

Natural fibers and the potential of babassu coconut in soil reinforcement: A review

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improvement, Sustainability.**

Abstract— Improvement of the soil's properties in order to resist erosion is desirable, and soil reinforcement is one of the techniques used to achieve this. The incorporation of natural fibers into the soil to form a composite material has been widely investigated. The most common natural fibers used for soil reinforcement are green coconut, sisal, and jute fibers, which were the subject of the systematic review carried out in this study. The study also presented babassu coconut as a potential material for soil reinforcement. Using the methodology adopted, 76 publications related to the theme were selected and studied. This study made use of the Periodicals Portal virtual library and the articles selected were limited to peer-reviewed articles published between 2008 and 2019 in either Portuguese or English. The references of the selected articles were also analyzed. The data from the selected publications were analyzed and described under the following discussion topics: natural fibers in soil reinforcement (green coconut, sisal and jute), ideal fiber length and content for soil reinforcement, correlation between fiber content and ideal length, aspects of babassu, and future perspectives for the use of babassu. It was concluded that the natural fibers increase the mechanical properties of the soil and that the babassu husk fiber also has potential to improve the soil. It is necessary to investigate, among other characteristics, the ideal fiber length and content for the principal types of soil found in the northeast region, as well as to evaluate the effect of saturation and durability over time.

I. INTRODUCTION

Concern over soil erosion has reached a high level of importance in many regions of the world, due to the loss of

considerable amounts of arable land, the silting up of water bodies, and the occurrence of landslides [1, 2]. The form soil erosion takes may vary according to local climatic conditions. For example, tropical and semi-arid regions of

the Mediterranean are more impacted by water erosion due to the loss of vegetation cover [3, 4, 5].

The impact of raindrops on exposed soil and the power of water running across the surface of the soil promote the erosion process [3,6]. The presence of residue on the surface of the soil reduces the impact caused by precipitation and surface runoff, which thereby reduces soil particle disintegration and controls erosion [7]. This natural process can therefore be minimized by using techniques that create a resistant layer in the soil, preventing the easy penetration of water.

Currently, the most widely-used soil improvement technique is replacement, in which part of the soil is removed and other materials, such as recycled fibers and aggregates, are introduced. Choosing the best improvement technique depends on the environmental, geological, and hydrological factors peculiar to the study area. Reinforcement is therefore a mechanical method to improve soil characteristics and behavior by introducing composite materials having certain desired properties [8, 9].

The life cycle of composite material has a smaller impact on human health, the environment, and the consumption of natural resources, as well as the advantage of reduced energy consumption [10, 11]. A well-known reinforcement practice is the introduction of natural fibers into the soil matrix to form a composite material [12].

Natural fibers are abundant in tropical regions of the world and the most common are: Sisal, extracted from *Agave sisalana*, one of the first fibrous plants to be cultivated specifically for fiber extraction [10]; Jute (*Corchorus capsularis*), a fiber from a woody herb of the *Tilioidae* family; and coconut fibers, resulting from the processing of coconut bark that is generally discarded by the industry [13, 14].

The main objective of this study was to carry out a systematic review of the incorporation of the natural fibers sisal, jute, and green coconut into the soil matrix, in order to investigate the mechanical properties of the reinforced soils. The specific objectives were: (1) to discuss how the reuse of fibrous coconut residue contributes to cleaner production and sustainability, and (2) to present the babassu coconut as a potential soil reinforcement material by comparing its properties to those of green coconut.

This study is organized into sections. Section II presents a detailed description of the methods employed. In section III, the results obtained from the literature review are discussed, and subsections have been created in accordance with the objectives defined: natural fibers in soil reinforcement (green coconut, sisal, and jute); ideal fiber content and length in soil reinforcement; correlation

between ideal length and content of natural fibers; aspects of babassu coconut; and future perspectives for the use of babassu. Finally, section IV presents the conclusions of the study on the use of natural fibers in soil reinforcement for civil construction.

II. METHODOLOGY

This review followed the PRISMA ("Preferred Reporting Items for Systematic Reviews and Meta-Analysis") model [15]. The systematic review model uses systematic and explicit methods to critically identify, select, and evaluate relevant research, and to collect and analyze data from those studies that are included in the review. The meta-analysis refers to the use of statistical techniques in a systematic review to integrate the results of included studies [16].

