Citation: Mokhtar Benarioua , Salah Amroune, Said Zergane, et al. Comparative analysis of Weibull and Gaussian statistical methods for assessing the mechanical properties of natural fibers. *Journal of Harbin Institute of Technology (New Series)*. DOI: 10.11916/j.issn.1005-9113.2024104

Comparative Analysis of Weibull and Gaussian Statistical Methods for Assessing the Mechanical Properties of Natural Fibers

Mokhtar Benarioua[1], Salah Amroune[2], Said Zergane[2], Barhm Mohamad[3], Amin Houari[4], Khalissa Saada[2] and Kouider Madani[5]*

(*1. Laboratory of Structural Mechanics and Materials, University of Batna 2, Batna 05078, Algeria;*
2. Laboratory of Materials and Mechanics of Structures (LMMS), Faculty of Technology, University of M' sila, M' sila 28000, Algeria;
3. Department of Petroleum Technology, Koya Technical Institute, Erbil Polytechnic University, Erbil 44001, Iraq;
4. Department of Mechanical Engineering, M' hamed Bougara University of Boumerdes, Boumerdes 35000, Algeria;
5. Department of Mechanical Engineering, LMSS, University of Djillali Liabes, Sidi Bel Abbes 22000, Algeria)

Abstract: A detailed comparative examination of the Weibull and Gaussian statistical methods is offered to analyze the mechanical properties of natural date palm fibers. Tensile tests were conducted on 35 fiber samples using a universal testing machine to gather data on stress, strain, and Young's modulus. This data was then analyzed through both statistical approaches to evaluate their ability to model important mechanical characteristics, including tensile strength, strain at break, and Young's modulus. The study identifies the strengths and weaknesses of each statistical method when it is applied to natural fibers, emphasizing their suitability for modeling different mechanical properties. The results of this analysis provide important insights that can guide the selection of the most appropriate statistical method, depending on the type of mechanical property being studied and the specific characteristics of the data. This research makes significant contributions to advancing the understanding of natural fiber mechanics and improving the methods used for their characterization.

Keywords: Weibull distribution, Young modulus, Gaussian distribution, static traction, natural fibers

CLC number: TB332　　**Document code**: A　　**Article ID**: 1005-9113(2025)00-0000-06

0 Introduction

Statistical methods offer a large range of approaches for analyzing data for different purposes. For example, linear regression is employed to establish relationships between continuous variables[1], while logistic regression is specific to predicting binary variables using continuous or categorical predictors[2]. Similarly, the t-test and Wilcoxon-Mann-Whitney test allow the means of two groups to be compared, but the former assumes normality of the data while the latter is more robust to non-normal data or outliers[3-5]. To compare the means of several groups, ANOVA is preferred with normally distributed data, but if this assumption is not respected, the non-parametric Kruskal-Wallis test is more appropriate for comparing groups when data do not meet parametric assumptions. Dimensionality reduction can be achieved using Principal Component Analysis (PCA), which identifies linear combinations of variables that explain the maximum variance. In contrast, factor analysis aims to uncover underlying relationships among the observed variables[6-8]. Finally, supervised classification uses labelled data to predict new labels, while unsupervised classification, such as clustering, looks for internal structures in unlabeled data. The choice between these methods depends on the characteristics of the data and the specific objectives of the analysis, requiring in-depth understanding for judicious selection.

This comparative study focuses on the detailed evaluation of statistical methods, including Weibull distribution and Gaussian distribution, applied to modelling crucial mechanical properties of natural fibers. These fibers are essential to many industries,

Received 2024-11-21.

* Corresponding author: Barhm Mohamad, Ph.D, Lecturer. Email: barhm.mohamad@epu.edu.iq.

from textiles to construction, and their mechanical properties, such as tensile strength, elongation strain, and Young's modulus, determine their suitability for different applications. Thus, a thorough understanding of these traits is crucial to comprehending the mechanical behaviour of natural fibers and optimizing their utilization[9-18].

