Data and Metadata. 2025; 4:823
doi: 10.56294/dm2025823

ORIGINAL

Development and Mechanical Evaluation of a Biocomposite Based on Abaca Fiber and Acrylic Resin

Desarrollo y Evaluación Mecánica de un biocompuesto a base de Fibra de Abacá y Resina Acrílica

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Cite as: Zambrano A, Mora Muñoz E, Naranjo Toro M. Development and Mechanical Evaluation of a Biocomposite Based on Abaca Fiber and Acrylic Resin. Data and Metadata. 2025; 4:823. https://doi.org/10.56294/dm2025823

Submitted: 09-07-2025 **Revised:** 06-09-2025 **Accepted:** 03-12-2025 **Published:** 04-12-2025

Editor: Dr. Adrián Alejandro Vitón Castillo

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ABSTRACT

The biocomposite made from a nonwoven abaca fiber reinforced with acrylic resin is proposed as an ecological alternative to synthetic leather. The objective of this research was to develop and characterize the material, evaluating the effect of two variables: the length of the abaca fiber (2 cm and 5 cm) and the concentration of acrylic resin (70 % and 80 %). The manufacturing process consisted of immersing the nonwoven fabric in the resin solution, followed by drying at 120°C. A completely randomized 2^2 factorial design was implemented, with a total of 20 experimental runs. The response variables were tensile strength and elongation, evaluated using a Titan 5 James Heal dynamometer under ISO 1421. Statistical analysis was performed using Statgraphics Centurion software and revealed that fiber length has a significant positive effect on tensile strength, while elongation is less relevant. The results obtained with 5 cm fibers and 70 % acrylic resin achieved a tensile strength of 118,3 N; in terms of elongation, the value obtained was 50,2 mm with 2 cm fibers and 70 % resin. Taken together, these findings position vegetable leather as a functional and sustainable material with high potential for application in the textile and composite materials industries.

Keywords: Abaca; Biocomposite; Nonwoven; Elongation; Tensile Strength.

RESUMEN

El biocompuesto elaborado a partir de un no tejido de fibra de abacá reforzado con resina acrílica, se propone como alternativa ecológica al cuero sintético. Esta investigación tuvo como objetivo desarrollar y caracterizar el material, evaluando el efecto de dos variables: la longitud de la fibra de abacá (2 cm y 5 cm) y la concentración de resina acrílica (70 % y 80 %). El proceso de elaboración consistió en la inmersión del no tejido en la solución de resina, seguido de un secado a 120°C. Se implementó un diseño factorial 2^2 completamente aleatorizado, con un total de 20 corridas experimentales. Las variables respuesta fueron la resistencia a la tracción y la elongación, evaluadas mediante un dinamómetro Titan 5 James Heal bajo la norma ISO 1421. El análisis estadístico se realiza con el software Statgraphics Centurion, y reveló que la longitud de fibra tiene un efecto positivo significativo sobre la resistencia a la tracción, mientras que la elongación es menos relevante. Los resultados obtenidos con las fibras de 5 cm y 70 % de resina acrílica, logrando una resistencia a la tracción de 118,3 N; en cuanto a la elongación, el valor obtenido fue de 50,2 mm con fibras de 2 cm y 70 % de resina. En conjunto, estos hallazgos posicionan al cuero vegetal como un material funcional y sustentable, con alto potencial de aplicación en la industria textil y de materiales compuestos.

Palabras clave: Abacá; Biocompuesto; no Tejido; Elongación; Resistencia a la Tracción.

INTRODUCTION

All consumer goods, including fashion, require intensive use of resources, and this sector faces unprecedented sustainability challenges: by 2030, its water consumption is projected to increase by 50 % to 118 billion m^3; its carbon footprint will reach 2,791 billion tons of CO_2 e; and the waste generated will exceed 148 million tons.[1]

