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Tensile Strength and Morphological Properties of Chemically-Treated Composite Abaca-Coco Coir Twine and Rope as Natural Geotextile Materials

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Abstract

The use of natural fibers has recently received attention due to their potential as sustainable, green alternatives to geosynthetics. This study investigates the morphological properties of raw and chemically-treated abaca and coconut coir fibers. Fibers were immersed in a 6% NaOH solution for 24 hours to remove surface impurities. Twines and ropes were fabricated using abaca fibers and coconut coir. Each abaca and coconut coir twine has a diameter of 5.0 ± 1.0 mm, while the composite abaca-coconut rope has an average thickness of 10.0 ± 1.0 mm. The fabrication adhered to the standards set by the Department of Public Works and Highways (DPWH) for bioengineering coconet applications, as specified in D.O. No. 29, Series of 2008. The resulting fibers, twines, and ropes were evaluated for tensile strength using ASTM D3822 for single fibers and ASTM D2256 for twines and ropes. Scanning Electron Microscopy (SEM) was used to analyze the morphological changes after treatment. The results showed significant improvements in the morphological properties of abaca and coconut coir fibers, particularly after alkaline treatment, compared with DPWH-standard coconut coir-based geotextile materials. Notable changes were observed, including increased surface roughness, enhanced fibrillation, and removal of surface impurities. These findings imply the potential of alkali-treated abaca and coconut coir fibers as durable, high-performance, and locally sourced natural geotextiles for bioengineering and soil stabilization.

***Keywords**:* abaca, alkaline treatment, coconut coir, morphological properties, scanning electron microscopy

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1. Introduction

The geotextile industry achieved a market valuation of \$7.10 billion globally in 2022 and was projected to grow at an annual rate of 6.6% from 2023 to 2030. This growth was largely attributed to accelerating urbanization and industrialization in developing countries (Wu *et al.,* 2020). Geotextiles are recognized for myriad functions, including separation, filtration, reinforcement, and erosion control. It had been categorized into two broad types: synthetic and natural. However, concerns about the environmental footprint of synthetic geotextiles, which are primarily derived from petrochemicals, have sparked interest in biodegradable alternatives. Both studies by Scholz *et al.* (2021) and Bai *et al.* (2022) underscored environmental degradation and microplastic pollution associated with polypropylene-based geotextiles, particularly in coastal environments.

The shift towards sustainable materials for geotextile applications has become a trend driven by increasing environmental awareness and the opportunity to invest in natural fiber-based geotextiles, according to Wu *et al.* (2020). Among the applied natural geotextile fibers, coir has the highest average diameter, density, and flexural rigidity, while pineapple fibers have the highest water absorption rate. These fibers can be blended or layered to increase their durability, strength, and compatibility, given their properties (Sebastian & Divya, 2024).

Recently, the Philippine construction industry has begun to appreciate the use of geotextiles for soil stability, and engineers continue to seek methods to enhance the performance of these materials, such as combining them. For instance, Adajar *et al.* (2023) demonstrated that nonwoven coconut coir, as an alternative geotextile material, enhances soil stability and slope stabilization. The difference between treated and untreated coir indicates that mercerized coir has higher tensile strength, while untreated coir has higher puncture resistance. Their data indicate that coir provides better slope stability and prevents soil erosion compared to synthetic geotextile materials. Caingles and Lira (2025) studied coconut and pineapple fibers to produce a natural geotextile net for soil erosion control. On the other hand, abaca fiber, as a natural fiber, absorbs water readily due to its hemicellulose content, which endows it with hydrophilic properties and enhances tensile strength (Karimah *et al*., 2021).

One of the focal points of the study is the effect of chemical treatment on abaca and coir fibers, specifically on their morphological properties and the direct correlation of these properties to improved fibral strength. The process of mercerization was derived from the study by Holanda *et al.* (2024) on the influence of sodium hydroxide treatment on *Typha domingensis* fibers for geotextile manufacturing. The optimal concentration of sodium hydroxide in a solution is 6%. *Typha domingensis*, or cattail, is a grass and therefore belongs to a different species from abaca and coconut. This is the main gap in the study, as the impact of chemical treatment on other types of plant fibers was not addressed.

