



Circular Economy Applicable to Waste from the Sustainable Production of *Musa textilis* in Costa Rica

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Abstract. The *Musa textilis* crop is known worldwide as Abaca or Manila hemp, and for many decades the pseudostem fibers have been used as export raw material for the manufacture of cellulose-based products. It is one of the most resistant natural fibers to salinity and has excellent mechanical properties, flexibility, and durability. In the Americas, the two leading countries in the production of Abaca fiber are Ecuador and Costa Rica. There is a good base of information on the agronomic aspects of the crop, the use of improved materials, fiber production techniques and quality characterization. However, there is a lack of information on the estimation of the production of residues and the alternatives for their valorization. The understanding of biomass production, characteristics and types of waste can awaken the interest of producers and companies to generate new products within the concept of waste utilization and circular economy. This work provides guidance on the estimation of waste and presents a proposal of alternatives for the use of fibers to add value. This research is also useful to motivate Banana producers in the search for alternative uses of large volumes of waste generated in the productive activity.

Keywords: *Musa textilis* · fiber · biomaterial · bioeconomy

1 Introduction

Musa textilis is a monocotyledonous species belonging to the Musaceae family and endemic to the Philippines [1]. It is known worldwide as Abaca or “Manila hemp” and is an herbaceous plant with a growth architecture similar to banana and plantain plants; although unlike these, its commercial utility is not directed towards food, and although it produces small fruits, its commercial raw material comes from the pseudostem fibers, which are extracted using very rustic techniques or with mechanical assistance.

This fiber is considered a potential substitute for wood in the manufacture of paper pulp because it is characterized by excellent mechanical (tension-bending) and chemical properties (63% of cellulose, 21% of hemicellulose, 14% of lignin, and 2% of impurities) [2]. Currently much of the processed material is focused on the manufacture of high-quality paper and specialized use such as tea bags and filters of different types [3, 4].

Abaca has a production cycle that depends on soil and climate conditions and the fiber can reach maturity between 12 and 18 months [5]. To obtain quality fiber, it is necessary to harvest the mature pseudostems and separate the shells to decorticate the fiber, using portable machines called “deco”, which comes from the word “decorticate”. There are currently more than 50 machines in the country and their number will increase soon; however, recently at the end of 2023 the “Spindle” machine was introduced in the country, which improves the quality of the decortication and requires a different preparation of the shells containing the fibers.

Crop management and fiber extraction generate various sources of waste, ranging from leaves and thinning of the pseudostems to waste from the use of the “deco” machines. A residue like bagasse is generated, composed of pieces of fiber and plant tissue residues. There are also sheets left over from the separation of the layers of the pseudostem. Semi-processed fiber residues are also generated. The use of the “Spindle” machine generates similar waste; however, the largest volume of waste is generated from tuxing, which refers to a specific process of defibering the plant to separate the fibers from the xylem. During tuxing, a series of mechanical operations are performed to extract the long and resistant fibers that make up the abaca, which are then processed with the machine. According to [6] in an analysis of the potential of the solid waste remaining from Abaca processing as a substrate to produce oyster mushroom (*Pleurotus* spp), within the most relevant data provided during interviews and tours, it was found that the largest amount of waste obtained from processing of Abaca, are generated from the pseudostem, where approximately 94% is waste. For their part [7] in a study in Ecuador, report that of the total harvested Abaca material, 96.41% is wasted in its process and only 3.59% is what is sold as fiber to the international market.

1.1 Research Problem and Its Importance

The fiber extraction process generates a considerable volume of waste that has not been quantified in Costa Rica, and its potential economic value is not known. It is estimated that for every kilo of dry fiber, between 3 and 5 kilos of dry matter waste (leaves, fibers and bagasse) are generated and the rest is water. Furthermore, taking into consideration that sustainable management of Abaca can bring social, economic, and environmental benefits, it would be contributing to reducing social inequality, creating new sustainable productive options, and generating positive impacts of climate action. Efficient management of natural resources contributes to the national bioeconomy strategy. Specifically, the Sustainable Development Goal and the Impact on SDG 12: Responsible production and consumption, which seeks alternatives for responsible consumption and recovery of waste.