Animal leather is derived from animal skin and has been widely valued for its properties such as strength, durability, and biocompatibility, with applications ranging from fashion to biomedicine.[2] Animal skin undergoes a series of treatments called tanning, resulting in a soft material. Production and processing generate solid, liquid, and gaseous waste that pose environmental problems. The effluents are considered to contain high levels of chromium (Cr), fatty acids, sulfur, and volatile organic compounds. In addition, the tanning industry is characterized by high water and energy consumption and faces sustainability challenges.[3] Animal leather, despite being biodegradable and rich in collagen, requires the use of Cr and glutaraldehyde for conventional tanning.[4] Cr(III) prevails in tanning due to its hydrothermal stability and excellent physical properties. Still, its use generates hazardous by-products such as chromate oxyanions and Cr(VI) salts, which pose a serious environmental risk.[5] Concerns about the toxicity of hexavalent Cr in leather products have led to the development of more sustainable and accessible analytical methods, such as smartphone-assisted colorimetry. These innovations highlight the urgency of replacing Cr tanning with metal-free alternatives.[6] The use of conventional tanning agents, such as Cr, can alter the original chemical properties of hides, even affecting scientific methods such as isotopic traceability.[7] Leather, when subjected to long-term exposure to humid and anoxic environments, loses tannins and lipids, degrading its collagen.[8]

Given the environmental impacts of Cr tanning, the leather industry is exploring sustainable alternatives, such as vegetable tannins, which have demonstrated good technical performance and lower toxicity,[9] and 1,3,5-triazine derivatives, which offer cleaner, more efficient processes.[10,11] Vegetable tannins used as ecological tanning agents tend to darken the leather and significantly increase the organic load of effluents.[12] Chestnut and quebracho tannins eliminate small, non-tannic molecules, resulting in fractions that dye the leather in lighter tones and reduce the organic load of effluents by 13,5 % and 19,1 %, respectively.[12] In addition, the bark of Syzygium cumini (L.), as a possible source of tannins for tanning, measures its total polyphenol content and the tannin/non-tannin ratio.[5] Furthermore, neem leaves are a renewable and effective tanning agent, capable of replacing Cr and conventional tannins, and promoting ecological and sustainable tanning.[13] In turn, Azadirachta leaves are a renewable tanning agent, producing green leather with excellent mechanical properties, good film adhesion, and antimicrobial activity, validating their replacement of Cr and imported tannins.[14]

The fashion industry is seeking sustainable alternatives to animal leather, developing materials such as biocomposites derived from agro-industrial and microbial waste,[15] which offer competitive mechanical properties and reduce reliance on non-renewable resources.[16] These studies reveal attributes such as durability, aesthetics, and alignment with ecological values that influence their acceptance.[17] To reduce the environmental impact of tanning, the scientific community has researched some familiar sources of bioleder, such as natural latex, pineapple, fungi, jellyfish, and bacterial cellulose,[15] trout skins, an abundant aquaculture by-product, as a source for high-performance ecological leather.[18] Similarly, researchers have presented an innovative leather-like material called BC-BioLeath (Bacterial Cellulose-Based BioLeather), demonstrating that bacterial cellulose, combined with agro-industrial waste and conventional tanning processes, can generate high-performance, competitively priced bioleather, offering a truly circular and sustainable solution for the fashion industry.[19,20] By transforming agri-food waste such as coffee grounds, sugarcane bagasse, banana peels, and pitahaya into bioleder using alginate-calcium hydrogels with glycerol and vegetable oil, followed by drying at 50°C, the sugarcane bagasse bioleder achieved the highest elongation (29 %) and a tensile strength of 176 N, and the biocomposites biodegraded completely in 21 days.[21] In turn, mycelium-derived materials have gained attention as biodegradable alternatives to synthetic leather, although their scalability and standardization still pose challenges.[22] Gel-based vegan leathers are made from natural and synthetic polymers, have limited mechanical strength, and require improvements through hybrid composites, nanotechnology, and sustainable processes for commercial viability.[3]

The conventional leather industry faces criticism for its environmental, social, and ethical impact. In response, studies have been conducted using materials such as fungal mycelium, which have emerged as sustainable alternatives, though they still pose technical challenges.[23] As a sustainable alternative to vegan leather, a multilayer fungal biocomposite was developed from fungal biomass cultivated with bread waste and tanned with vegetable tannins. Sheets treated with glycerol and binder were formed, achieving a strength of 20,5 MPa and 14,8 % elongation, with a performance close to that of natural leather.[24] Vegan leathers made from symbiotic cultures of bacteria and yeast (SCOBY) have shown sustainable potential, although they still have limitations in terms of performance and standardization.[25] Recent studies have evaluated different plant substrates, such as black and green tea mixtures, as the most efficient in the production of microbial cellulose.[26] For the production of vegan leather based on jute and mycelium, a strain of Bacillus subtilis was isolated from black tea waste to produce the biopolymer PHA, used as a cross-linking agent. Functional and mechanical analyses showed improvements in strength, mycelium interconnection, and thermal stability, as demonstrated by SEM and FTIR. Although the WVP was slightly lower than that of conventional leather, the overall properties position this material as a promising substitute for synthetic and animal leather, with the potential to contribute to the circular economy.(27) Despite the rise of vegan leather, the incorporation of electronic objects as design components remains unexplored, limiting both the diversification of sustainable textures and finishes and the creative valorization of e-waste in eco-friendly fashion.(28)

