract [47].

Syagrus coronata (Mart.) Becc. is a plant with multiple uses, such as ornamentation 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 (Barbosa et al.,2021) [48, 49]. 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.

Juncus sp., is an angiosperm with flowers belonging to the botanical family Juncaceae, commonly known as Juncus. This genus is widely distributed throughout the world and is found in a variety of habitats, including swamps, meadows, and pastures [50]. This species is known for its tall, green, or reddish stems, which can reach a height of 1.5 meters [51]. 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 [52]

The *Juncus flowers* are small and discreet. They are arranged in dense clumps along the stem and are typically green or brown in color. Juncus sp. is a valuable species for many uses, including erosion control, habitat creation, and wet zone restoration [53]. 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 Juncus 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 J. rigidus were used in the manufacture of writing instruments, sandals, and baskets. *Juncus* sp. is a resistant, versatile, and attractive species that has a wide range of uses and ecological benefits [54].

Vouchers containing samples of non-herbal preserved species (ASE) were obtained from the Department of Biology (DBI) at the Federal University of Sergipe in 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" [55]. This collection was carried out under the registration code SisGen A2B3842.

2.2 Implementation of the Experiment

In the previous stage of the research carried out by the Laboratory of Soil Erosion and Sedimentation - LABES/UFS, the fibers of *Syagrus coronata, Typha domingensis, and Juncus* sp. Were used (Fig. 1a). In order to provide greater durability to these natural geotextiles, they were sprayed with a colorless and waterproof wood resin from the Hydronorth ® brand (Fig. 1b). This process aimed to make the material less permeable to slow down the degradation process and, consequently, increase its resistance to climatic variables. To achieve full coverage, the waterproofing resin was applied on both sides of the two geotextiles. The geotextiles were randomly distributed and subjected to the following treatments: a) Geotextile without waterproofing resin (Control), geotextile treated with a layer of TYPE A waterproofing resin, and geotextile made of TYPE B fibers treated with 2 (two) layers of waterproofing resin (double layer).

The experimental trial was carried out on a slope with an area of 14 m^2 in a soil classified as a Typic Quartzipsamment located on the Campus of the Universidade Federal de Sergipe-UFS (coordinates 10°55'47.2"S 37°06'12.6"W), in the Municipality of São Cristóvão, state of Sergipe, northeastern Brazil (Fig. 1c).

The geotextiles were subjected to natural degradation arranged on a slope (Fig. 1), from which 5 (five) samples were removed from each scheduled tail of the central part of the geotextile during the maximum period of 120 days (4 months) of exposure. This was the maximum period during which the geotextile maintained its integrity for the performance of two resistance tests. Four collections were made at different periods, T_0 (0 days), T_1 (30 days), T_2 (60 days), T_3 (90 days) and T_4 (120 days).

The intact and degraded samples was subjected to mechanical tests. For the non-confined tensile test, the fiber samples will be cutted according to NBR 12824 [56], with 30 cm of compression.

To test the tensile strength of the geotextiles, undamaged samples were removed that were not affected by weather conditions, as well as degraded samples from the field. The evaluated mechanical characteristics meet the requirements of the geotextiles in terms of their functions in slope stabilization, where they are subjected to traction, compression, flexion, among others. In this research, the main parameters of mechanical resistance were measured through tests that obtained stress-strain curves at rupture, rigidity, and toughness. The non-confined tensile strength tests were carried out in the UFS Materials Engineering Laboratory, using an EMIC Model DL universal testing machine with a maximum capacity of 300 kN [57, 58].

2.3 Statistical Analysis

To assess the temporal interaction between the different treatments and the physical characteristics of the two geotextiles (T_1 – 1st day, at T_4 – 120th day), a factorial ANOVA (3x2x4) was conducted for repeated measurements to understand the effect of "degradation time" on the mechanical resistance characteristics of the three geotextiles, including the influence of the application of waterproofing resin. The normality of the two data sets was evaluated using Kolmogorov -Smirnov (KS) and Shapiro-Wilk (SW) residual tests. The assumption of homogeneity of variance was validated by the Levene test [59].

Post-hoc analyses for the main effects were conducted using Hochberg's GT2 test at a 5% probability level since the samples were mostly homogeneous. This was done to compare the two effects of the interactions (fiber*resin application*time of exposure). The effects of the difference between the initial natural degradability and the natural degradability over 120 days of exposure were tested using the Bonferroni test, also at a 5% probability level.

