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Physical-mechanical properties of *Musa acuminata* particles composites

Propiedades físico-mecánicas de compuestos de partículas de *Musa acuminata*

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Abstract

Introduction: Currently, the development of materials from renewable resources is growing worldwide; non-wood lignocellulosic fibers from different plant species or agro-industrial residues are an interesting source of raw material.
Objective: The objective of this work is the development and physical-mechanical characterization of a composite material based on *Musa acuminata* pseudostem particles and a thermosetting resin.
Method: The composite was prepared with particles of an average size of 450 µm, washed with a NaOH solution and oven-dried at 70 °C for 24 h. The moisture content was controlled. In manufacturing, the particles were glued with urea formaldehyde resin in a drum-type mixer and pressed in thermal plates at 160 °C and 107 psi. The composites were analyzed mechanically, obtaining data on modulus of rupture, elastic modulus and tensile strength. Penetration hardness and water absorption resistance tests were also performed. Moreover, thermographic tests were performed on the surface of the material. The results were compared with those obtained in commercial composites.
Results: It was observed that the *Musa acuminata* composite presented greater resistance to moisture absorption, higher elastic modulus and was more resistant to tensile stresses. Additionally, the commercial composite showed lower penetration resistance. The *Musa acuminata* composite achieved higher thermal insulation in thermographic tests.
Conclusions: *Musa acuminata* is a species with a high agro-industrial flow and a considerable producer of residues, which has interesting viable physical-mechanical characteristics to produce particle agglomerates that meet engineering standards.

Key Words

Musa acuminate; Particles composites; Mechanical properties; Water absorption; Thermography.

Resumen

Introducción: Actualmente el desarrollo de materiales a partir de recursos renovables crece a nivel mundial; las fibras lignocelulósicas no maderables provenientes de diferentes especies vegetales o residuos agroindustriales se posicionan como una interesante fuente de materia prima.

Objetivo: El objetivo de este trabajo es el desarrollo y caracterización física y mecánica de un material compuesto en base a partículas del pseudotallo de *Musa acuminata* y una resina termoestable.
Metodología: El compuesto fue elaborado con partículas de tamaño promedio de 450 µm, lavadas con una solución de NaOH y secadas en horno a 70 °C durante 24 h, fue controlado el contenido de humedad. En la fabricación, las partículas fueron encoladas con resina urea formaldehido en mezcladora tipo tambor y prensadas en planchas térmicas a 160 °C y 107 psi. Los compuestos fueron analizados mecánicamente, obteniendo datos de módulo de ruptura, modulo elástico y resistencia a la tracción. También, se realizaron pruebas de dureza a la penetración y resistencia a la absorción de agua. Adicionalmente, sobre la superficie del material se realizaron ensayos termográficos. Los resultados fueron comparados con los obtenidos en compuestos comerciales.
Resultados: Se observó que el compuesto de *Musa acuminata* presentó mayor resistencia a la absorción de humedad, mayor modulo elástico y fue más resistente a esfuerzos de tracción. Además, el compuesto comercial presentó menor resistencia a la penetración. El compuesto *Musa acuminata* logro mayor aislación térmica en pruebas termográficas.
Conclusiones: La *Musa acuminata* es una especie con alto flujo agroindustrial y un considerable productor de residuos, la cual posee interesantes características físico-mecánicas viables para la producción de aglomerados de partículas que cumplan con los estándares ingenieriles.

Palabras clave

Musa acuminata; Compuestos de partículas; Propiedades mecánicas; Absorción de agua; Termografía.

I. INTRODUCTION

Currently there is an increasing global interest in the manufacture of materials from renewable resources [1]. Therefore, vegetable and non-timber origin fibers derived from different lignocellulosic species and from agro-industrial waste have become relevant as a source of raw material [1]-[2]-[3]. Vegetable fibers offer interesting productive advantages due to their ease of extraction (because they are easily obtained), innocuousness and biodegradability characteristics [4]. Accordingly, fibers of lignocellulosic origin could be included as a contributing material in the manufacture of composite materials [2].