The search tool was the CAPES Periodicals Portal, a Brazilian virtual library in which high-level articles, books, and periodicals can be consulted, such as Scopus and SciDirect. The searches were carried out using the keywords "reforço de solo e fibra de juta" ("soil reinforcement and jute fiber"), "reforço de solo e fibra de coco" ("soil reinforcement and coconut fiber"), "reforço de solo e fibra de sisal" ("soil reinforcement and sisal fiber"), "reforço de solo e materiais não convencionais" ("reinforcement of soil and unconventional materials"), "reforço de solo e erosão" ("Soil reinforcement and erosion"), "propriedades mecânicas e fibras naturais" ("mechanical properties and natural fibers"), and "coco e babaçu" ("coconut and babassu"), where 2,041 publications were found.

The choice of criteria was motivated by the need for technical reliability of the subject, current information and analysis of the research developed in Brazil and in other countries, respectively.

The selection of publications was performed according to the following criteria: (1) considering only peer-reviewed articles; (2) considering only articles published between 2008 and 2019; (3) considering only articles in Portuguese and English; (4) excluding duplicates. Further on, the articles were excluded if didn't consider mechanical properties of coconuts and its application in the reinforcement of soils. This selection was first made through the screening of titles, and then the screening of abstracts from the remained articles. Finally, after thoroughly screening the selected full articles, they were excluded if not in accordance with the objective of this study (Fig. 1).

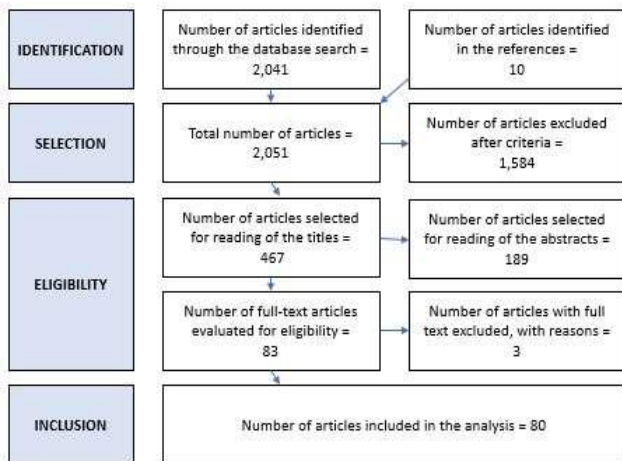


Fig. 1: Search Flowchart (adapted from [15])

The literature selection was then performed in stages. The steps were eliminatory, in the following order: (1) reading of the titles, (2) reading of the abstracts, (3) reading the articles in full. The references of review publications identified through the database search were consulted to find other sources pertinent to the study topic.

The objective of this study was to focus on the advantages of using natural fibers for soil reinforcement and how such use favors sustainability and clean production. In addition, it sought to characterize the babassu coconut to make its incorporation into the soil matrix viable in future studies. The selection resulted in a final list of 80 articles that were studied in depth.

III. RESULTS AND DISCUSSION

• Natural fibers in soil reinforcement (green coconut, sisal, and jute)

The use of natural fibers as building material is indicated mainly for regions where raw fiber materials are locally available [17]. Sisal and jute are species cultivated specifically for fiber extraction, while coconut fibers are extracted from the shell of the coconut fruit, a waste residue of the productive process [10].

The extractivism of the green coconut is aimed at the consumption of coconut water, and when mature (the “dry coconut phase”), for the production of industrialized products. The babassu coconut is exploited to remove the almond, which is destined for the production of oil. Babassu almond is the second most sold non-timber forest product in Brazil, at around 120 thousand tons annually, reaching a value of almost R\$ 150 million [18].

In 2010, approximately 481 thousand tons of dry green coconut husk and 99 thousand tons of babassu coconut husks were produced [19]. Fig. 2 shows the coefficient of

waste generation during the production of green coconut, babassu coconut, sisal, and jute, for each ton produced. It can be seen that coconut crops generate the least amount of waste, considering the technical coefficients (t waste / t product) of 0.85 for green coconut and 0.93 for babassu coconut [19].