To determine the statistical impact of the application of waterproofing resin on the physical resistance of the geotextile, effect sizes were evaluated using Eta squared (η^2) and Cohen's *d* for the ΔM test [60]. Effect sizes refer to the power that an independent variable (IV) has on a dependent variable (DV). In this study, the effect size obtained by DV characterizes the effect of the geotextile treatment in relation to the control treatment (T_1 without waterproofing resin).

Bootstrapping procedures (1000 retests; 95% CI BCa) were implemented to achieve greater reliability in the results, correct deviations from normality in the distribution of the sample, adjust for differences between the two group sizes, and present a 95% confidence interval for differences between the two groups'stockings [61]. Due to the nature of the experiment, missing data were imputed using multiple imputation based on the likelihood function [62]. All statistical tests were conducted with a significance level of $p < 0.05$.

3. Results and Discussion

3.1 Traction Tests

3.1.2 Maximum Tensile Strength (α max)

The Table 1 presents a comparative analysis of the maximum tensile strength of geotextile fibers with and without the application of waterproofing resin over an experimental period of 120 days. It appears that the Thypha *domingensis* (control-without the application of waterproofing resin) has statistically significant higher values and a high power of effect for maximum tensile strength at the end of 120 days of exposure (6.732 N/m-1) compared to TYPE A treated fibers (ΔM = 4.826 n/mm $^{-1,}$ Bca 95% [0.729–8.923], $p < 0.019$, *Cohen's d* = 1.649).

When comparing the untreated fibers with the TYPE B treated fibers, no statistically significant mean differences were observed (ΔM = 1.580, Bca 95% [-2.5163–5.6771], $p < 0.681$, *Cohen's d* = 0.540). These results indicate that the addition of two layers of waterproofing resin (TYPE B) results in greater resistance to fiber rupture compared to fibers treated with one layer of resin (TYPE A) without impairing the natural performance of *Thypha domingensis* fiber.

Table 1

Descriptive statistics and multiple comparisons of two levels of resistance to maximum traction (N/mm^{-1}) of fibers for all groups.

geotextile (fibers)	Maximum tensile strength (α max) (N/mm^{-1})		
	T_1 (30 days of exposure)		
	without resin	**TYPE A**	**TYPE B**
syagrus coronata	13,351 (5,398) Aa	13,351 (9,445) Aa	22,378 (6,528) Aa
Thypha domingensis	10,066 (2,430) Aa	9,361 (4,362) Ab	8,970 (3,564) Ab
Juncus sp.	10,270 (2,661) Aa	6,207 (1,889) Bb	3,088 (1,216) Bb
	T_2(60 days of exposure)		
	without resin	**TYPE A**	**TYPE B**
syagrus coronata	0.664 (0.376) Bb	3,353 (5,602) Ab	3.892 (0.900) Bb
Thypha domingensis	5,697 (3,483) Aa	6,399 (1,924) Aa	6,736 (2,745) Aa
Juncus sp.,	0.346 (0.123) Bb	2,807 (1,461) Ab	2.662 (0.461) Ab
	T_3(90 days of exposure)		
	without resin	**TYPE A**	**TYPE B**
syagrus coronata	0.540 (0.490) Ab	0.590 (0.447) Ab	0.840 (0.369) Ab
Thypha domingensis	4,315 (4,315) Aa	3,449 (1,892) Aa	4,932 (1,693) Aa
Juncus sp.,	0.400 (0.229) Ab	0.893 (0.556) Ab	0.946 (0.573) Ab
	T_4(120 days of exposure)		
	without resin	**TYPE A**	**TYPE B**
syagrus coronata	N.C	0.578 (0.347) Aab	1,263 (1,941) Ab
Thypha domingensis	6,732 (5,016) Aa	1,905 (1,332) Ba	3,460 (2,264) Ba
Juncus sp.,	N.C	0.906 (0.529) Aab	0.411 (0.248) Ab

Note: N.C = no continuity, TYPE A = Fibers treated with a layer of waterproofing resin and TYPE B = Fibers treated with two layers of waterproofing resin. Underwritten values represent Standard Deviation. Means followed by the same capital letters horizontally for the three levels of resin and lowercase letters vertically for the different fibers with the same application level do not differ statistically by Hochberg's GT2 test at a 5% probability.

For this same period, the fibers of *Syagrus coronata* and *Juncus* sp., not treated with waterproofing resin, will present deterioration and low resistance after 90 days of degradation (Fig. 2a), and the *Thypha domingensis* present greater plasticity in comparison to the other fibers tested.