The scientific community has shown that superfine fiber synthetic leather has low breathability and poor sustainability due to its petrochemical origin.(29) In addition, recent studies in personal mobility have shown that synthetic leather, commonly used in garments such as motorcycle suits, suffers a significant loss of tensile strength after prolonged exposure to outdoor conditions. This degradation is mainly associated with ultraviolet radiation, which reduces the material's durability, especially its polyurethane surface layer.(30) A recent study developed biodegradable polyesters reinforced with hydrogen bonds, which, when applied as a coating on mycelium fabrics, showed high mechanical strength, good texture, and more than 60 % biodegradation. These materials have a lower environmental impact and are emerging as a sustainable, efficient alternative to conventional leather.(31) this study aims to develop a biocomposite from abaca fibers and acrylic resin and to evaluate its tensile strength and elongation, weight, and thickness, considering its potential as a functional and sustainable substitute for animal and synthetic leather.

METHOD

Experimental Design. A 2^2 multilevel factorial design was used, with two factors and two levels per factor, yielding 20 treatments. The design was executed in 5 blocks. The experiments are completely randomized. The degrees of freedom for error are set at 12. The response variables are tensile strength, elongation, and thickness; the study factors are abaca fiber length (2 and 5 cm) and acrylic resin at 70 % and 80 %. STATGRAPHICS Centurión Version 16.1.18 statistical software was used for the analysis.

The biocomposite was produced in the Textile Engineering Laboratory at the Technical University of the North using Bungalanón variety abaca fibers, natural latex as a binder, and acrylic resin. It was produced through a sequence of experimental stages: 1. The abaca fibers underwent a pre-treatment process in an anionic solution (2 cm^3/L, bath ratio 1:20) at 40 °C for 20 minutes, to remove impurities that could affect the adhesion and cohesion of the material. They were then rinsed with water and dried in the shade. 2. To form the nonwoven fabric, the treated fibers were cut into two and 5-cm pieces and arranged manually in a homogeneous manner on a flat surface to form a uniform layer. This blanket or nonwoven fabric was then sprayed with 10 % natural latex from a distance of 30 cm. The material was left to dry for 60 minutes at room temperature, and a weight of 30 g/m^2 was obtained using the procedure described in ISO 3801:1977. — Textiles — Determination of mass per unit area (grammage) and thickness using the Lama specimeter equipment. ISO 2589:2016 - Leather — Determination of thickness. 3. The nonwoven fabric was then impregnated with 70 % and 80 % acrylic resin by weight, ensuring uniform coverage. The samples were dried at 90°C to promote resin cross-linking and improve structural integrity and surface finish, resulting in a biocomposite density of approximately 13 g/cm^2. The resulting material exhibited flexibility and internal cohesion comparable to synthetic leather. This process is explained in figure 1.