Fig. 2: Coefficients of waste generation for green coconut, babassu coconut, sisal, and jute (created from data presented by [19]¹, [20]², and [21]³)

The use of coconut shell fibers is an important step forward in making use of agricultural waste residue, and has several advantages, such as: adding value to coconut by-products; being an easy-to-use material; having better durability compared to other natural fibers; being moth-proof, fungus-proof, and moisture-proof; and, when incorporated into the soil structure, providing strength and durability [22, 23, 24].

The incorporation of fibers into the soil is known as a reinforcement technique. In general, synthetic and natural fibers can both be used for this purpose. However, due to the increasing focus on maintaining the environment, the use of natural fibers is advised. For this reason, natural fibers must have a low biodegradation potential, that is, a slow degradation rate, a characteristic of fibers containing a high lignin content, such as sisal, jute, and coconut fibers [23, 25].

The mechanical and physical properties of natural fibers differ among species, but generally have superior specific resistance, lower weight, and more eco-friendly characteristics [26]. [20] analyzed the environmental performance of the production of natural sisal fiber and compared it to synthetic glass fiber, discovering that sisal fiber production has around 75% to 95% lower greenhouse gas emissions.

Soil improvement through the addition of randomly distributed fibers has the potential to be applied to reinforce the subsoil under heavy loads and excessive deformations, superficial foundations such as in landfills on weak soil, and other earthworks [27]. It allows the use of clay as a structural element that can be subjected to

bending or pulling forces [28]. In clay soils, for example, fiber addition improves the stress-strain response [29].

Studies have indicated that the inclusion of natural fibers in the soil matrix can lead to the prevention of visible cracks [30]; the reduction of composite mass up to 110°C, due to the water loss from the fibers, because they are a natural hydrophilic material [31]; other results are shown in Table 1.

Table.1: Results of the inclusion of natural fibers in the soil matrix

Properties	Increase	References
Compressive strength	37%	[32]
Penetration resistance	56%	[33]
Tensile strength	30%	[34]
Cohesion and peak soil tension	20%	[35]

The inclusion of natural fibers in the soil matrix causes increased permeability promoted by the presence of pore structures in the fibers and due to the water flowing along the soil-fiber interface along with the flow through the soil pores [36, 37].

The natural fiber reinforced composites may have mechanical properties comparable to non-composites used for the same purpose, having the advantage of reduced energy consumption [11, 35]. [10] studied the life cycle of a composite and concluded that they have a smaller impact on human health, the environment, and consumption of natural resources throughout the cycle.

The special challenges for the use of natural fibers are concern for adhesion, fiber quality, low impact strength, long-term storage problem, hydrophilic fibers, compatibility problems, fiber degradation during processing, orientation and distribution of fibers as well as moisture [38]. Natural fibers are not very stable at elevated temperatures and could absorb moisture and subsequent swelling and degradation, which restricts them to applications in moist environments [39, 40].

- **Ideal fiber content and length in soil reinforcement**

The amount of natural fiber incorporated into the soil is a variable that can compromise its benefits as a reinforcement. [41, 42, 43] concluded that the best experimental yield was found for samples incorporating a higher content of smaller length fibers. The compressive, shear, and tensile strength tend to decrease with excessive fiber content. The tensile strength and modulus of elasticity of the composite increase with the addition of

fibers up to a certain point, that is, until they reach the optimum content, and decrease afterwards [44, 45]

In the publications consulted, different fiber contents were determined to improve the physical and mechanical properties of the soils. The fiber lengths and contents incorporated to reinforce the different types of soil are shown in Table 2, organized by fiber type. For each fiber, the data were subdivided according to the soil studied.

The coconut fiber content to reinforce sandy soil varied between 0.2% and 1.5% of the dry sample weight with lengths between 5 mm and 50 mm. It was noticed that lower content was associated with longer length, except in the study by [25]. For coconut fiber-reinforced clay, the content was between 0.5% and 2%. The three studies consulted tested the introduction of fiber in 0.5% increments and no relationship was observed with regard to length. In silty and clayey soils with low compressibility, the contents were between 1% and 2% and between 0.4% and 1.6%, respectively. In addition, [46] indicated the use of fibers with a length of 25 mm for reinforcement of clayey soil with low compressibility.