The degradation of two geosynthetics under environmental conditions, such as humidity, UV-vis irradiation, wind and particle abrasion, attack by microorganisms, and temperature variations represent the main disadvantage of long-term use of these materials [63–65]. However, the chemical and structural stability of the synthetic polymers present in the composition of the geosynthetics are crucial factors in determining the useful life and operational performance of these materials [66].

In this sense, new geotextiles have been designed considering protective treatments based on resistant polymers such as waterproofing resin, in order to provide better stability during the geocompost service period [67].

3.1.3 Strain at break (ε)

A normal distribution of two residues for tensile strength showed that only *Syagrus fiber coronata*, treated with litter for 60 days in group T_2 (60 days) [KS = 0.405, p = 0.007; SW = 0.680, p = 0.006], did not exhibit normal distribution. Levene's test showed that all groups had homogeneity of variance. Therefore, more conservative post-hoc statistical models (Hochberg's GT2 and Bonferroni) recommended for homogeneous data that follow normality [68], were used, as well as *bootstrapping* with 1000 retests, to obtain more reliable data.

General results of ANOVA show that no statistically significant differences were observed between the resistances to deformation obtained in mechanical tests when comparing the means of the fibers tested ($F(2, 240) = 0.392$, $p = 0.676$; $\eta^2 = 0.003$). Statistically significant differences were observed when comparing the resin application levels ($F(2, 240) = 12.589$, $p < 0.001$; $\eta^2 = 0.028$), as well as for the exposure times to fiber degradation ($F(4, 240) = 6.886$, $p < 0.001$; $\eta^2 = 0.105$). The interaction between the different variables also demonstrated statistically significant differences ($F(11, 240) = 16.617$, $p < 0.001$; $\eta^2 = 0.204$).

Table 2 shows the descriptive statistics of geotextile fibers treated with resin, which were subjected to different exposure times to degradation.

When analyzing the fibers treated with a single layer of TYPE A waterproofing resin at the final time of the experiment (T_4), which corresponds to 120 days of exposure, the *Juncus sp.* treated with TYPE A (simple layer) (Fig. 3b) exhibited a statistically significant result with a high power of effect on the maximum deformation resistance. This result was observed in comparison with the *Syagrus coronate* fiber treated with the same protective technique (ΔM = 4.21%, Bca 95% [2.70% – 5.10%], $p < 0.001$, *Cohen's d* = 4.885), how much in comparison to Thypha domingensis (ΔM = 2.90%, Bca 95% [1.50% – 3.80%], $p < 0.001$, *Cohen's d* = 3.403).

The use of biodegrading agents and waterproofing materials to increase fiber aggregation promotes greater durability and deformation resistance of geotextiles. This improvement can be attributed to the increased amount of energy required to cause failure of the material and its aggregates, dressings, or protective treatments, thus contributing to its greater durability (Gao et al., 2022).

Table 2
Descriptive statistics and multiple comparisons of the two levels of deformation of the fibers for all groups.

geotextile (fibers)	Resistance to deformation (ε) (%)		
	30 days of exposure		
	without resin	**TYPE A**	**TYPE B**
syagrus coronata	3.33% (0.836) Aa	3.89% (1,508) Aa	2.75% (0.592) Ab
Thypha domingensis	3.86% (0.957) Aa	2.64% (0.711) Aa	2.60% (1.727) Ab
Juncus sp.,	4.02% (0.563) Ba	4.31% (0.018) ABa	10.29% (0.735) Aa
	60 days of exposure		
	without resin	**TYPE A**	**TYPE B**
syagrus coronata	2.35% (1,327) Aa	3.12% (2,142) Aa	2.03% (1,475) Aa
Thypha domingensis	3.16% (0.835) Aa	2.66% (0.893) Aa	3.49% (0.979) Aa
Juncus sp.,	1.33% (0.371) Bb	3.52% (0.008) ABa	3.68% (0.015) Aa
	90 days of exposure		
	without resin	**TYPE A**	**TYPE B**
syagrus coronata	1.49% (0.621) Aa	1.55% (1.326) Ab	1.00% (0.542) Ab
Thypha domingensis	2.55% (0.673) Aa	2.62% (0.914) Aab	2.18% (0.837) Ab
Juncus sp.,	1.49% (0.017) Aa	3.82% (0.855) Aa	4.51% (0.024) Aa
	120 days of exposure		
	without resin	**TYPE A**	**TYPE B**
syagrus coronata	N.C	0.65% (0.351) Ac	0.43% (0.273) Ab
Thypha domingensis	2.40% (0.302) Aa	2.58% (0.835) Aa	2.56% (0.827) Aa
Juncus sp.,	N.C	4.81% (0.014) Ab	2.93% (0.029) Aa