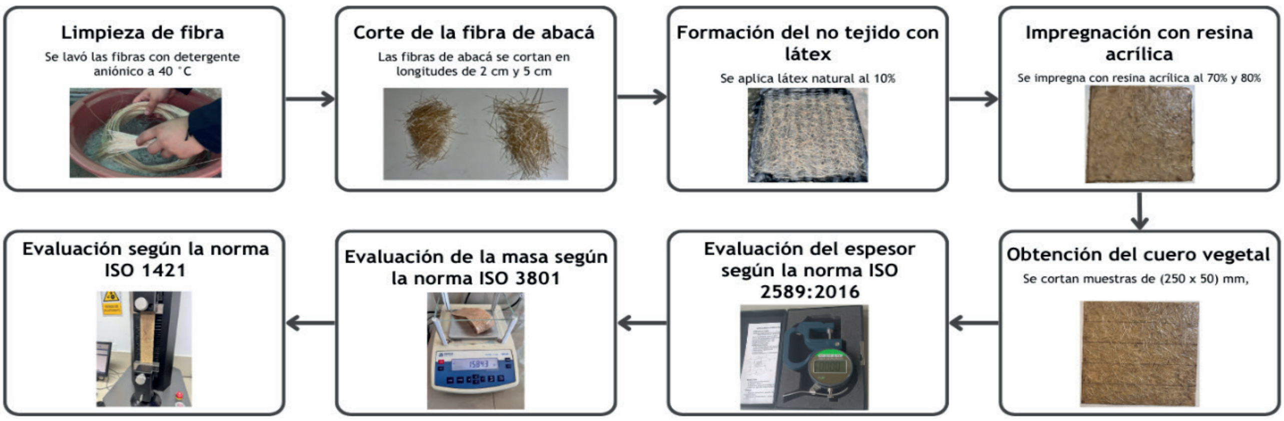


Figure 1. Biocomposite manufacturing process

Tests performed according to standards

The tensile strength and elongation, weight, and thickness properties of the biocomposite were tested according to the following standards:

- ISO 1421:2016 Rubber- or plastic-coated fabrics: determination of tensile strength and elongation at break.
- ISO 3801:1977 — Textiles — Determination of mass per unit area (grammage).
- ISO 2589: 2016 IULTCS/IUP 4. Leather Physical and mechanical tests — Determination of thickness.

The samples obtained were previously conditioned in the laboratory in a controlled environment for 24 hours.[32]

Tensile strength

The tensile strength and elongation of the samples were evaluated according to the procedure set out in ISO 1421:2016: Rubber or plastic coated fabrics: determination of tensile strength and elongation at break.[33] Test specimens measuring 250 mm long by 50 mm wide were prepared in accordance with the procedure set out in ISO 1421. Each sample was tested on the Titan 5 textile dynamometer, using T27 jaws, applying a progressive load and a tensile speed of 100 ± 10 mm/min until fracture. The maximum force and elongation values were recorded, allowing the mechanical behavior to be accurately quantified (figure 2a).

Determination of mass

ISO 3801:1977 — Textiles — Determination of mass per unit area (grammage).[34] The weight of the biocomposite was determined as the average value, in the equation 1, according to the procedure in the standard, which consisted of cutting five samples measuring 10 cm x 10 cm, then weighing them on a precision analytical balance with a sensitivity of 0,01 g. This property allows the density to be characterized (figure 2b). To calculate the weight, the following formula was used:

Equation 1. Weight

Grammage = (Sample weight (g))/(Sample area (cm^2))

Thickness determination

ISO 2589: 2016 IULTCS/IUP 4. Leather Physical and mechanical tests - Determination of thickness.[35] To determine the thickness of the biocomposite according to the procedure of ISO 2589:2016, the thickness gauge with the Lama specimeter was used, applying constant and perpendicular pressure on the contact area. Measurements were taken at five points on each sample. The average value of 2,5 mm was recorded. This property is essential for evaluating uniformity (figure 2c).

(a) (b) (c)

Figure 2. Testing process for the characterization of the biocomposite

RESULTS

The experimental design used considered two study factors: tensile strength, distributed across five blocks. A total of twenty tests were performed to evaluate the response variables under randomized conditions. The analysis of variance used 12 degrees of freedom for the error term, ensuring adequate estimation of experimental variability and the reliability of the results.

The biocomposite was made from abaca fiber and acrylic resin and underwent tensile strength and elongation tests in accordance with ISO 1421; the results are presented in Table 1. Firstly, it was observed that the samples with 70 % acrylic resin achieved tensile strengths (117,21–121,65 N), while those with 80 % resin achieved

96,46–122,36 N. The highest tensile strength recorded was 122,36 N, corresponding to the sample in Block 4 with 80 % resin and 5 cm fibers, while the lowest strength was 52,19 N, measured in Block 3 with 80 % acrylic resin in 2 cm fibers. The determination of the mass of the biocomposite using the ISO 3801:1977 procedure yielded an average value of 13 g/cm^2. The average thickness, according to the ISO 2589 procedure, is 2,5 mm.