Green coconut fibers were found reinforcing other types of soils, such as: termite clay, strong clay, marine clay, cohesive soil, red soil, expansive soil and soft soil. For these soils, the fiber contents varied between 0.5% and 2% and lengths between 15 mm and 50 mm. It should be noted that the preparation of samples with fiber content greater than 2% had a greater incidence of fiber agglomeration and the formation of weak planes within the sample [47]. An increase in the tendency of fiber to agglomerate also can occur with the use of longer fibers [48]. Thus, to achieve strong composites, well-separated fibers are required [49].

In the studies that used jute fiber, smaller amounts of fiber were incorporated when compared to the coconut fibers. For low-compressibility silty soils, the recommended fiber content was between 0.75% and 1%, without specifying length. For sand reinforced with jute, the content varies from 1% to 1.5% and, according to [50], the ideal length is 5 mm. For the fine-grained silty clay and the expansive soil, the ideal jute fiber content was the same, 6% of the dry sample weight. However, the expansive soil requires a longer fiber length, minimum 12 mm, compared to a length of 6 mm for fine-grained silty clay.

In the studies that looked at sisal fiber, the relationship between fiber content and length was also noticed. For the silty clay soil, when the fiber content is 1%, a fiber length of 10 mm is recommended, while for a 0.1% fiber content, the length should be 70 mm. The same is observed with sisal-reinforced clay, where fiber contents of 0.3% to 0.5%

are correlated to a length of 30 mm, while for 6% content, the recommended length is 10 mm.

Studies developed by [51] and Sotomayor and [52] indicated the introduction of 0.5% of green coconut fibers in Brazilian soils, clay sand and sand, respectively, with lengths of 20 mm and 50 mm. [53] found that for a sand reinforced with sisal fibers, the 0.5% content also presented better mechanical results, where there was an increase in the resistance peak of 87% to 118%.

Two studies with the use of babassu fibers were found to improve the characteristics of sand, both to produce soil blocks. [54] used the content of 40% and random length for the fibers and [55] used content of 0.3% and lengths of 15 mm and 20 mm. Due to the non-relationship between the variables of the cited studies, the correlation between content and length for babassu coconut fibers was not analyzed.

Table 2: Characteristics of the studies included

References	Soil	Fibers	Fiber content (%)	Fiber length (mm)	Unconfined compressive strength (kPa)	Undrained Triaxial compression (kPa)	Tensile strength (kPa)	Shear stress (kPa)
[25]	Sand	Green coconut	1	25 - 50	-	-	-	-
[56]	Sand	Green coconut	0.2	30	-	-	-	43 (50 kPa) 90 (100 kPa) 138 (150 kPa)
[22]	Sand	Green coconut	0.8	15	2260 ⁽¹⁾	-	170	-
[57]	Sand	Green coconut	< 1	-	-	-	-	-
[58]	Sand	Green coconut	0.5	50	-	-	-	-
[27]	Sand	Green coconut	0.5 - 1	-	-	-	-	-
[50]	Sand	Green coconut	1.5	5	-	-	-	-
[23]	Clay	Green coconut	0.5	20 - 30	770	-	108	-
[59]	Clay	Green coconut	1	-	780	-	90	-
[17]	Clay	Green coconut	0.5 - 1	-	-	350-400 (100 kPa)	-	-
[29]	Clay	Green coconut	0.5 - 2	15	-	-	-	-
[51]	Clay sand	Green coconut	0.5	20	597	-	29.8	40 (50 kPa) 80 (100 kPa) 90 (150 kPa) 125 (200 kPa)