The application of statistical methods to describe the mechanical properties of natural fibers is critical since it aids in understanding, predicting, and improving the behavior of these materials in a variety of applications. For illustration, some recent studies have been conducted on jute, hemp, linen, sisal, and banana fibers[19], Sida Rhombifolia fibers [20], and jute fibers in synergy with curaua, sisal, and glass fibers[21]. It would be valuable to investigate how the results would have been if statistical methods are applied in the modeling process, and how this would affect their momentum in terms of ensuring reliability and reproducibility, quantifying variability, identifying patterns and relationships, facilitating comparisons, developing predictive models, etc.

This study focuses on comprehensively analyzing the ability of the Weibull distribution and Gaussian distribution to accurately model these fundamental mechanical properties of natural fibers directions. By evaluating how each method captures and represents tensile strength, strain, and Young's modulus, this research seeks to highlight the specific benefits and limitations of each approach in this particular context. These detailed analyses will provide valuable insights into the relative effectiveness of these statistical methods, allowing determination of the most suitable method based on specific data or particular mechanical property requirements for natural fibers.

1 Material and Methods

1.1 Samples Collection

Representative samples of natural date palm fibers were collected to ensure sufficient diversity in the mechanical properties of these fibres.

1.2 Samples Preparation

Samples were prepared according to specific standards, likely by cutting or shaping fibers to achieve standardized dimensions (as shown in Fig. 1).

1.3 Measuring Diameters

Prior to conducting quasi-static tensile tests, the diameters of the date palm fibers were measured at three distinct locations along the length of each fiber. These measurements were performed using an optical microscope integrated with a digital camera and managed by image processing software to ensure precision and consistency. For each fiber, three diameter readings were recorded, and their arithmetic mean was considered as the representative diameter value. The measured average diameter across all samples was 380 ± 35.43 μm, where 380 μm represents the mean, and ±35.43 μm denotes the standard deviation, indicating the variation among the samples. To facilitate further mechanical analysis, the fiber cross-section was assumed to be circular. Based on this assumption, the cross-sectional area was calculated using the averaged diameter (as shown in Fig.1).

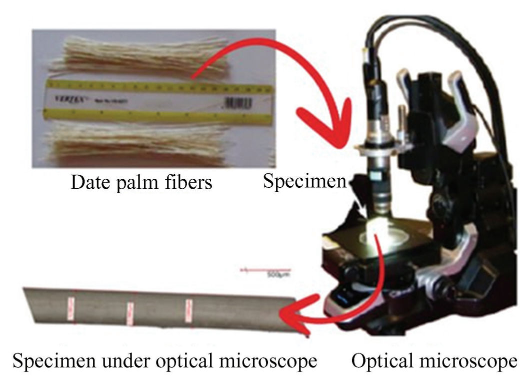
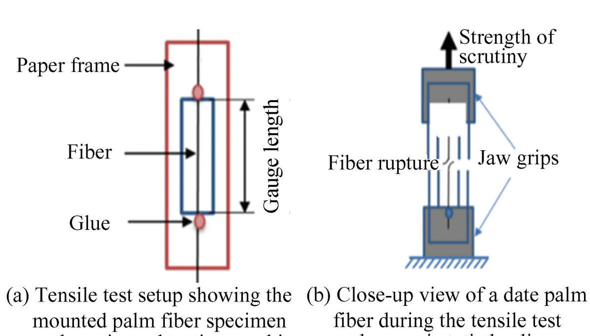


Fig. 1 Date palm fibers and equipment used measuring diameters

1.4 Tensile Tests

As shown in Fig. 2, tensile tests were carried out on a universal machine, where the samples were subjected to tensile stresses up to failure. During these tests, stress, strain and Young's modulus data were recorded at regular intervals or until complete failure of the samples.



(a) Tensile test setup showing the mounted palm fiber specimen on the universal testing machine (b) Close-up view of a date palm fiber during the tensile test under quasi-static loading

Fig. 2 Specimen tested in traction

1.5 Data Analysis

Data collected from the tensile tests were processed and analyzed. This includes calculating the tensile strength, strain at break and Young's modulus for each sample.