2 Methods

The study was carried out on a productive and representative farm of the Caribbean region of Costa Rica, specifically located at the La Chávez site in Horquetas de Sarapiquí, Heredia, Costa Rica (10°23'01.6 "N, 83°56'36.1"W, 68 masl). The site has a very humid tropical forest climate (bmh-T); with an average annual precipitation of 4062 mm and an average annual temperature of 25.9 °C [8]. The soil is classified within the order Ultisol and suborder Humults, [9], with a pH less than 5.5, an acidity saturation of 40% and a very slight slope (< 5%).

2.1 Acquisition Waste Biomass Data

Destructive sampling was used from a sample of 40 pseudostems. Each pseudostem was cut at a height of 10 cm from the ground, and the leaves and pseudostem were obtained separately to obtain the weight in kilograms, both on a wet basis and on a dry basis. The pseudostem was sectioned into "layers" that were classified into external layers (second quality) and internal layers (first quality), which were decorticated with a "deco" machine until the fibers and waste were obtained. The fibers were dried in the sun for 3 h until reaching a humidity of around 12%. From each plant, 3 subsamples of tissues were obtained (leaves, pseudostem, fibers, residues) and the wet weight and dry weight were obtained in a laboratory oven (temperature set at 80 °C for 72 h).

2.2 Characterization of the Chemical Properties of Abaca Fiber in Costa Rica

From a collection of 5 different varieties (genotypes) of Abaca in a place close to the study area, a characterization of the chemical properties of the fibers was carried out. Samples of the fibers and waste were taken randomly to carry out laboratory analysis and tests for the use of fibers as a composite material. The material was processed in the laboratory, ground, and dried in the oven. The chemical properties were evaluated: lignin and holocellulose content according to the TAPPI T222 om-02 standard (2002); as well as, extractives in cold and hot water according to ASTM D1110–21 (2021), extractives in 1% NaOH according to ASTM D1109–21 (2021), extractables with dichloromethane according to ASTM D1108–21 (2021), extractives with ethanol-toluene according to ASTM D1107–21 (2021), ash content according to ASTM D1102–84 (2021), volatile content according to ASTM D1762–84 (2021), fixed carbon according to ASTM D3172-13e1 (2021) and the caloric value according to ASTM D5865/D5865M-19 (2019). Likewise, the content of carbon (C), hydrogen (H), nitrogen (N) and sulfur (S) was estimated with an Elementar analyzer model Vario Micro Cube (Elementar, Langenselbold, Germany).

2.3 Use of Residual Fiber as Composite Material

Boards were made from combinations of wood sawdust and Abaca waste fiber. The boards consisted of a single layer with dimensions of 350 x 350 x 12 mm and a target standard density of 0.65 g cm⁻³. The adhesive available in the country and provided

by one of the industries dedicated to the manufacture of boards was used; which corresponds to the adhesive Melamine Urea Formaldehyde (MUF) with its respective catalyst (AkzoNobel 1247/2526, AkzoNobel Wood Coatings, USA), with an adhesive load of 12% based on the dry weight of the particles in a 5:1 ratio (adhesive: catalyst) according to the manufacturer's instructions. The viscosity of said adhesive was characterized by having an average value of 17,500 MPa and a pH of 9.5 to 10.7 (all values at 25 ± 2 °C). The combinations used as treatments were the following: T1 (40M:60A), T2 (60M:40A), T3 (50M:50A), T4 (100M:0A) and T5 (0M:100A), where M is *Gmelina arborea* and A is *Musa textilis*.

2.4 Statistical Analysis of the Data

For the analyzes based on ANOVA, a completely randomized design was used, for which the assumptions of normality of the residuals and the homogeneity of the variances were verified with the Shapiro-Wilks and Levene tests, respectively. The ANOVA applied considered a significance level of 0.05, and determined if there were significant differences between treatments; if necessary, the comparison of means test according to Tukey was applied to identify treatment groups with different behavior. In situations in which the assumptions of the ANOVA were not met, the non-parametric Kruskal Wallis test was executed together with a comparison of medians if significant differences were found. All analysis was run in Infostat software. 2020e [10].