References	Soil	Fibers	Fiber content (%)	Fiber length (mm)	Unconfined compressive strength (kPa)	Undrained Triaxial compression (kPa)	Tensile strength (kPa)	Shear stress (kPa)
[47]	Low compressibility silt	Green coconut	1.5 - 2	15	470	420-500 (50 kPa) 500-570 (100 kPa) 610-790 (150 kPa)	-	-
[46]	Low compressibility clay	Green coconut	0.8	15 - 25	190.82 - 200.86	-	-	-
[24]	Low compressibility clay	Green coconut	0.4 – 1.,6	15	79.67 - 114.77	-	-	-
[60]	Termite mound clay	Green coconut	1 – 2	6	460 - 530 ⁽¹⁾	-	-	-
[61]	Cohesive soil	Green coconut	0.8	20	215	-	-	-
[62]	Marine clay	Green coconut	0.6	-	-	-	-	-
[23]	Expansive soil	Green coconut	1	10 - 50	-	-	-	-
[63]	High clayey	Green coconut	0.5	50	-	-	-	-
[64]	Red soil	Green coconut	1 - 2	15	-	-	-	-
[54]	Sand	Babassu coconut	40	-	1180 ⁽¹⁾	-	-	-
[55]	Sand	Babassu coconut	0.3	15 - 20	8390 ⁽¹⁾	-	-	-
[65]	Low compressibility silt	Jute	1	14	-	-	-	-
[66]	Low compressibility silt	Jute	0.75	20 – 40	1000	-	-	-
[50]	Sand	Jute	1.5	5	-	-	-	-
[43]	Soil of coastal area	Jute	0.2 – 0.25	25	290 – 310	-	-	-
[41]	Fine grained silty clay	Jute	0.6	6	-	-	-	205 (100 kPa)

References	Soil	Fibers	Fiber content (%)	Fiber length (mm)	Unconfined compressive strength (kPa)	Undrained Triaxial compression (kPa)	Tensile strength (kPa)	Shear stress (kPa)
								210 (200 kPa) 225 (300 kPa) 250 (400kPa)
[67]	lateritic	Jute	0.75	35	450	-	-	-
[68]	Expansive soil	Jute	0.6	12 – 18	445	480 (250 kPa)	-	271 (300kPa)
[53]	Sand	Sisal	0.5	25	-	254.67 (50 kPa) 513.41 (100 kPa) 789.39 (150 kPa)	-	-
[69]	Silty clay	Sisal	0.1	70	3500 ⁽¹⁾	-	-	-
[70]	Silty clay	Sisal	1	10	-	-	-	-
[71]	Clay	Sisal	0.6	10	410	-	8.3	245 (50 KPa) 490 (100 kPa) 637 (kPa)
[72]	Clay	Sisal	0.3 – 0.5	30	-	190-220 (50 kPa) 160-270 (100 kPa) 210-330 (150 kPa)	-	-
[73]	Low compressibility clay	Sisal	0.75	25	3500	-	-	-

• **Correlation between ideal length and content of natural fibers**

In order to prove the existence of a relationship between the random variables "fiber content" and "fiber length", this study used the data presented in Fig. 3 and applied the statistical method of correlation. The behavior of each fiber was identified in isolation. All values recommended by fiber type were associated, regardless of soil characteristics.

Correlation is any relationship that involves dependence between two variables [74]. To find the correlation, it is necessary to calculate the correlation

coefficient (ρ), which is the covariance divided by the product of its respective standard deviations, shown in Eq. 1. In turn, covariance (COV) is a non-standardized measure, from which it is therefore relatively difficult to draw conclusions about the relationship between two variables. The covariance calculation is important to find the correlation value, determined by Eq. 2 [75].

$$\rho_{XY} = \frac{COV_{XY}}{\sigma_x \sigma_y} \tag{Eq. 1}$$

$$COV_{XY} = E [XY] - \mu_x \mu_y \tag{Eq. 2}$$

Where μ_x and μ_y are the means of the x and y values, σ_x and σ_y are the standard deviations of the x and y values; $E[XY]$ is the mean of the product of two independent random variables. In Fig. 3, it is possible to graphically observe the relationship between the study variables. It should be noted that the studies that did not determine a value for ideal content and/or length were excluded from the statistical analysis and, whenever a study presented a range of values, the minimum, maximum, and mean values were used.