As the performance of coconut coir is also investigated in the study, Cereno *et al.* (2011) provided significant insights into its performance as a geotextile material. However, the study failed to consider other physical properties, such as tensile strength, as it focused mainly on water retention and sediment accumulation. The idea to combine abaca and coconut coir is inspired by a study by Hernandez *et al.* (2018), which investigated the properties and behavior of banana fiber and coconut coir (Baconet) geotextiles. The latter examined the mechanical properties of the fiber but omitted the alkaline treatment process and the scrutiny of its subsequent morphological properties.

To address gaps in the extant literature, the present study investigated the engineering properties of abaca and coconut coir, individually and as blended rope-twine composites known as ABACON. These were assessed with and without alkaline treatment. The raw fibers and the fabricated twines and ropes were subjected to tensile strength tests and Scanning Electron Microscopy (SEM) to evaluate performance mechanically and microscopically. By conducting this research, the study aimed to support the ongoing national effort to develop viable, eco-friendly geotextile alternatives grounded in Philippine agricultural resources.

2. Methodology

2.1 Materials

The raw materials used in this study included abaca (*Musa textilis*) and coconut coir (*Cocos nucifera*) fibers. All materials were locally sourced from the province of Lanao del Norte. Abaca leaves were obtained from the Iligan

City Abaca Plantation Farm, and fiber extraction was conducted at Carmelo CMRG, Inc., in Purok 7, Santiago, Iligan City. Meanwhile, mature coconut husks were acquired from coconut plantations within the same province. The extracted coconut fibers were processed at the Malingao Community Service Multipurpose Cooperative (MCOCO), which also served as the separation and processing facility for the coir samples. Sodium hydroxide (NaOH) was used as the alkaline treatment agent for selected fiber samples sourced from La Victoria, Cogon, Cagayan de Oro City. Deionized water, stainless-steel containers, and drying trays were used during the chemical treatment process.

2.2 Methods

2.2.1 Making of test samples

The test samples were prepared from the fibers, including control and treated fiber sets, twines, ropes, and ABACON nets. Three replicates were produced to both untreated and treated fibers, twines, and ropes for statistical reliability. Twines were fabricated from abaca and coir fibers with a 5.0 ± 1.0 mm diameter, as shown in Table 1. In accordance with DPWH DO No. 29 series of 2008, the ropes and twines were produced using twining machines available at the processing sites, with the samples delivered to their testing centers at Mindanao State University – Iligan Institute of Technology (MSU-IIT), Iligan.

Table 1. The control and treated samples groups of twines

Design	Twine diameter
Control (Untreated)	
Abaca twine	5.0 mm ± 1.0 mm
Coconut twine	5.0 mm ± 1.0 mm
Treated with Alkaline	
Abaca twine	5.0 mm ± 1.0 mm
Coconut twine	5.0 mm ± 1.0 mm

Ropes with a diameter of 10.0 ± 1.0 mm were produced maintaining a 50:50 fiber composition ratio as shown in Table 2. The ratio of abaca to coconut coir is reminiscent of a study by Sivaranjani and Mahalakshmi (2023), which examined the properties of coir and abaca fibers in mulch mats and weaving for sustainable agriculture. The applied blend achieved a balance in tensile strength distribution and flexibility.

Table 2. The control and treated groups of ropes thickness

Design	Rope thickness
Control (50% Abaca rope and 50% coconut rope)	10 mm ± 1.0 mm
Treated (50% Abaca rope and 50% coconut rope)	10 mm ± 1.0 mm

2.2.2 Fiber alkaline treatment

The fibers were chemically treated with an alkaline solution to improve structural and mechanical properties. The procedure followed the methodology of Holanda *et al.* (2024), which examined the effects of a 6% sodium hydroxide treatment on natural fibers.