3 Results

3.1 Estimates of Biomass, Fiber and Residues

Table 1 summarizes the results obtained from the study of biomass per plant component. The wet weight of plant pseudostems ranged from 7.8 kg to 34.2 kg, while leaf tissues ranged from 0.8 kg to 4 kg. These values, when summed up, gave total wet weight values ranging from 9 kg to 37.3 kg, with a moisture content ranged from 78.50% to 86%. Likewise, pseudostem dry weight ranged from 0.94 kg to 4.10 kg, while leaf dry weight ranged from 0.21 kg to 1.04 kg. Thus, the total aboveground dry weight ranged from 1.25 kg to 4.96 kg. From a pseudostem residue perspective, approximately 75% of the dry biomass is residue. To this must be added the dry biomass of the leaves, which equals 1.87 kg. If a plantation has approximately 4000 crop stems per hectare, the residual biomass per hectare equals 1.45 tons. Under the site conditions of this study, a harvest of class 1 and 2 fiber is equivalent to 2.24 tons of anhydrous fiber and 2.50 tons of fiber at 12% moisture content

3.2 Characterization of the Chemical Properties of Abaca Fiber in Costa Rica

The chemical characterization (Table 2) showed the following conditions: i. For holo-cellulose, only genotype MT03 showed a significantly different value (87.91%) from the other genotypes, which showed no statistical difference (average 90.67%). ii. Lignin showed variation according to genotype; MT07 and MT11 showed high values (average

Table 1. Summary of the descriptive statistics of the wet and dry biomass of the different components of the Abaca plants (n = 40)

VARIABLES	MEAN	SD	CV	MIN	MAX
Height (cm)	367,53	64,78	17,63	250	504
Diameter (cm)	11,75	1,79	15,26	8,40	16
Stem wet weight (kg)	19,33	6,73	34,81	7,80	34,20
Leaf wet weight (kg)	1,87	0,84	45,27	0,80	4
Total wet weight (kg)	21,19	7,34	34,63	9	37,30
Stem dry weight (kg)	2,32	0,81	34,76	0,94	4,10
Leaf dry weight (kg)	0,48	0,22	45,29	0,21	1,04
Total dry weight (kg)	2,80	0,97	34,71	1,25	4,96
Fiber wet weight (kg) 1	2,16	0,87	40,46	0,56	3,99
Fiber dry weight (kg) 1	0,42	0,19	45,75	0,01	1,05
Fiber wet weight (kg) 2	0,76	0,36	45,12	0,14	1,55
Fiber dry weight (kg) 2	0,14	0,07	50,44	0,01	0,36

Note: SD is the standard deviation of the mean, CV is the coefficient of variation, MIN is the minimum value, MAX is the maximum value. 1 and 2 refers to the quality of the fiber. In Costa Rica, two fiber qualities are currently used, and they differ in the purchase price

14.81%), in contrast to MT01, MT03 and CF01, which were lower at 11.95%. Iii. MT07 and MT11 showed the lowest values in cold water, ethanol-toluene, and dichloromethane extractives; in the case of hot water extractives, only MT07 showed significant differences. iv. Extractives with sodium hydroxide showed no differences between genotypes; the average value was 1.31%. Elemental analysis showed that MT07 and MT11 indicated statistical differences in the composition of C, H, N and S; in contrast, the remaining three genotypes showed no significant differences among themselves.

Table 2. Fiber chemical properties of five genotypes of *Musa textilis*.

VARIABLE		VARIETY				
		MT01	MT03	MT07	MT11	CF01
Holocellulose (%)		89,62 ^A (0,95)	87,91 ^B (0,46)	89,38 ^A (0,98)	93,06 ^A (0,37)	90,65 ^A (0,56)
Lignin (%)		14,43 ^A (0,28)	15,46 ^A (0,23)	13,49 ^B (0,39)	12,13 ^B (0,26)	12,66 ^B (0,10)
	Hot water (%)	11,01 ^A (0,18)	10,17 ^A (0,41)	7,75 ^B (0,24)	10,88 ^A (0,15)	3,90 ^C (0,20)