Note: N.C = No continuity. TYPE A refers to fibers that have been treated with a layer of waterproofing resin, while TYPE B refers to fibers that have been treated with two layers of waterproofing resin. The underwritten values represent the standard deviation and means that are followed by the same capital letters horizontally, for the three levels of resin, and lowercase letters vertically, for the different fibers with the same application level, are not statistically different according to Hochberg's GT2 test at a 5% probability level.

Figure 3a shows the fibers treated with the control (without waterproofing resin). After 90 days of exposure to climatic variables in the field, the three natural fibers exhibited a statistically significant loss of resistance compared to the values initially obtained for the same treatment. The *Juncus* sp. fibers showed a loss of resistance of approximately 63.03% (ΔM = 0.025, p = 0.045, Bca 95% [6% – 10%], *Cohen's d* = 1.791), while the *Syagrus coronata* fibers showed a loss of about 55.20% during the analyzed period (ΔM = 1.9%, p = 0.020, Bca 95% [0.5% – 3%] *Cohen's d* = 1.678).

Among the three fibers tested, the fiber of *Thypha domingensis* showed less resistance to deformation at rupture when compared to the other two fibers studied, with a difference of approximately 33.99% (ΔM = 1.5%, p = 0.029, Bca 95% [0.3% – 2.8%] *Cohen's d* = 1,491). Additionally, in Fig. 3a, it appears that the fibers of *Syagrus coronata* and *Juncus* sp., which were not treated with waterproofing resin, may not resist biodegradation after 120 days of exposure. However, this behavior was corrected when waterproofing resin was applied.

The results, presented in Figs. 3b and 3c, indicate that treatment with waterproofing resin promotes a longer time of use in the field for all three natural fibers studied, as observed by Vivek et al. [69]. This behavior indicates a more rapid process of structural alteration in the untreated samples, which is caused by the loss of lignin and the alteration of cellulose crystallinity due to biodegradation exposure.

Under low-stress conditions, natural geotextiles can accommodate a greater number of fibers in the stress-strain relationship, optimizing the deformation capacity of the material. These results are similar to the findings of Matheus et al. [70]in their analysis of manufactured geotextiles. In engineering context, geotextiles are frequently subjected to tensile forces, whether uniaxial, biaxial, or more complex scenarios, and may also occasionally be exposed to sharp objects.

In this sense, the application of a layer of waterproofing resin seems to act as an aggregator, improving the accommodation of the cellulosic group [71, 72]. Therefore, applying an excess amount of resin appears to reduce the deformation capacity of natural fibers, making the material more ductile.

Another behavior that can be observed is the gradual degradation of Juncus sp. fibers after 90 days (Fig. 4b and 4c). Long-term changes can result in a reduction of two values of the mechanical properties of the material, particularly if it is more crystalline. In such cases, there is less empty space present, resulting in less deformability [73]. Thus, it is important to consider the effects of long-term changes when choosing materials for certain applications.

Indeed, several studies have demonstrated the efficacy of waterproofing resin treatment in enhancing the durability and resistance of natural fibers. For instance, Hu et al. [74] reported improved mechanical properties of natural fibers treated with waterproofing resins, increasing their resistance to degradation in various environmental conditions. Similarly, Joseph et al. [75] observed that natural fibers treated with waterproofing resins exhibited significantly lower hydrophilicity and higher tensile strength when compared to untreated fibers.

Further research, such as the study conducted by Liu et al. [76], found an increase in tensile strength and thermal stability in natural fiber composites treated with waterproofing resins. Moreover, Khalid et al. [77] emphasized the importance of treating natural fibers with waterproofing resins to obtain better mechanical properties and moisture resistance for engineering and civil construction applications.

While not directly related to the production of geotextiles, vegetable fibers are a viable option due to their good combination of mechanical and environmental properties [78] making them a promising ecological alternative to traditional cementitious materials. However, it is necessary to employ associated protection techniques to adapt these fibers to the technical requirements and guarantee their resilience over the necessary time for their use in the field, considering these structural issues.