The closer the individual points are to the linear regression line, the stronger the relationship between the

variables. It can be seen that there is a tendency for the points to cluster near the regression lines for the three fibers (coconut, jute, and sisal), but the correlation appears to be weak. Regarding the regression line for sisal fiber, the points are less dispersed than those for the other fibers. While it is not possible to accurately determine the relationship between fiber content and length, a trend can be perceived. Other statistical analyses would need to be carried out to look at this in more depth.

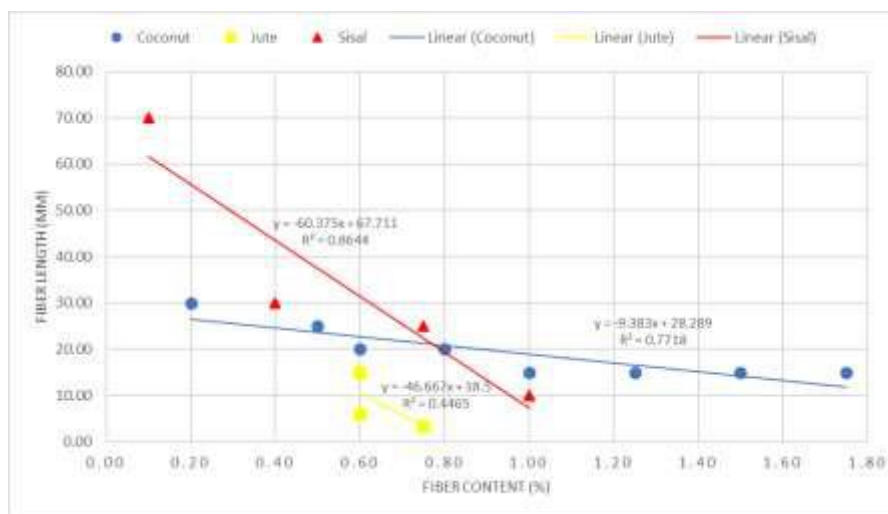


Fig. 3: Relationship between content and length for natural fibers (green coconut, jute, and sisal)

Once the correlation is characterized, it can be described in mathematical form through an equation. The measurement of the degree, the correlation sign, and the variation ratio is made by analyzing the COV values, ρ , and coefficient of determination (R^2) between the two random variables. The R^2 varies between 0 and 1, and the closer the value is to 1, the more explanatory the model is. Its value gives the ratio of the variable Y explained by the variable X through an adjusted function [75], according to Table 3.

Table.3: Covariance values, correlation coefficient, and coefficient of determination for the variables "ideal fiber content" and "ideal fiber length"

Relationship between variables	COV	P	R^2
Coconut	-2.81	-0.552	0.3042
Jute	-0.68	-0.406	0.1645
Sisal	-5.78	-0.859	0.7375

Correlation measures the strength and direction of the linear relationship between two variables. Negative values of covariance indicate that values above mean of one variable are associate with mean values below the other variable. Thus, it is observed the inversely relationship between "ideal fiber content" and "ideal fiber length".

In the analysis associated with the jute and coconut fibers, the COV, ρ , and R^2 values show that the variables have a very weak relation and the proposed equation is not sufficiently explanatory, because COV and R^2 values close to zero indicate that the two variables are not related [76]. However, the relationship between the random variables for sisal fibers was closer, that is, 73.75% of the variation in fiber length can be explained by the fiber content.

• Aspects of babassu

The fruit (coconut) of the babassu palm can be divided into layers: the epicarp, the hard and fibrous outer layer; the mesocarp, the starch-rich layer that lies below the epicarp; the endocarp, the most resistant layer, as shown in

Fig.4. The shell is made up of these three layers together, which make up 93% of the total weight of the coconut. The other 7% corresponds to the weight of the almond [19].

The babassu coconut fibers are concentrated in the epicarp. Analysis of dry epicarp samples at 75°C and 90°C showed 59% and 61% crude fiber content [77]. In green coconuts, the fibers are found in the husk, which corresponds to about 80% of their gross weight [78]. Visually analysis of the babassu coconut and the green coconut show that the babassu coconut has a length and diameter much smaller than the green, however, both have a high percentage of fiber.