A 6% NaOH solution (approximately 1.5 M) was prepared by dissolving 300 g of sodium hydroxide (NaOH) in 5 L of distilled water. This calculation is based on the molecular weight of NaOH, which is 40 g/mol; thus, 300 g corresponds to 7.5 moles of NaOH. When this amount of solute is dissolved and the total volume of the solution is adjusted to 5 liters, the molarity is obtained by dividing the moles of solute by the volume of solution in liters: M=7.5 mol/5 L=1.5 M. Therefore, the 6% solution is chemically equivalent to a 1.5 molar NaOH solution, which provides a moderately strong alkaline medium suitable for fiber treatment, effectively promoting delignification and surface modification of natural fibers. Thereafter, the fiber samples were submerged in the solution for 24 hours, then rinsed with running water and air-dried under ambient conditions to terminate the triggered chemical reaction and stabilize the fiber structure.

2.3 Laboratory testing of control and treated fiber rope, twine, and net

2.3.1 ASTM D3822 tensile properties of single textile fibers

Abaca and coconut coir fibers were tested for tensile properties in accordance with ASTM D3822, which outlines the procedure for determining the tensile strength and elongation of individual textile fibers. Equation 1 was used to calculate the tensile strength of fibers under specified loading conditions.

$$\sigma = \frac{F_{max}}{A_0} \tag{1}$$

where σ is the tensile strength in MPa; F_{max} = maximum load in newtons (N); A_o is the original cross-sectional area.

2.3.2 ASTM D2259 tensile properties of yarns by the single-strand method

Abaca and coconut twines (5.0 mm ± 1.0 mm), as well as the combined abaca and coconut ropes (10.0 mm ± 1.0 mm), were tested according to ASTM D2256, which specifies the standard procedure for measuring the tensile strength of ropes by the single-strand method. Equation 2 was used to calculate the tensile strength of twines through the single-strand method.

$$T = \frac{F_{max}}{A} \tag{2}$$

where T is the tensile strength in MPa; F_{max} = maximum force applied before the material breaks (N); A = cross-sectional area of the twine in mm^2.

2.3.3 Scanning electron microscopy

Scanning electron microscopy (SEM) was performed to examine the surface morphology of untreated and alkaline-treated abaca and coconut coir fibers. Fiber samples were cut into short lengths and mounted onto aluminum stubs using conductive double-sided carbon tape. As in the study by Valášek *et al.* (2021), the specimens were sputter-coated with a thin layer of gold to enhance conductivity and reduce charging. The analysis was conducted at Mindanao State University – Iligan Institute of Technology (MSU-IIT) using a field emission scanning electron microscope, operated under high vacuum and at an accelerating voltage appropriate for fiber surface examination.

2.4 Statistical analysis

This study used a single-factor ANOVA (analysis of variance) and a post hoc test as statistical tools to determine whether there are meaningful differences among the means of independent groups. Single-factor ANOVA was used since there is only one independent factor, which is the 6% NaOH solution, and this concentration is applied to all fiber groups. ANOVA compares the variation between group means to the variation within groups using the F-ratio (Gahgah *et al.*, 2023). A statistically significant F-value ($p < 0.05$) indicates that not all group means are equal, suggesting that at least one group differs significantly from the others (Amroune *et al.*, 2022).

Moreover, a post hoc test, such as Tukey's Honest Significant Difference (HSD), is performed after obtaining a significant ANOVA result. Silva *et al.* (2025) explain that a post hoc test is used to compare each pair of group means and determine where significant differences lie, using an adjusted significance level.

3. Results and Discussion

3.1 Tensile strength of treated and untreated fibers

As shown in Table 3, untreated abaca and coconut fibers exhibited significant tensile strengths. reaching 1.73012 MPa and 1.84457 MPa, respectively.