In theory, composite materials are those produced based on the combination of two or more materials that, according to their characteristics and compatibility strengthen their physical and mechanical properties [5]. In the manufacture of this type of materials, the most relevant factors are the size or granulometry of the fiber and the type and quality of the binder that is generally derived from a polymer [5]-[6]. Likewise, depending on the application of the composite material, the polymeric binder can be of thermoplastic or thermosetting type [7].

Various plant species have been studied in the development of composite materials. These materials are called biocomposites according to the origin of the raw material used in their manufacture. Currently, research has been carried out with fibers derived from species such as jute, kenaf, sisal, rice husk, wax palm, sugar cane, coconut, pineapple, cotton, tamarind [8]-[9]-[10]. The most relevant results of these investigations have shown that the composite materials obtained have competitive physical and mechanical properties with the properties shown by commercial composites.

In Colombia, the agroindustry is one of the main economic activities, having the *Musa acuminata* (banana) as one of the products with the highest density in plantations [11]. In the region of Quindío banana cultivation is approximately 7.5 t ha^{-1} [12], among the residues of the harvesting process the most visible is the pseudostem; these residues are left in the plantation, promoting accumulation [13]. Therefore, this lignosellulosic raw material could have potential use in the production of biocomposite materials.

The pseudostem of the banana plant is also known in the country under the names of guasca, calceta or yagua. This pseudostem has a high moisture content and is formed by a group of leaf sheaths that seem to form a roll, as shown in figure 1. As the moisture content in the leaf sheaths decreases, they acquire resistance. Consequently, they have been used in the artisan fabrication of threads, ropes and load-bearing elements [14].

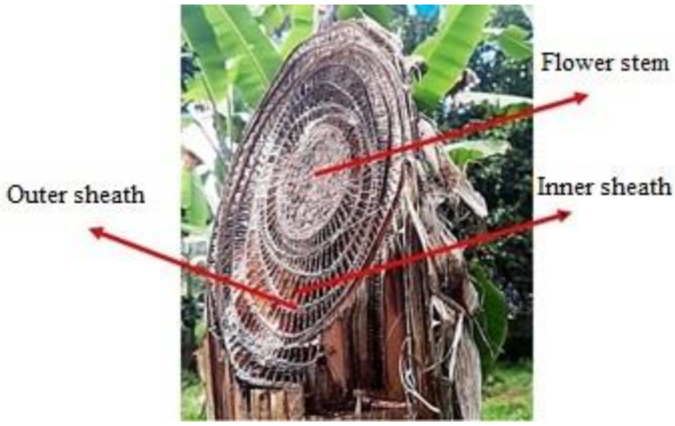

Figure 1. Image of the wall structure of the pseudostem of *Musa acuminta*. Source: authors.

This research proposes to manufacture biocomposite materials from fibers or particles of *Musa acuminata* with average sizes of 450 µm, US standard mesh No. 40 according to ASTM D1554-10 and urea formaldehyde [15]. Likewise, evaluate its physical and mechanical properties in accordance with the ASTM D1037 standard and compare them with the results obtained in commercial composites. The surface of *the Musa acuminata* pseudostem was chemically treated and then taken to the grinding process. The particles produced in the grinding process were mixed with a thermosetting resin and then, by means of the thermal plates' method, boards were elaborated. The physical and mechanical properties studied were based on thermography tests, moisture absorption, tensile and flexural tests, and penetration hardness.

The traditionally known composites are manufactured based on radiata pine particles and are commercially called particle boards, agglomerates or particle boards. This type of board uses in its manufacture short fibers or wood flour with an average size of 450 µm which are glued with a thermosetting polymeric synthetic resin derived from formaldehyde [15]. Particle boards are used in different engineering applications such as floors and walls, ceilings, office dividers, office and home furniture and are currently used in applications in the automotive and aerospace industries [16], [17], [18].

Papadopoulos' research [19], shows the use of 1mm and 3mm long fibers from *Musa acuminata* and a phenolic resin in the manufacture of chipboard. The boards manufactured with fibers of 1mm in length, showed that the values obtained in mechanical properties of flexural and tensile were equivalent to what is required by the international standards of particle board.