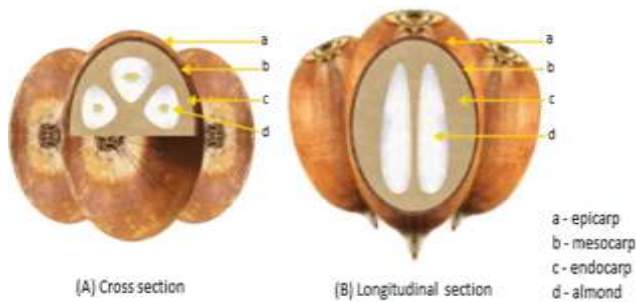


Fig 4: Sections of babassu coconut [79]

Generally, natural fibers are composed mostly of cellulose, lignin, and hemicellulose. Lignin is responsible for resistance and cellulose/hemicellulose is responsible for stiffness [12, 23]. The analysis of the chemical composition of the natural fibers is fundamental, as this can determine the applicability of the fibers for use as composite reinforcement material. The chemical compositions of the most conventional fibers (green coconut, jute, and sisal) and babassu coconut fibers are shown in Table 4

Table 4: Chemical composition of natural fibers (% by weight)

References	Fibers	Lignin (%)	Cellulose (%)	Hemicellulose (%)
[12]	Green coconut	40-45	32-43	21
[80]	Babassu coconut	17.8	62	13
[81]	Jute	12-13	61-71.5	13.6-20.6
[81]	Sisal	8-11	67-78	10-14.2

Among the conventional fibers, those extracted from green coconut have the lowest percentage of cellulose, but the highest amount of lignin [13, 82]. Furthermore, among all of the natural fibers, (green) coconut fiber has a better tear strength and maintains this property, to some extent, even in humid conditions [29].

Analysis of the chemical composition of the coconut species show that the babassu has a higher percentage of cellulose, which characterizes the material as stiffer than the green coconut, and this percentage is close to that of jute and sisal. However, the amount of lignin present in babassu coconut fibers, though greater than that found in jute or sisal, is about half that found in green coconut fibers.

[83] report that the physical and mechanical properties of the fibers are also determinants of the behavior of the composite. These properties are associated with the chemical compositions of the fibers [12]. The physical and mechanical properties of natural fibers related to soil reinforcement are summarized in Table 5.

In relation to density, the babassu coconut fibers present less value than the fibers of green coconut, jute and sisal. [54] concluded that the presence of babassu fiber in the production of adobe blocks decreases the weight of the block as the fiber concentration increases.

The Young module divides the materials into flexible and rigid, approximately. For this reason, a rigid material is one that has a high Young's modulus [84]. Thus, it is found that green coconut fibers and babassu coconut are the most flexible.

[85] observed that as babassu coconut fibers increase in the polyester composite matrix, there is an increase in the modulus of elasticity of the composite because the fibers have higher stiffness than the matrix.

The fiber's property of absorbing water is known as mucilage, a complex structure gelatinous substance that when reacted with water increased the volume, causing dimensional deformation in the composite, in addition to the mass increase. This may impair the mechanical performance of the material [55, 86].

The coconut babassu fibers have low water absorption, consequently, their incorporation into the soil composites causes little volumetric increase of the material. It is therefore possible to consider that babassu coconut has characteristics favorable for use as a composite reinforcement material.

Table 5: Physical and mechanical composition of natural fibers

References	Fibers	Density (g/cm ³)	Tensile strength (Mpa)	Young's modulus (GPa)	Ultimate elongation (%)	Moisture absorption (%)
[48, 67, 68]	Jute	1.3 - 1.5	393 - 800	10 - 55	1.5 - 1.8	340
[43, 70]	Sisal	1.4	526	18.3	6	203.2
[12, 24, 46, 50]	Green coconut	1.4	128	2.1	41.7	130 - 180
[55]	Babassu coconut	0.91	183.8	8.5	-	2

• Future perspectives for the use of babassu

Normally, following the extraction of the almonds, the remains of the babassu coconut are discarded or destined for the production of charcoal. It is estimated that 450-550 g of carbon dioxide (CO₂), 450-650 g of carbon monoxide (CO), 700 g of methane (CH₄), and 10-700 g of hydrocarbons are emitted for each kilogram of non-methane charcoal produced [87], these being the most powerful greenhouse gases [88].