Analysis of the effect of fiber length showed that 5 cm fibers provide an average strength of approximately 107 N, compared to approximately 64 N obtained with 2 cm fibers. In contrast, in terms of elongation, the 2 cm fibers provided higher data of 61,60 mm in Block 2 (80 % resin), while the 5 cm fibers recorded values between 15,34 mm and 43,85 mm. The results show that fiber length modifies mechanical properties: longer fibers increase tensile strength, while shorter fibers favor greater elongation.

The optimal tensile strength is 118,308 N with an acrylic resin concentration of 70 % and an abaca fiber length of 5 cm, indicating that reducing the resin content significantly improves the material's mechanical performance. In contrast, the elongation analysis showed optimal elongation of 50,184 mm at 70 % concentration and a fiber length of 2 cm.

Table 1. Tensile strength and elongation results

Block	Acrylic Resin (%)	Fiber Length (cm)	Tensile Strength (N)	Elongation (mm)
1	70	5	117,21	25,95
1	70	2	64,03	60,81
1	80	5	102,22	41,18
1	80	2	54,92	39,1
2	70	2	64,57	42,87
2	80	5	106,14	31,82
2	70	5	116,57	32,83
2	80	2	56,68	61,6
3	80	2	52,19	32,74
3	70	5	121,38	36,4
3	80	5	104,18	29,64
3	70	2	60,84	52,47
4	70	2	59,83	42,95
4	80	5	122,36	33,57
4	80	2	63,79	43,85
4	70	5	114,73	32,48
5	80	5	96,46	15,34
5	80	2	64,84	56,75
5	70	5	121,65	34,5
5	70	2	67,9	51,82

Source: taken from Zambrano[36]

DISCUSSION

Analysis of variance for tensile strength (ANOVA)

To evaluate the effect of the percentage of acrylic resin (A) and fiber length (B) on the tensile strength and elongation of the biocomposite, an analysis of variance (ANOVA) was applied under a multilevel factorial design.

Table 2 shows that the ANOVA revealed that factors A and B had a significant effect on tensile strength. Significantly, fiber length (B) showed a highly significant effect (F = 322,62; p = 0,0000), indicating that the differences observed between fiber length levels of 2 cm and 5 cm are statistically relevant. These results confirm that the experimental data align with the observed trend, in which greater fiber length improves load distribution and structural strength.

Similarly, the percentage of acrylic resin (A) also had a statistically significant effect (F = 8,83; p = 0,0117), suggesting that increasing the resin concentration improves the material's cohesion, though with a less substantial impact than fiber length.

On the other hand, the interaction between both factors (AB) was not significant (F = 1,54; p = 0,2388), indicating that the effects of each variable act individually on tensile strength. Similarly, the impact of the blocks was not significant (F = 0,54; p = 0,7064), indicating homogeneity across the experimental replicates and validating the consistency of the experimental design.

The total error was relatively low compared to the sum of squares explained by factors A and B, further reinforcing the model's validity. It decomposes the variability in tensile strength into specific components for each analyzed effect. It then evaluates the statistical significance of these effects by comparing their mean squares with an estimate of the experimental error. In this analysis, two effects have P-values less than 0,05, indicating that they are significantly different from zero at the 95 % confidence level.