4. Conclusions

The application of waterproofing resin, both in one and two layers, promotes greater durability and resistance capacity of the geotextile at maximum extension and deformation over a period of 120 days, compared to untreated fibers.

Regarding the maximum tensile strength, *Thypha domingensis* fiber showed the best results among the three studied fibers, both with one and two layers of resin, after 120 days.

Deformation is a critical factor to consider in the production of geotextiles, as the applicated values define the limits of use and quantity of fibers during production. In this sense the data shows that the three natural fibers, when treated with waterproofing resin present satisfactory values for resistance to deformation over 120 days of biodegradation.

Syagrus coronata fiber when treated with a layer, exhibits greater resistance to deformation after 120 days compared to other fibers.

Declarations

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Data availability

All data generated or analysed during this study are included in this published article (and its supplementary information files).

Code availability

No custom code used.

Conflict of interest

The authors declare no competing interests.

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Figures

Figure 1

(a) Images of two *Syagrus geotextiles coronata, Thypha Sundays, and Juncus* sp. Exposed on a slope, and (b) Details showing the geotextile contact alone.

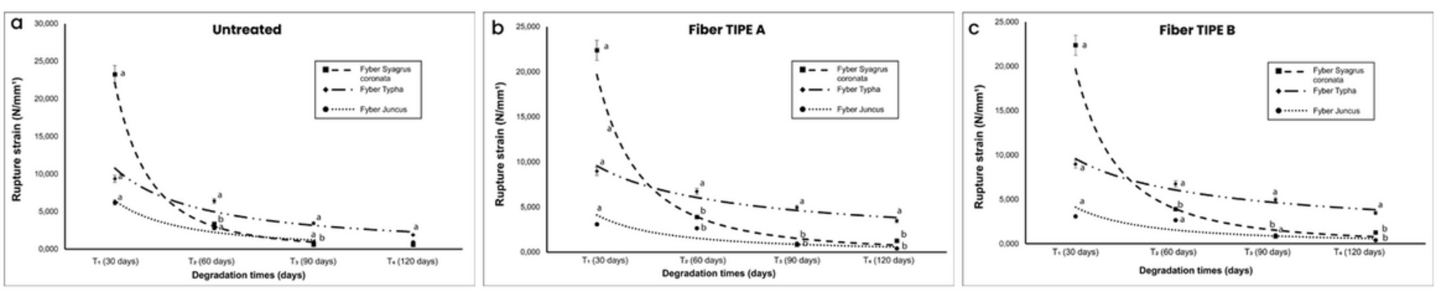

Figure 2

Behavior of Maximum tensile strength of the fibers studied over 120 days of exposure to biodegradation of fibers subjected to (a) control treatment, (b) TYPE A treated fiber, and (c) TYPE B treated fiber. Note: consecutive means of the same lowercase letters for the same fiber at different levels of degradation do not differ statistically by the Bonferroni test at a 5% probability.

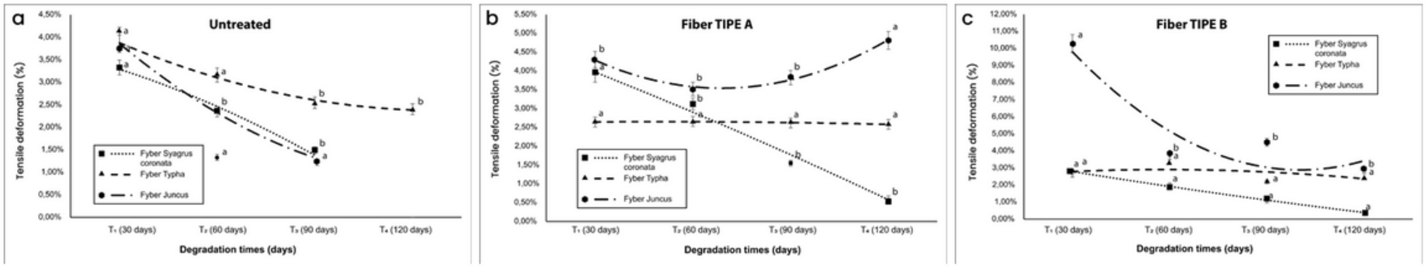

Figure 3

Strain of the studied fibers was measured after 120 days of exposure to biodegradation under three conditions: (a) control treatment, (b) TYPE A treated fiber and (c) TYPE B treated fiber.

Note: Consecutive means of the same lowercase letters for the same fiber at different levels of degradation did not differ statistically according to the Bonferroni test at a 5% probability level.