(continued)

Table 2. (continued)

VARIABLE				VARIETY		
		MT01	MT03	MT07	MT11	CF01
	Cold water (%)	11,27 ^A (0,24)	10,35 ^A (0,22)	6,76 ^B (0,20)	7,33 ^B (0,31)	3,67 ^C (0,16)
Extractives	Ethanol toluene (%)	11,07 ^A (0,11)	10,43 ^A (0,23)	5,93 ^B (0,15)	7,19 ^B (0,16)	2,14 ^C (0,13)
	NaOH 1%	1,33 ^A (0,10)	1,33 ^A (0,09)	1,30 ^A (0,09)	1,32 ^A (0,10)	1,31 ^A (0,09)
	Dichloromethane	9,23 ^A (0,11)	9,44 ^A (0,09)	4,56 ^B (0,10)	5,01 ^B (0,09)	4,89 ^B (0,10)
Nitrogen (%)		0,14 ^A (0,02)	0,11 ^B (0,01)	0,09 ^B (0,02)	0,10 ^B (0,02)	0,10 ^B (0,02)
Carbon (%)		62,21 ^A (1,15)	66,44 ^B (0,74)	66,11 ^B (0,50)	66,49 ^B (0,45)	66,57 ^B (0,41)
Hidrogen (%)		6,44 ^A (0,02)	6,72 ^A (0,10)	6,61 ^A (0,12)	6,78 ^A (0,43)	6,90 ^A (0,29)
Sulfur (%)		1,55 ^A (0,09)	1,50 ^A (0,07)	1,32 ^B (0,03)	1,33 ^B (0,02)	0,33 ^B (0,03)

Note: Values in parentheses correspond to the standard deviation; different letters indicate significant differences at 0.05

3.3 Use of Fiber as a Composite Material with Wood Sawdust

Table 3 shows the mean values corresponding to the property's density, moisture content, and HEΔ. The target standard density of the boards was set at 0.65 g cm⁻³, which classifies them as medium density boards according to the ASTM standard. According to the analysis carried out, the treatment that presented the density closest to the standard value was the control treatment (T4) with an average value of 0.64 g cm⁻³, followed by treatment T2. With what was observed, it is affirmed that as the proportion of *M. textilis* in the mixture increases, the density value decreases, although it is notorious that there were no significant differences between T1, T2 and T3 with the control treatment. These treatments obtained values below the standard target value, which may be due to several reasons; on the one hand, the high probability of losing particles in the demolding phase of the boards, and on the other hand, the variation in thickness caused by the change in temperature and humidity that occurs at the time of transferring the boards from the hot press to the conditioning chamber [11, 12].

Table 4 shows the mechanical properties evaluated. Regarding static bending, the modulus of rupture (MOR) showed that treatment T2 did not show significant differences with the control but did show significant differences with the treatments with more than 60% fiber (T1 and T5). Likewise, the modulus of elasticity (MOE) or flexural modulus did not show significant differences between the control treatment (T4) and the other treatments; the fact that treatment T2 (40% fiber) showed the highest value of MOE

Table 3. Physical properties of particle boards composed from different proportions of *Musa textilis* and *Gmelina arborea*

	TREATMENT	Density (g cm ⁻³)	Moisture content (%)	HEΔ (mm)
Average	T1	0,60 AB	15,73 D	0,57 C
	T2	0,61 AB	12,89 A	0,17 AB
	T3	0,58 AB	14,79 C	0,25 B
	T4	0,64 B	12,06 A	0,12 A
	T5	0,57 A	16,08 D	0,52 C

Note: Different letters indicate significant differences at 0.05. HEΔ% corresponds to the swelling in thickness due to a change in moisture content from 12 to 18%.

(17,04 GPa) is noteworthy. In relation to this, the amount of extractives present in the fiber used in this study [13] could contribute to the variations present in the results within the same treatment; since as stated by [14] to obtain the expected mechanical properties in the boards it is necessary that there is chemical compatibility between the components that conform it and additionally [15] also mention the interaction in the curing of the adhesive. [16] demonstrated the effects of chemical compatibility in boards with palm bagasse. Also, the orientation and distribution of fibers within the board has been shown to influence flexural strength, with incorrect orientation causing a decrease in strength [17].