Table 2. Analysis of Variance for Tensile Strength

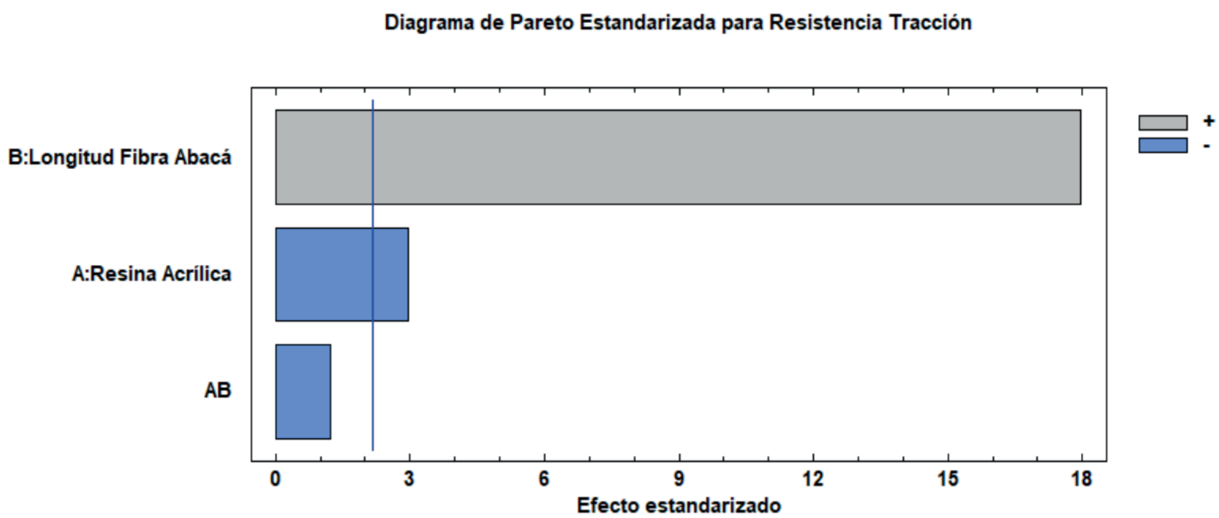
Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Ratio	P-value
A: Acrylic Resin	360,655	1	360 655	8,83	0,0117
B: Abaca fiber length	13 174,4	1	13 174,4	322,62	0,0000
AB	62,7642	1	62,7642	1,54	0,2388
Blocks	88,9502	4	22,2375	0,54	0,7064
Total error	490,028	12	40,8357		
Total (corr.)	14 176,8	19			

Source: taken from Zambrano[36]

R-squared = 96,5434 %
R-squared (adjusted for g.l.) = 94,5271 %
Standard error of the est. = 6,39028
Mean absolute error = 3,6067
Durbin-Watson statistic = 2,1959 (P=0,2710)
Lag 1 residual autocorrelation = -0,110481

The R-squared statistic indicates that the adjusted model explains 96,5434 % of the variability in tensile strength. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is 94,5271 %. The standard error of the estimate indicates that the residuals have a standard deviation of 6,39028. The mean absolute error (MAE) of 3,6067 is the average value of the residuals. The Durbin-Watson (DW) statistic tests the residuals for significant correlation based on the order of the data. Since the P-value is greater than 5,0 %, there is no indication of serial autocorrelation in the residuals at a 5,0 % significance level.

The Pareto chart presented in figure REF _Ref203851194 \h * MERGEFORMAT evaluated the effect of acrylic resin, abaca fiber length, and their interaction on tensile strength. The results indicate that fiber length had a highly significant positive impact, attributed to greater bonding and structural reinforcement in the nonwoven fabric. The concentration of acrylic resin also had an important, albeit adverse, effect, possibly due to reduced material flexibility. The interaction between the two factors was not significant, indicating that fiber length is the primary determinant of mechanical performance.

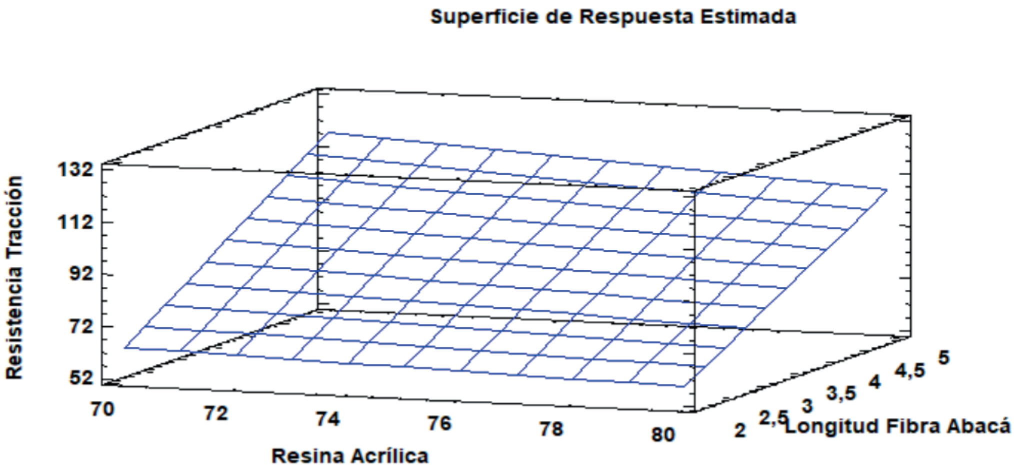


Source: taken from Zambrano[36]

Figure 3. Standardized Pareto chart for tensile strength

Figure 4 shows the Estimated Response Surface obtained in the analysis of tensile strength as a function of two experimental factors: Acrylic Resin and Abaca Fiber Length. The graph shows the interactions among these factors, with the X-axis corresponding to the levels of acrylic resin, the Y-axis to the length of the abaca fiber, and the Z-axis to the measured tensile strength.