Nadharia *et al*. [20], manufactured particle board from *Musa acuminata* residues and were compressed without binder. In the manufacturing process, they used three different temperatures (111 °C, 121 °C and 131 °C) for 15 minutes until the fibers were agglomerated. The results in mechanical tests indicated that the manufactured boards met the results required by the Japanese Industrial Standards (JIS).

Wang *et al*. [21], used banana residue fibers and a thermosetting resin in the manufacture of particle board, analyzed the mechanical properties and verified that the results were equivalent to the Chinese standards for particle board. The results showed that the boards had modulus of rupture and elastic modulus that met the requirements of Chinese national standards.

Jimmim *et al.* [22], elaborated composites based on fibers from the pseudostem of the banana plant agglomerated with a phenolic resin in percentages of 8%, 9%, 10% and 12%. The most relevant results showed that the boards manufactured with the addition of 9% of resin, had a behavior equivalent to the commercial boards in tests of resistance to crushing and resistance to the removal of screws.

Aseer *et al.* [23], studied the effect of reinforcing a polymer with the addition of particles of banana plant residues. The addition of particles was in percentages of 20%, 30%, 40% and 50% with respect to the weight of the polymer. The most relevant result was that the composites manufactured with the addition of 40% of particles increase the mechanical properties of flexural, tensile and impact resistance of the polymer.

Ribeiro *et al.* [24], elaborated chipboards based on particles from the pseudostem of the banana tree and phenolic resin. This research showed that the elastic modulus, flexural strength and compressive strength of the boards based on banana pseudostem particles were lower than those established in commercial standards.

III. MATERIALS AND METHODS

A. *Materials*

In this research, particulate material (PM) from the pseudostem of *Musa acuminata* was used, it was collected in plantations located in the central Andes region of Colombia, specifically in the region of Quindío. The resin used to agglomerate the particulate material is urea formaldehyde UREQUIM 65 from Aserquim, Colombia, this type of resin is usually used in the manufacture of wood composites. The particle solid content of the resin is 63%, gelation time from 40 s to 60 s and PH from 9.0 to 25 °C. As a catalyst in the manufacturing mixtures of the composite material, 1050 from Aserquim-Colombia was used. The composite materials were elaborated in the Natural Fibers and Agglomerates laboratory of the Interdisciplinary Institute of Sciences of the University of Quindío, Colombia

B. Methods

The composite materials were manufactured in three stages:

Stage 1: the pseudostem was cut into 50 mm x 50 mm sheets and immersed in a NaOH solution according to the procedure of Mejía *et al.* [25]. The pseudostem sections in a section-solution weight ratio of 1: 5 are treated in aqueous NaOH solution at 5% (p / v) for 1 hour at room temperature. Then, material is washed with distilled water and dried in laboratory oven at 70 °C for 24 hours. The treatment described above is used to remove a resin from the *Musa acuminata* that hinders the coupling with urea-formaldehyde.

Stage 2: the dry cuts are subjected to grinding in a knife grinding machine to reduce the material to average size of 450 µm (US standard mesh No. 40). Guadua particles images were obtained using the NIKON SMZ800 stereoscope equipment (Figure 2). The ground material was screened on a W.S Tyler RO-TAP rotary screen using 450 µm screen. Moisture measurements were made on the ground material using the Mettler Toledo HB 43 moisture balance. It was emphasized that the humidity percentage was between 3% and 13%, according to ASTM D6007 and UNE-EN 120 standards [26]-[27].

Figure 2. Stereoscopic Image (30X) of *Musa acuminata* US standard mesh No. 40 pseudostem particles. Source: authors.

Stage 3 or manufacturing stage: by mechanical means in a drum-type mixer, the ground material and the resin were mixed for 7 minutes. The resin content was 13% mixed with 5% catalyst regarding the dry weight of the ground material. Then, the mixture was placed in stainless steel dishes made for this purpose and molded to a Dicson-Colombia thermal plate molding equipment. The temperature used in the molding process was 160 °C and a pressure of 107 psi for 10 min.

Physical-mechanical characterization: tests were carried out according to ASTM D1037-12 [28]. In the water absorption and thickness swelling test, immersion in water for 2 h and 24 h was used. Likewise, the composite material was subjected to mechanical tests of traction, bending and penetration hardness in Ibertest UMIB-600 series universal servo-hydraulic machine.