In a survey conducted to estimate the commercial value of babassu products, it was verified that the mesocarp can be traded at R\$ 0.50 kg and the endocarp (fibrous layer destined for charcoal production) at R\$ 0.75 kg [89]. The commercialization of waste from babassu coconut production can generate direct and indirect jobs, promote clean production, and generate economic gains of approximately R\$ 53,260,000.00 per year. To calculate this value, it was considered that the mesocarp represents 20.4% of the coconut and the endocarp 58.4% [18]. Production data from 2010 was used, in which 98,631 thousand tons of waste from this type of coconut were generated in Brazil [19]. These facts agree with the statement of [90]: Natural fibers have the advantage of being renewable resources and marketing appeal.

Northeastern Brazil, where babassu palm tree cultivation is concentrated, is a region that has suffered greatly throughout its history due to economic and social inequalities, such as lack of infrastructure and education, as well as flagrant poverty. This study proposal can help reduce the disposal of babassu coconut residue in the environment, provide a new source of income for local communities that export babassu oil, and reduce the cost of soil reinforcement in the region.

IV. CONCLUSION

The present study focused on a review of the use of natural fibers as soil reinforcement and showed that babassu coconut is also a material with great potential for this use. The proposal is focused on the reuse of the fibrous husk of the babassu coconut, a waste product generated by the extraction of coconut oil, grown principally in the state of Maranhão, Brazil, and which can also be used to produce charcoal through an extremely polluting process. For the region where the major babassu coconut producers are concentrated, this study proposes a sustainable method that can be integrated into the grain size stabilization technique. The main conclusions of the study are:

- (1) In the green coconut industry, the processing of fibers for marketing is common and has appropriate technologies for reuse. However, this scenario is not yet seen in the babassu coconut industry.
- (2) The use of natural fibers in soil reinforcement is beneficial mainly in places where the raw material is available and helps the environment because its production process is cleaner than that for synthetic fibers.
- (3) The production of green coconut and babassu coconut presents low coefficient of waste generation.
- (4) The incorporation of natural fibers into the soil matrix increases permeability as well as tensile, compression, penetration, and shear strength.
- (5) For reinforcement of soils with natural fibers, the fiber content may not exceed 2% of the dry sample weight and length should not exceed 50 mm, as both tend to agglomerate the fibers and form weak planes of interaction with the soil.
- (6) The study statistically analyzed the relationship between the random variables "fiber content" and "fiber length" and noticed the existence of a trend with, inversely proportional, a weak relationship.

- (7) Babassu coconut has a high fibrous content and its fibers have a high percentage of cellulose, with this characteristic being associated with the rigidity of the material.
- (8) The fibers of green coconut and babassu are very flexible.
- (9) Babassu coconut fibers has lower density value and lower moisture absorption rate than the fibers of green coconut, jute and sisal.
- (10) The production process of babassu coconut treats the husk (epicarp, mesocarp, and endocarp) as waste. This waste can be used to make charcoal, which produces greenhouse gases.
- (11) The use of the babassu husk helps to ensure production standards, sustainable consumption, and the promotion of a less wasteful use of the fruit. It also strengthens the cultivation of the species and guarantees the maintenance of the social system linked to its extraction.

V. LIMITATION OF THE USE OF BABASSU COCONUT FIBERS

The principal barriers to the development of solutions that fully use babassu are due in large part to the conservative stance of the industry and the lack of technologies that facilitate processing. For the construction sector, the use of babassu coconut fibers as a construction material would provide direct reductions in the consumption of natural resources and, consequently, would minimize the generation of construction waste.

VI. SUGGESTION FOR FUTURE STUDIES

For future studies, it is highly recommended that the surface of the natural fibers be treated to improve their bonding with the soil matrix. Also, it is recommended to perform tests with strengthened or nano-modified fibers for use as soil reinforcement. In addition, the saturation effect and the long-term durability of the composite soil/fiber mixture needs further analysis.

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