The estimated response surface indicates that strength increases significantly with increasing fiber length, with a steep upward slope. In contrast, the effect of acrylic resin is negligible, with a gentler slope that is statistically significant. The surface generated is almost flat with respect to the interaction between the two factors, confirming their independence. Taken together, these results indicate that fiber length is the primary factor determining the material's mechanical behavior, while the resin serves as a complementary modifier.



Source: taken from Zambrano[36]

Figure 4. Estimated response surface for tensile strength

Analysis of Variance for Elongation (ANOVA)

To analyze the effects of acrylic resin concentration (A) and abaca fiber length (B) on the elongation of the biocomposite, a two-factor ANOVA with completely randomized blocks was used. Table 3 summarizes the analysis results, allowing the statistical influence of each variable on the material's deformation capacity before breakage to be identified.

The ANOVA results show that the length of the abaca fiber had a statistically significant effect on elongation (F = 15,14; p = 0,0021). This finding aligns with experimental evidence showing that samples with shorter fibers (2 cm) exhibit greater deformation capacity. This trend can be attributed to lower structural rigidity, which allows the material to elongate under mechanical stress. In contrast, the effect of acrylic resin concentration was not significant (F = 0,39; p = 0,5440), suggesting that within the range analyzed (70 %-80 %), the resin did not affect the material's elongation. This could be because the fiber structure provides the primary reinforcement, while the polymer matrix primarily affects cohesion and rigidity rather than flexibility.

A significant interaction between the two factors was also observed (F = 0,02; p = 0,8891), indicating that their effects are independent. Additional analysis of the blocks showed no significant differences (F = 0,17; p = 0,9499), supporting the homogeneity of the experimental design.

These results indicate that, to optimize elongation in the abaca fiber-based biocomposite, fiber length is a critical variable. At the same time, the resin percentage can be adjusted without significantly altering the material's deformation capacity.

Table 3. Analysis of Variance for Elongation

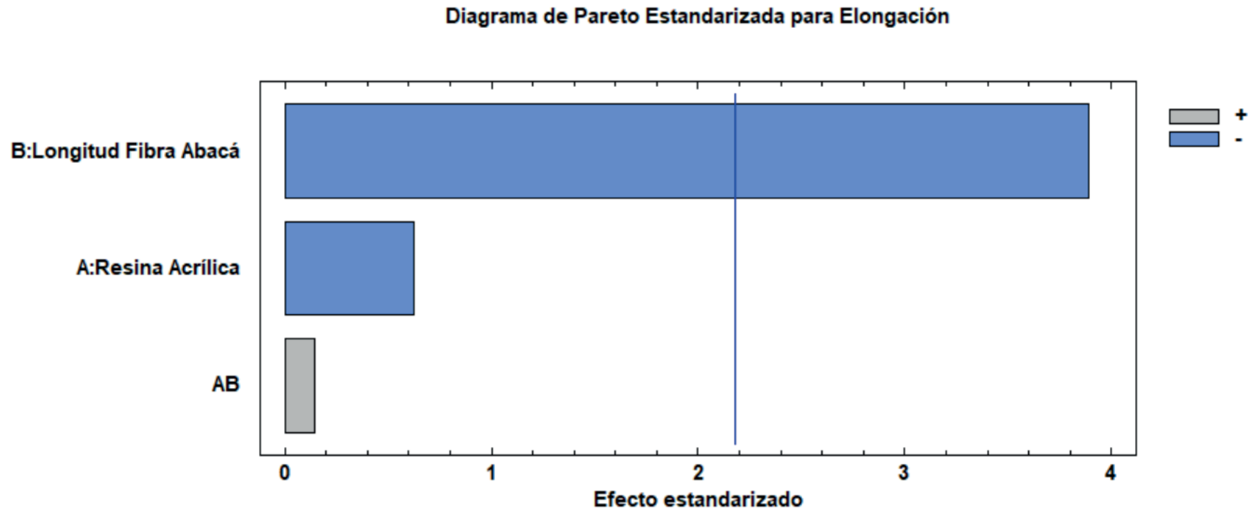
Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Ratio	P-value
A: Acrylic Resin	37,785	1	37 785	0,39	0,5440
B: Abaca fiber length	1466,33	1	1466,33	15,14	0,0021
AB	1,96564	1	1,96564	0,02	0,8891
Blocks	65,6488	4	16,4122	0,17	0,9499
Total error	1162,52	12	96,8768		
Total (corr.)	2734,25	19			