The physical-mechanical tests were carried out in triplicate and the average value obtained was analyzed.

Thermography characterization: the thermographic analyzes were made according to the ISO 10878 (2013) standard, the thermal insulation capacity of the composites was analyzed in a stove assembly for 10 min [29]. In this test, the composites were placed on the burner controlling the temperature. The temperature of the environment and the percentage of humidity in the laboratory were also controlled. The test was carried out on three different days with equivalent schedules. In this test, the stove is heated to the highest average temperature in the Andes-Colombia region. Subsequently, the compound is placed on the burner and after 10 minutes the data of the temperature reached on the back face of the burner are taken using a Fluke IR thermometer.

The previously described tests, and for comparison purposes, were carried out on commercial composites from Tablemac. These commercial composites are similar in characteristics to the composites manufactured for this research. Tablemac uses radiata pine flour (US standard mesh No. 40) glued with urea formaldehyde.

This analysis was done in triplicate and the average value obtained was analyzed.

Microscopic characterization: the adhesion compatibility between the fibers and polymeric resin was analyzed by means of a JEOL 5910 LV electron microscope (SEM), a material fracture zone was observed and pore diameters were measured.

IV. RESULTS

The surface area of the commercial and *Musa acuminata* pseudostem-based composites are shown in Figure 3. It is observed that there is a difference in porosities between the surfaces of both composites which has a potential impact on the physical-mechanical properties of the material.

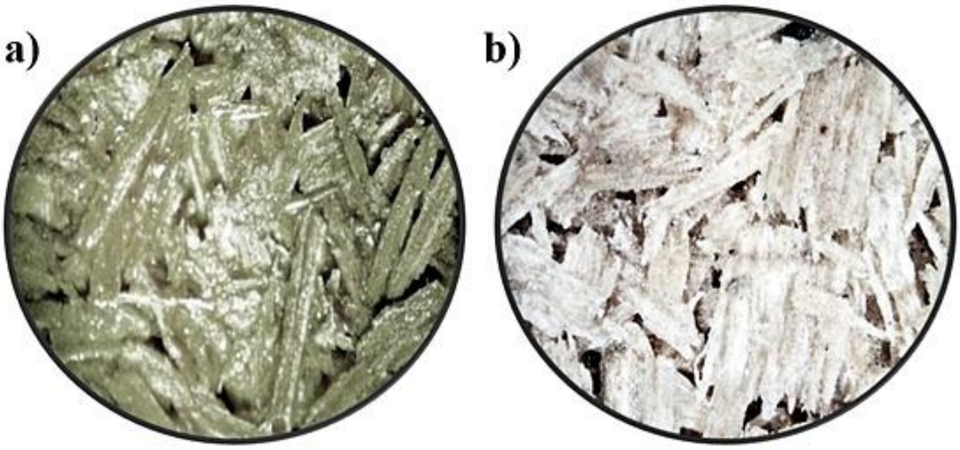

Figure 3. Stereoscopic Image (40X) of particle composites a) *Musa acuminata*, b) commercial composites. Source: authors.

Musa acuminata composites were obtained with a density of 0.689 g/cm^3. According to this result and the ASTM standard for particle board, it is classified as medium density.

A. Mechanical analysis of *Musa acuminata* composites

Table 1 shows the results obtained in flexural and tensile tests performed on both *Musa acuminata* composites and commercial composites.

Table 1. Mechanical test results on *Musa acuminata* and commercial composites.

Sample	Flexural module (MOR) kg/cm^2	Elastic module (MOE) kg/cm^2	Tensile strength kg/cm^2
Musa acuminata composite	17,96 ± 0,3	30,59 ± 0,5	0,53 ± 0,1
Commercial	18,72 ± 0,3	20,39 ± 0,3	0,44 ± 0,1

Source: authors

The results show the existence of a difference in modulus of rupture (MOR) between the commercial composite (18.72 kg/cm^2) versus *Musa acuminata* composite (17.96 kg/cm^2). However, this difference in flexural strength is around 5% which could mean it is inconsequential. In contrast, it could be an evidence that the commercial composite presented greater resistance to flexural tensile stresses than the *Musa acuminata* composite. Regarding tensile strength tests, the *Musa acuminata* composite obtained an elastic modulus of 30.59 kg/cm^2, which compared to that presented by the commercial composite (20.39 kg/cm^2) shows a difference in tensile strength of 50%. The above indicates that the *Musa acuminata* composite presents greater rigidity in the elastic zone. Furthermore, the *Musa acuminata* composite (0.53 kg/cm^2) was 20% more resistant to tensile stress than the commercial compound (0.44 kg/cm^2).