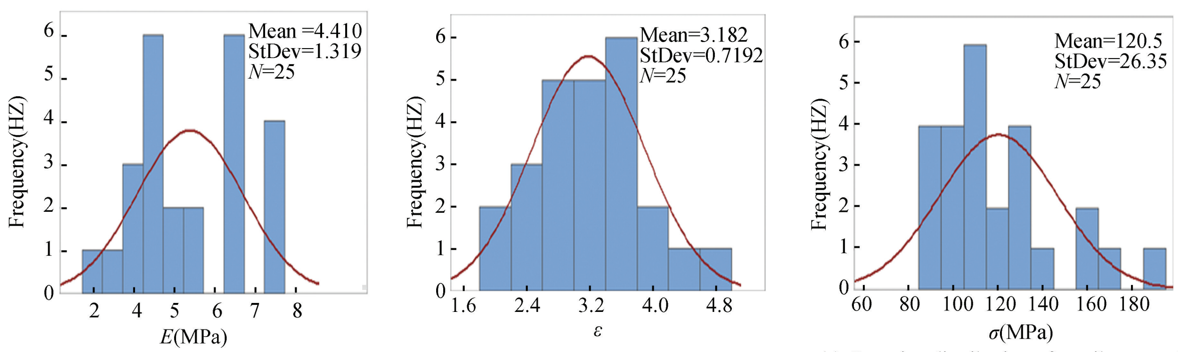
1.6 Application of Statistical Methods

Both Weibull statistical method and Gaussian distributions were applied to the data obtained from the tensile tests. A comparison of the results show that it possible to assess the adequacy of each model to characterize the mechanical properties of natural date palm fibers, and the capacity of each one to adapt to the fibers mechanical data properties. This made it possible to highlight the strengths and limitations of each method in this specific context. These experimental methods provide a framework for evaluating the mechanical properties of natural fibers and comparing the effectiveness of statistical methods in this context.

2 Results and Discussion

2.1 Tensile Test Results

The data collected during the tensile tests on the 35 samples were analyzed to obtain the tensile stress (σ), strain at break (ε) and Young's modulus values (E) for each sample. These raw results are presented in Fig. 3, with means (mean), standard deviations (StDev), and other descriptive parameters (N).



(a) Gaussian distribution of Young's modulus for natural date palm fibers

(b) Gaussian distribution of strain at break for tested fibers

(c) Gaussian distribution of tensile strength values for date palm fibers

Fig. 3 Gauss distribution of fiber mechanical properties (E, ε and σ)

2.2 Application of Statistical Methods

The results of applying Weibull statistical methods and Gaussian distributions to the tensile test data are shown in Figs. 4-6. This includes how each method modeled the mechanical characteristics of natural fibers and the corresponding parameters obtained.

2.3 Comparison of Statistical Models

A detailed comparison of the models resulting from the two statistical methods is carried out. This includes the correspondence of the models to the experimental data, the accuracy of predicting mechanical properties and the differences between the two methods in terms of the validity of the models obtained.

2.4 Discussion

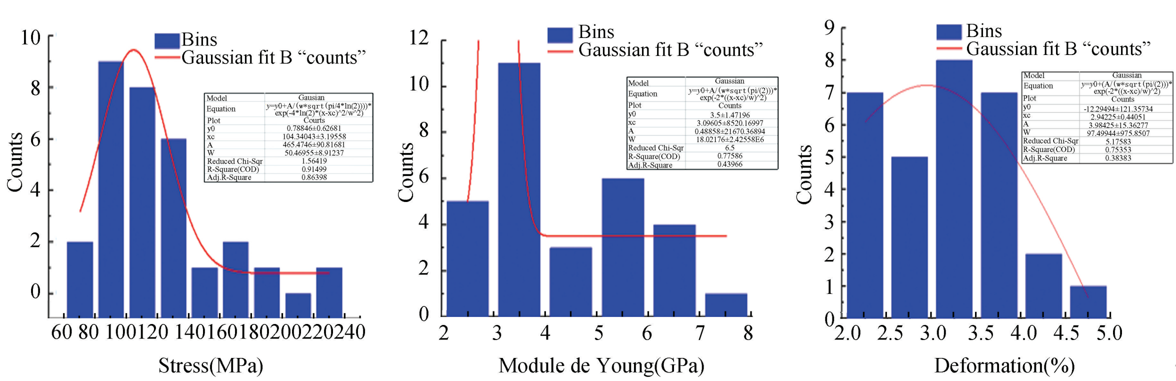
As shown in Figs. 3(a), (b) and (c), the distribution histograms of fiber mechanical properties (E, ε and σ) represent bell-shaped curves, indicating that the measured data can be described satisfactorily under the normal law or Gaussian law. This later was more effective in describing deformations and Young's modulus (as shown in Fig.3(a)).