Source: taken from Zambrano[36]

R-squared = 57,483 %
R-squared (adjusted for g.l.) = 32,6814 %
Standard error of the est. = 9,8426
Mean absolute error = 6,36245
Durbin-Watson statistic = 2,65197 (P=0,6991)
Lag 1 residual autocorrelation = -0,35734

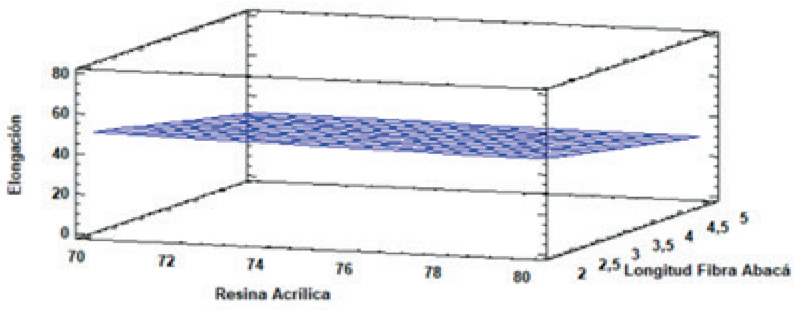
The R-squared statistic indicates that the adjusted model explains 57,483 % of the variability in Elongation. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is 32,6814 %. The standard error of the estimate indicates that the residuals have a standard deviation of 9,8426. The mean absolute error (MAE) of 6,36245 is the average value of the residuals. The Durbin-Watson (DW) statistic tests the residuals for significant correlation based on the order in which the data are presented in the file. Since the P-value is greater than 5,0 %, there is no indication of serial autocorrelation in the residuals at a 5,0 % significance level.

Figure 5 shows the standardized effect analysis for biocomposite elongation. Abaca fiber length was identified as the most influential factor, with a statistically significant adverse effect, indicating that longer fibers reduce material elongation, possibly due to increased structural rigidity. Acrylic resin concentration also had a negative impact, although not significant. The interaction between the two factors was irrelevant. Overall, it is concluded that the material's elongation is mainly determined by fiber length.



Source: taken from Zambrano[36]
Figure 5. Standardized Pareto diagram for elongation resistance

Figure 6 shows the estimated response surface for the elongation of the biocomposite as a function of abaca fiber length and acrylic resin concentration. The graph shows a relatively flat surface with a slight decrease in elongation as fiber length increases, attributed to greater structural rigidity. The influence of acrylic resin is minimal and does not produce significant variations. Overall, it is confirmed that elongation is not very sensitive to factor interactions, with fiber length being the only factor with a moderately adverse effect. These results align with the standardized effects analysis and reinforce the idea that the material's elongation is primarily determined by its structural configuration. Despite the variations introduced, the deformation capacity of the biocomposite remains within functional ranges for textile applications.



Source: taken from Zambrano[36]
Figure 6. Estimated response surface for elongation resistance

CONCLUSIONS

This study demonstrated the feasibility of producing a biocomposite from abaca fiber and acrylic resin. It evaluated the effects of fiber length (2 and 5 cm) and acrylic resin concentration (70 % and 80 %) on tensile strength and elongation. The results showed that increasing the fiber length significantly increases tensile strength, while shorter fibers contribute to greater elongation, indicating more flexible behavior. The formulation containing 70 % acrylic resin and 5 cm fiber length yielded the highest tensile strength.

This biocomposite offers a functional balance between sustainability, mechanical strength, and potential applications in sectors such as design, fashion, and footwear. Its production involves the use of renewable natural resources, such as abaca, and the controlled use of synthetic polymers, positioning it as an alternative to animal leather and conventional synthetic leather.

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FINANCING
None.

CONFLICT OF INTEREST
The authors declare that there is no conflict of interest.

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