The mechanical behavior of the material facing flexural strength and tensile strength may be explained through the adhesion quality result of the treated fiber of *Musa acuminata* with the resin. In addition, it should be noted that the maximum tensile stress of the *Musa acuminata* fiber is around 550 MPa [30], less than the wood fibers, which is around

648 MPa [31]. Likewise, the composite mechanical behavior elaborated for this investigation is in agreement with the one exposed in investigations by Boopalan *et al*. and Alavudeen *et al*., who showed improvements in physico-mechanical properties of banana pseudostem composites compared to composites made from other plant fibers [32]–[33].

B. Hardness analysis by penetration resistance test

The hardness tests (table 2) showed the resistance of the material to penetration efforts revealing the footprint and its depth caused by a punch. It can be observed that the footprint diameter generated on the surface of the *Musa acuminata* composite is 55% smaller than that presented by the commercial composite, and the depth of the footprint in the commercial composite is twice as deep as that obtained in *Musa acuminata* composite. This indicates that the composite based on *Musa acuminata* particles has greater resistance to penetration compared to the commercial composite. This may be explained by the existence of lower porosity in *Musa acuminata* composite (Figure 3) and the quality of adhesion obtained in the washing treatment carried out on the particles, causing better particle-resin coupling during manufacturing.

Table 2. Result of penetration hardness tests.

Sample	Footprint Diameter (mm)	Footprint Depth (mm)
Musa acuminata composite	2,79 ± 0,3	1,00 ± 0,1
Commercial	4,34 ± 0,3	2,16 ± 0,3

Source: authors

C. Analysis of water absorption and thickness increase due to swelling

The percentages of water absorption and the increase in thickness due to the swelling are shown in table 3. The percentage of water absorption after 24 h in *Musa acuminata* composites (30%) was lower than that obtained in commercial composites (86%). Given these results, *Musa acuminata* composite has impermeability characteristics by allowing less water flow and subsequent absorption of the material. This could be caused by the coupling achieved between the Musa acuminata particles and the resin and also by the porosity resulting from the manufacturing process.

Table 3. Percentage of water absorption and thickness increase.

Sample	Weight (g)			Increase (%)		Thickness (cm)		Swelling
	Initial	2 h	24 h	2 h	24 h	Initial	Final	(cm)
Musa acuminata composite	4,0 ±0,1	5,0 ±0,1	5,2 ±0,1	25,0	30,0	0,50 ±0,1	0,52 ±0,1	0,02
Commercial	4,4 ±0,1	7,3 ±0,2	8,2 ±0,2	65,0	86,0	0,50 ±0,2	0,61 ±0,2	0,11

Source: authors

D. Thermographic analysis

Table 4. Thermography test results

Sample	Burner *T* (°C)	Plate *T* (°C)
Musa acuminata composite	39,8 ± 0,4	22,7 ± 0,3
Commercial	39,8 ± 0,4	24,11 ± 0,4

Source: authors

In the thermographic analysis (table 4), it can be observed that the opposite side of the surface exposed to the burner of *Musa acuminata* composite was lower than the temperature shown by the commercial composite. This represents the heat transfer allowed by the compound due to the temperature of the burner. The *Musa acuminata* composite (22.7 °C) was 6% of greater thermal insulator than the commercial composite (24.11 °C). That is to say, the heat transfer due to the burner temperature was lower in the *Musa acuminata* composite. This test may be indicative that the *Musa acuminata* composite presented lower porosity.