From Figs. 3(b) and (c), it can be seen that the rupture frequency of samples below the average stress is twice that of recorded above. This makes the latter not sufficient to clarify the rupture properties nature of the fibers studied. This justifies the need to use statistical rupture probability methods based on an acceptable rupture probability.

Regarding the Gaussian adjustment, Figs. 4(a), (b) and (c) show that it was acceptable for stress, Young's modulus, and average for deformation, with R^2 of 0.91499, 0.77586 and 0.75353 respectively. It should be noted that the same behaviour was repeated for Lorentz model (as shown in Figs. 5(a), (b) and (c)).

2.5 Weibull's Method

The Weibull plots, illustrated in Figs. 6(a), 6(b) and 6(c), were used to analyze three mechanical properties: stress (σ), Young's modulus (E), and strain (ε). In Fig. 6(a), the normal probability plot displays the cumulative probability against the raw data values. The data points for all three properties closely follow linear trends, indicating a reasonable fit to the Gaussian distribution. The statistical parameters provided in the inset table include the location (mean), scale (standard deviation), and Anderson-Darling (AD^*) test values. Among the properties, strain exhibits the lowest AD^* value (0.385), suggesting it conforms more closely to a normal distribution, followed by tensile strength (σ) and Young's modulus (E). This indicates that the Gaussian model is particularly effective for modeling continuous properties like deformation and elastic behavior. In contrast, Fig. 6(b) shows the Weibull probability plot, where data are plotted against a threshold-adjusted scale. This model is particularly suited for failure-related properties. The plotted curves reveal greater dispersion, especially for strain and modulus, reflecting the presence of heterogeneous defects and variability among the samples. The table accompanying this plot lists the shape, scale, and threshold parameters along with the AD^* values. The tensile strength data show a better alignment with the Weibull model, indicated by a shape parameter of 1.061 and a high scale value of 29.41. This suggests that tensile strength exhibits the stochastic characteristics typical of failure phenomena, making the Weibull distribution a more appropriate choice for analyzing σ. In summary, the normal distribution provides a better fit for strain and Young's modulus, while the Weibull distribution is more suitable for characterizing the variability in tensile strength due to the presence of microstructural defects. Fig. 6(c) displays a more complex threshold-based probability model, where the data are adjusted to include threshold values before fitting. This approach is particularly useful when the data exhibit a lower limit or shift, often relevant in failure mechanics. The fitted curves show noticeable deviation from linearity, and the data appear more scattered, particularly for Young's modulus and strain. The table associated with this figure provides statistical parameters including location, scale, threshold, and AD^* values. Interestingly, the tensile strength (σ) again exhibits a high threshold (92.74) and moderate AD^* value (0.681), suggesting that it remains somewhat consistent with a threshold-based behavior, possibly due to fiber defects or pre-existing flaws. The unusual negative thresholds observed for ε and E indicate a deviation from standard probabilistic trends, implying that these parameters are not well captured by this model.

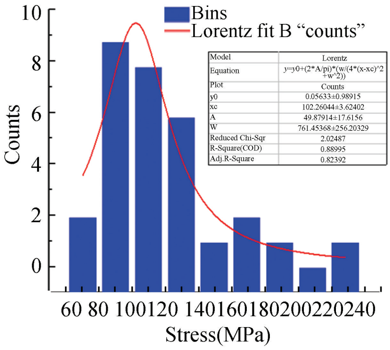


(a) Histogram and Gaussian fit of stress distribution
(b) Histogram and Gaussian fit of Young's modulus distribution
(c) Histogram and Gaussian fit of deformation distribution