Table 3. Physical properties of treated and untreated fibers based on a 5000n tensile strength test

Fibers	Thickness (mm)	Width (mm)	Gauge Length (mm)	Maximum Force (N)	Tensile Strength (MPa)
Coconut (Untreated)	1	1	100	1.84457	1.84457
Abaca (Untreated)	1	1	100	1.73012	1.73012
Coconut (Treated)	1	1	100	2.61863	2.61863
Abaca (Treated)	1	1	100	23.6646	23.6646

After alkaline treatment, the tensile strength of abaca fibers increased dramatically to 23.6646 MPa, representing an approximate 1,267% improvement. Coconut fibers also demonstrated a measurable increase from 1.84457 MPa to 2.61863 MPa, representing a 42.0% enhancement. This significant change, especially in abaca, may be attributed to improved molecular orientation and the removal of hemicellulose and lignin, which interfere with tensile load transfer.

3.1.1 Statistical analysis of treated and untreated fibers

The null hypothesis in Table 4 states that there is no significant difference in mean tensile strength between the untreated and treated fiber groups. However, the results of the one-way ANOVA revealed a statistically significant difference in tensile strength ($F = 34{,}064.12$, $p < 0.05$), so the null hypothesis is rejected. The treatment process markedly increases the fiber's tensile strength, particularly for Abaca fibers, whose mean strength rose from

1.73 MPa (untreated) to 23.66 MPa (treated). With a very high F-value and minimal within-group variation, the treatment effect accounts for nearly 100% of the total variation.

Table 4. Statistical data of untreated and treated abaca and coconut fibers using one-way ANOVA

Source of Variation	Sum of Squares (SS)	Degree of Freedom (df)	Mean Square (MS)	F	Fcrit ($p<0.05$)	Decision
Between Groups	1089.45	3	363.15	34,064.12	4.07	Reject H_0
Within Groups	0.085	8	0.0107	—	—	—
Total	1089.54	11	—	—	—	—

Since the ANOVA results were significant, a post hoc test was performed to determine which treatment groups differed from one another (Table 5). The honest significant difference (HSD) critical value of 0.242 was computed based on the ANOVA results, indicating that any mean difference greater than the HSD is statistically significant ($p < 0.05$). The post hoc test revealed that treated Abaca fibers responded more effectively to mercerization than coconut fibers, achieving the highest tensile strength of 23.66 MPa, corresponding to an approximate 1,267% improvement. Moreover, untreated samples show no meaningful difference in tensile strength, with a mean difference of only 0.11, which is below the HSD critical value of 0.242.

Table 5. Post hoc test of untreated and treated abaca and coconut fibers

Comparison	Mean Difference (MPa)	Significance ($p < 0.05$)	Data Interpretation
Abaca (treated) vs Abaca (untreated)	+21.93	Highly Significant	Treatment drastically improves abaca fiber strength.
Abaca (treated) vs Coconut (treated)	+21.04	Highly Significant	Even compared to treated coconut, treated abaca is far stronger.
Coconut (treated) vs Coconut (untreated)	+0.78	Significant	Treatment significantly increased coconut fiber strength. |
Abaca (untreated) vs Coconut (untreated)	+0.11	Not significant	Nearly identical tensile strengths for untreated fibers.

3.2 Tensile strength of treated and untreated twines

In terms of twine performance, as seen in Table 6, untreated abaca and coconut twines recorded tensile strengths of 0.53723 MPa and 0.50183 MPa, respectively. Following treatment, abaca twine reached 0.83091 MPa, a 54.7% increase, while coconut twine improved to 0.59895 MPa, a 19.3% increase. Although these values are lower than those of single fibers due to stress distribution across larger cross-sectional areas and twisted geometry, the positive influence of chemical treatment remains evident.

Table 6. Physical properties of treated and untreated twines based on a 5000N tensile strength test

Twines	Thickness (mm)	Width (mm)	Gauge Length (mm)	Maximum Force (N)	Tensile Strength (MPa)
Coconut Twine (Unreated)	4.89	8.17	100	20.0486	0.50183
Abaca Twine (Untreated)	5.2	8.13	100	22.7118	0.53723
Coconut Twine (Treated)	4.55	7.15	100	19.4852	0.59895
Abaca Twine (Treated)	5.63	9.67	100	45.2368	0.83091

3.2.1 Statistical analysis of treated and untreated twines

The null hypothesis in Table 7 states that there is no significant difference in tensile strength between the treated and untreated twine groups. Since the F-value (F=1,156.5) is greater than the F-statistic (Fcrit=4.07), we reject the null hypothesis. Hence, the results are statistically significant ($p<0.05$). Moreover, the low within-group variance of 0.00002 indicated good consistency and reliability.