Table 4. Mechanical properties of composite particleboards with different proportions of *Musa textilis* and *Gmelina arborea* species.

Properties		T1	T2	T3	T4	T5
Static bending (SB)	MOE (GPa)*	10,03A (5,43)	17,04B (7,26)	13,73AB (2,32)	13,76AB (8,02)	8,84A (8,60)
	MOR (MPa)*	22,91AB (3,05)	28,02C (8,45)	26,04ABC (8,39)	28,06BC (5,04)	18,92A (9,20)
Parallel tension (T)	MOE (MPa)	18,82A (18,10)	58,38B (24,18)	36,57AB (16,09)	104,97C (27,32)	21,54A (14,54)
	Strain maximum (MPa)	0,84A (0,50)	0,98A (0,34)	0,88A (0,31)	2,31B (0,58)	0,78A (0,42)
Tension perpendicular (IB)	Strain maximum (MPa)	0,17A (0,07)	0,25AB (0,06)	0,23AB (0,09)	0,62C (0,06)	0,29B (0,05)
Hardness (H)	Load maximum (kg)	149,13A (32,57)	225,33BC (39,44)	191,78B (20,73)	235,16C (26,86)	141,57A (41,52)

Note: Values in parentheses represent the corresponding standard deviation. Different letters indicate significant differences at 0.05. Parameters marked with an (*) correspond to results analyzed with nonparametric tests (n = 10)

4 Discussion

It is demonstrated in this study that the largest proportion of the total dry biomass of Abaca plants during a fiber harvest corresponds to residues (approximately 40% of the dry biomass). About 20% of these residues contain fibers that are not part of the raw material that can be sold, and the rest are plant tissues and parts of the leaves that do not contain fibers. However, there is great potential for generating compost from this material. Residual fibers can be used locally in composite materials.

Based on the chemical properties of the fibers, the fiber of genotypes MT01 and MT03 was recommended for stationery, biodegradable materials, and fast degradation composites. These products are proposed due to the need for materials with high cellulose and hemicellulose content and low lignin content; as it facilitates the pulping and pulping homogenization process and enhances the creation of higher quality paper [18]. [1] mention that this is the key to have low strength fibers to develop single-use biodegradable biomaterials or short life cycles. Furthermore, [19] recommend using fibers with low mechanical strength and low lignin levels for environmentally friendly, moderate-use, low value-added materials, which is compatible with both genotypes.

With respect to the use of fiber as a composite material, the gradual reduction of *Musa textilis* fiber proportions promoted progressive increases in density, moisture content, MOR, MOE and IB values. Thus, proportions greater than 40% of *M. textilis* significantly decreased the overall quality of the boards. Despite this, in all treatments with proportions lower than 50% fiber, the MOR values exceeded the maximum reference points of the standard used. Therefore, the density (0.64 g cm^{-3}), MOR (28.06 MPa) and IB (0.62 MPa) properties of the boards corresponding to treatment T4 (control, 100% wood) met the minimum specifications established for particleboard categorized for use in dry conditions. However, T2 and T3 meet the minimum specifications required in these properties mentioned for low-density LD-2 grade boards.

5 Conclusions

Based on the results of the characterization of the fibers, it is demonstrated that there are differences and therefore, the differentiated use of genotypes must be considered for the specific use of fibers in the development of composite materials. It is important to initiate tests with mixtures with plastics to determine the specific uses of biomaterials. It is recommended to continue with new research on the application of different fibers in matrices with polymers and other natural fibers and evaluate the efficiency and quality of the products and the creation of a new market. Therefore, these results are a first step to change the paradigm of *M. textilis* plantations in the tropics.

The quality of the composite boards obtained in this study are susceptible to improvement. The future challenge is to continue experiments to enhance the general properties of the boards. To this end, it is recommended to carry out a broader study that involves other species of lignocellulosic and wood fibers, the use of lower proportions of fiber, the application of pretreatments to the fiber, the use of organic additives with different doses of adhesive and particle sizes.

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