E. Analysis by electron microscopy

Figure 4 shows the porosity existing in the fracture zone of the *Musa acuminata* composite and the commercial composite. The image shows that the pores density in the *Musa acuminata* composite is lower than in the commercial one, in addition, some pores of the commercial composite were larger. This may be explained by the quality of adhesion achieved between the *Musa acuminata* particles and the resin, giving the material better mechanical characteristics.

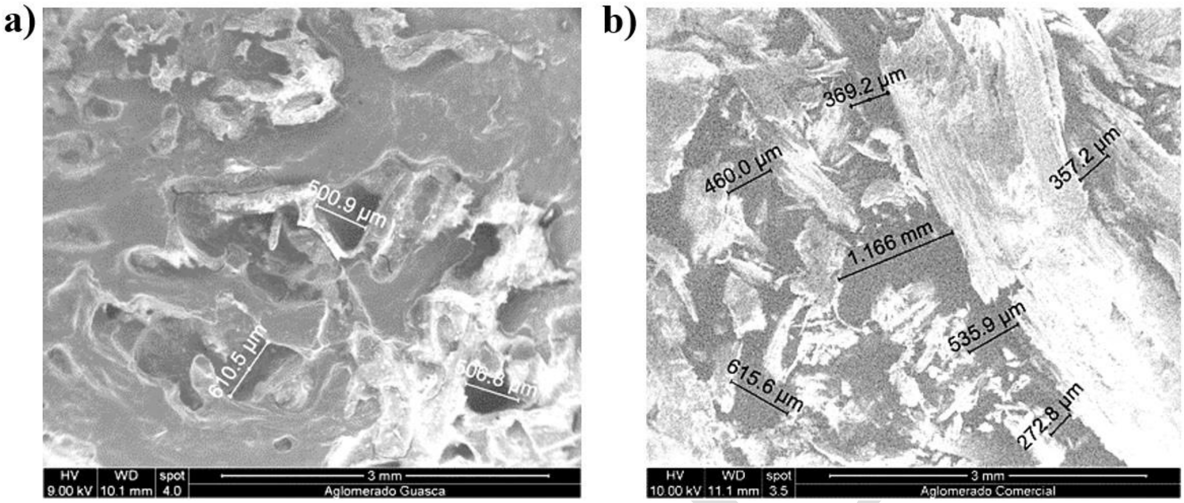

Figure 4. SEM Image, a) *Musa acuminata* agglomerate and b) commercial agglomerate. Source: authors

V. CONCLUSIONS

The composites manufactured in this research are a potentially commercially viable and sustainable alternative to commercial composites since the particles from *Musa acuminata* do not represent high economic and environmental costs.

The analysis of physical and mechanical properties of composites based on *Musa acuminata* pseudostem particles has significant differences compared to the physical and mechanical properties of commercial composites. The Musa acuminata composite was found to have a 20% greater resistance to tensile stress than the commercial composite and a 50% greater modulus of elasticity giving it characteristics of greater rigidity. The modulus of rupture in the commercial composite was slightly higher than that shown by the *Musa acuminta* composite. However, the commercial composite allowed greater penetration of the punch into the surface of the material, producing an footprint 55% larger in diameter and greater depth than that obtained in the *Musa acuminata* composite. Furthermore, the *Musa acuminata* composite was shown to have higher resistance to water absorption and thickness swelling in moisture absorption tests. The behavior in physical-mechanical properties of the material is also associated with the quality of the particle-resin adherence obtained due to the initial treatment to which it was subjected.

The thermographic analysis showed that the *Musa acuminata* composite allowed less heat transfer, which could be an indication for future research of the material as a thermal insulator. The obtained results in the physical-mechanical characterization of the material showed the economic and sustainable potential that the integration of the *Musa acuminata* may have in the industrial production of particle agglomerate type composites.

The composites based on *Musa acuminata* particles, according to the results obtained for this research, presented physical-mechanical properties that were competitive with those exhibited by commercial composites. These composites can be taken into account in the field of civil engineering as furniture elements, partitions and structures subjected to light loads. Likewise, to deepen the analysis of this composite material, the addition of ignition retardants in the manufacturing process as well as acoustic tests to determine its absorption, reflection, impedance, admittance, and loss of transmission could be considered.

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