Table 7. Statistical data of untreated and treated twines using one-way ANOVA

Source of Variation	Sum of Squares (SS)	Degree of Freedom (df)	Mean Square (MS)	F	Fcrit ($p<0.05$)	Decision
Between Groups	0.0694	3	0.02313	1,156.5	4.07	Reject H_0
Within Groups	0.00016	8	0.00002	—	—	—
Total	0.06956	11	—	—	—	—

Since the one-way ANOVA results for the two groups were statistically significant, a post hoc test was performed. The HSD critical value of 0.0417 suggests that any mean difference greater than 0.0417 is statistically significant at the 95% confidence interval. In Table 8, only untreated twines show no significant effect. The treated twines have a mean difference that is greater than 0.0417, indicating that the mercerization has improved the mechanical strength of twine groups.

Table 8. Post hoc test of untreated and treated abaca and coconut twines

Comparison	Mean Difference (MPa)	Significance ($p < 0.05$)	Data Interpretation
Abaca (treated) vs Abaca (untreated)	+0.30	Significant	Treatment greatly increased tensile strength.
Abaca (treated) vs Coconut (treated)	+0.23	Significant	Treated abaca is stronger than treated coconut.
Coconut (treated) vs Coconut (untreated)	+0.10	Significant	Treatment improved coconut twine strength.
Abaca (untreated) vs Coconut (untreated)	+0.03	Not significant	Untreated twines are similar in strength.

3.3 Tensile strength of treated and untreated ABACON ropes

The tensile strength values of ABACON ropes, as presented in Table 9, also demonstrated improved mechanical performance following alkaline treatment. The untreated ABACON rope recorded a tensile strength of 0.87578 MPa. After treatment, this increased to 1.27298 MPa, reflecting a 45.4% improvement. The moderate yet consistent enhancement confirms the synergistic behavior of hybridizing abaca and coconut coir fibers, likely improving inter-fiber cohesion and overall tensile capacity.

In essence, the reduced strength gains in twisted structures arise because load transfer is no longer direct and uniform as in single, unidirectional fibers. Instead, the load must pass through frictional and shear interactions between fibers, resulting in an uneven stress distribution. When some fibers break or slip, the surrounding fibers experience localized overloads rather than the load being evenly shared. This inefficient stress sharing, governed by inter-fiber friction, contact pressure, and helix geometry, limits the overall structural efficiency. As shown by recent experimental and numerical studies, these shear-limited mechanisms impose an upper limit on the tensile strength of ropes and yarns, meaning that improvements in individual fiber strength do not translate proportionally to the whole twisted assembly (Narjabadifam *et al.*, 2024; Irfan *et al.*, 2023).

Table 9. Physical properties of treated and untreated ABACON ropes based on a 5000n tensile strength test

Ropes	Thickness (mm)	Width (mm)	Gauge Length (mm)	Maximum Force (N)	Tensile Strength (MPa)
ABACON Rope (Untreated)	10.84	11.9	100	112.9716	0.87578
ABACON Rope (Treated)	10.26	11.5	100	150.1996	1.27298

3.3 Statistical analysis of treated and untreated ABACON ropes

The null hypothesis in Table 10 suggests that there is no significant correlation in tensile strength between untreated and treated ABACON ropes. However, the F-value (F=9,120) is greater than the F-statistic (Fcrit=7.71), thus the null hypothesis is rejected. Therefore, there is a statistically significant difference between treated and untreated ABACON ropes.

Table 10. Statistical data of untreated and treated ABACON ropes using one-way ANOVA

Source of Variation	Sum of Squares (SS)	Degree of Freedom (df)	Mean Square (MS)	F	Fcrit ($p<0.05$)	Decision
Between Groups	0.228	1	0.228	9,120	7.71	Reject H_0
Within Groups	0.0001	4	0.000025	—	—	—
Total	0.2281	5	—	—	—	—

Moreover, the post hoc test in Table 11 revealed that the mean difference of 0.39 exceeds the HSD critical value of 0.0114; the results are statistically significant. Hence, the treatment process resulted in a significant improvement in tensile strength.

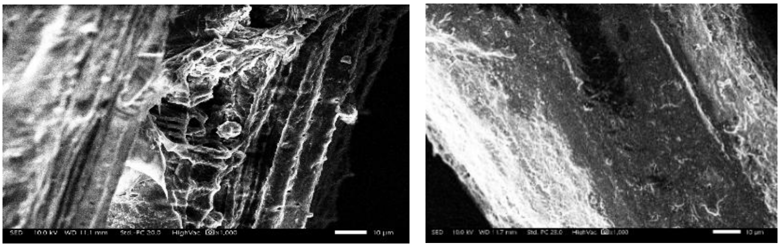
Table 11. Post hoc test of untreated and treated ABACON ropes

Groups Compared	Mean Difference (Δ)	Tukey HSD Critical Value	Significance Level	Decision
ABACON (treated) vs ABACON (untreated)	0.39	0.0114	$p < 0.05$	Significant

3.2 Morphological properties of fibers, ropes, and twines

Scanning electron microscopy (SEM) was conducted to observe the morphological changes in the surface structure of abaca and coconut coir fibers before and after alkaline treatment. Images were obtained for both treated and untreated samples at 1000x and 2000x magnifications to highlight differences in fiber integrity, surface roughness, and microstructural uniformity.

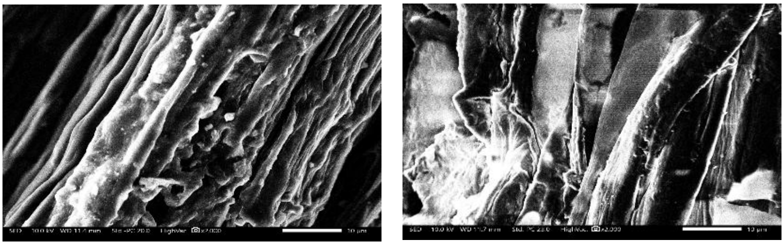
As shown in Figure 1a, at 1000x magnification, untreated coconut coir fibers appeared rough and irregular, with a surface layered in impurities, waxes, and non-cellulosic components such as lignin and pectin. Several globular formations and blocked pores were observed, consistent with prior findings that coconut fibers contain a high degree of surface-bound organic material (Sreenivasan *et al.*, 2011). Conversely, treated coconut fibers at 1000x magnification displayed smoother and more homogeneous surfaces, as shown in Figure 1b. The previously obscured fibrillar structure was exposed, and the removal of surface debris confirmed the successful breakdown of lignin and pectin. These changes suggest enhanced fiber-matrix interaction and better stress distribution during tensile loading.



(a) (b)

Figure 1. Coconut fibers (a) untreated at 1000x magnification vs. (b) treated at 1000x magnification

Conversely, untreated abaca fibers at 2000x magnification exhibited less-organized surface striations, as shown in Figure 2a. The abaca fibers showed longitudinal ridges and microfibrillar alignment, yet with obstructed pores and the presence of non-cellulosic residues. In contrast, Figure 2b showed that the surfaces of treated abaca fibers appeared cleaner and more compact, indicating a more fibrillated structure. This surface roughness indicates the partial delignification of the fiber, which exposes the underlying cellulose microfibrils and enhances surface area and interfacial adhesion with polymer matrices. The overall surface morphology demonstrated greater cohesion and potential for improved load-bearing capacity, as reported in previous literature (Kurien *et al.*, 2021).

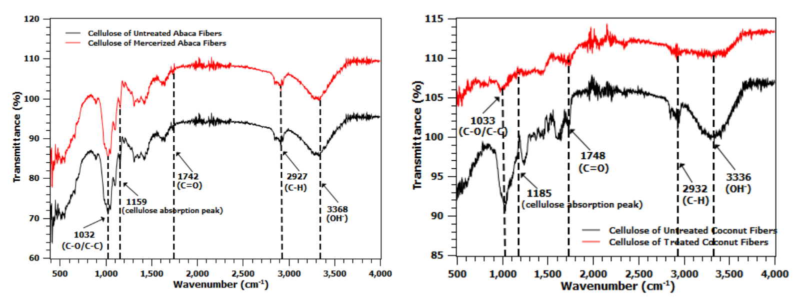


(a) (b)

Figure 2. Abaca fibers: untreated at 2000x magnification (a) vs. treated at 2000x magnification (b)

The SEM observations support the mechanical testing results, in which treated abaca fibers showed the greatest improvement in tensile strength. The morphological refinements, such as reduced impurities, clearer fibrillar networks, and smoother surfaces, are consistent with the theory that alkaline treatment enhances fiber crystallinity and interfacial bonding potential, findings highly analogous to those of Holanda *et al.* (2024) and Suárez *et al.* (2021). These structural changes, induced by sodium hydroxide immersion, confirm the effectiveness of mercerization in preparing natural fibers for geotechnical applications, particularly when tensile reliability is paramount.

Moreover, the SEM analysis is directly correlated with the chemical changes observed in the FTIR spectra of treated abaca and coconut fibers (Figure 3). Smoother exposed fibrils and lesser surface impurities are ascribed to the disappearance of the hemicellulose and lignin at absorption peaks of 1742 to 1748 cm^{-1} (carbonyl C=O group). This is in consonance with the study by Anand Raj et al. (2024), in which the loss of those bands indicated the removal of non-cellulosic components. Meanwhile, the increased crystallinity of treated fibers is reflected in the broad transmittance of the O–H stretching band around 3336–3368 cm^{-1}, indicating a relative increase in cellulose hydroxyl groups and altered hydrogen bonding due to cellulose exposure. Additionally, the improved interfacial adhesion in treated fibers is attributed to enhanced stress transfer in fiber-reinforced composites, as previously reported (Escobar *et al.*, 2023). Moreover, the C–O–C and C–O stretching vibrations in the 1032–1185 cm^{-1} region are attributed to the removal of surface impurities and the dominance of cellulose structures after the treatment. This confirms that the NaOH solution effectively disrupted the lignin–hemicellulose linkages and removed amorphous lignin components.



(a) (b)

Figure 3. Chemical characterization of untreated and treated abaca fibers (a) vs. chemical characterization of untreated and treated coconut fibers (b)

4. Conclusion and Recommendation

This study demonstrated that alkaline treatment significantly enhances the tensile and morphological properties of abaca and coconut coir fibers, reinforcing their suitability for geotextile applications. Among the tested materials, treated abaca fibers exhibited the greatest improvement in tensile performance, while coconut coir fibers and hybrid ABACON ropes showed consistent strength gains, confirming the synergistic benefit of fiber hybridization. SEM analysis revealed that alkaline treatment effectively removed surface impurities and non-cellulosic components, leading to improved fibrillation and stress transfer, which explains the observed mechanical enhancements. The findings imply that alkali-treated abaca and coconut coir fibers are viable, sustainable alternatives to conventional geosynthetics for bioengineering and soil stabilization applications. Their improved mechanical performance supports their use as locally sourced natural geotextiles, particularly when employed in composite configurations to balance strength and biodegradability. Despite these promising results, the study is limited to short-term mechanical and morphological evaluations conducted under laboratory conditions. Long-term durability, environmental exposure effects, and other critical geotextile properties such as permeability, puncture resistance, and biodegradation behavior were not assessed. Future studies should address these limitations and optimize fiber blend ratios and treatment conditions to enhance field performance and application-specific suitability.

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