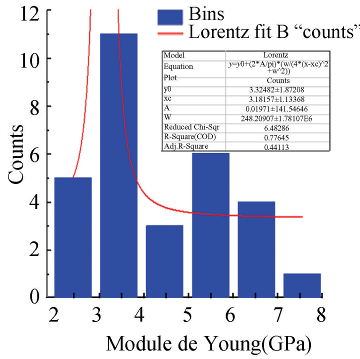
Fig. 4 Gaussian model

3 Conclusions

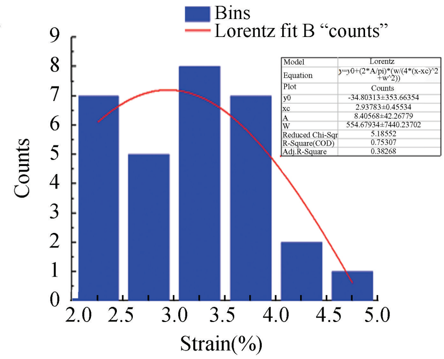
This in-depth comparative study of statistical methods applied to modeling the mechanical properties of natural fibers highlights significant conclusions. By evaluating the Weibull distribution and Gaussian distribution to represent the tensile strength, strain at break, and Young's modulus of natural fibers, the specific strengths and limitations of each approach can be observed.



(a) Lorentz distribution applied to tensile strength of date palm fibers

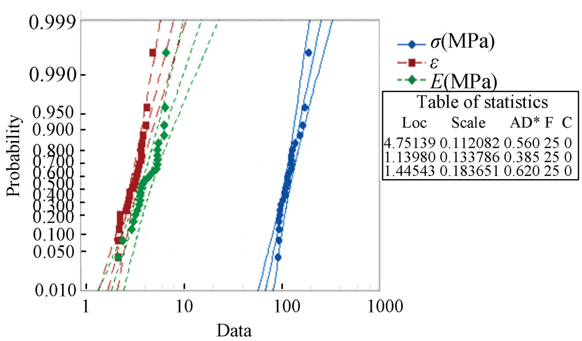


(b) Lorentz fit to Young's modulus distribution of fiber samples

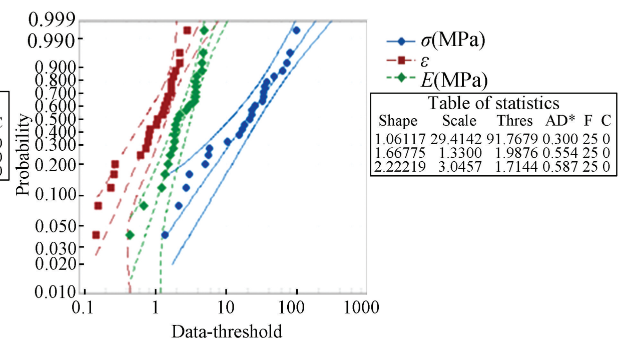


(c) Lorentz model for strain at break across tested fiber specimens

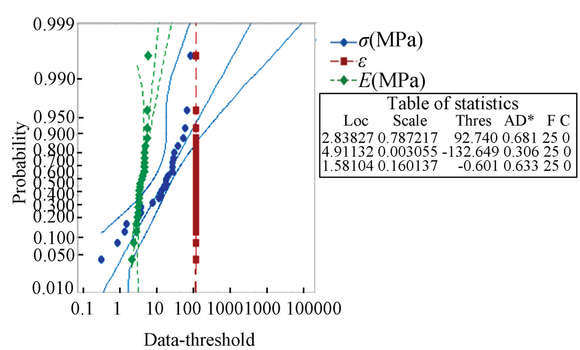
Fig. 5 Lorentz model



(a) Normal probability plot of (σ, ε, E) fitted with location-scale parameters



(b) Weibull probability plot of σ, ε, and E based on shape, scale, and threshold parameters, illustrating variability due to fiber heterogeneity



(c) Threshold-adjusted distribution plot of σ, ε, and E, highlighting non-linear fitting behavior and deviations in strain and modulus response

Fig. 6 Probabilities plots

It can be seen that the Weibull distribution proves to be a robust model for representing the tensile strength and durability of natural fibers. Its ability, to model fracture data and estimate fiber's life span, was remarkable. In contrast, the Gaussian distribution was found to be more suitable for characterizing aspects such as deformation and Young's modulus of natural fibers, providing a better representation of morphological variations and continuous measurements.

These results highlight the importance of choosing the statistical method based on the specific properties to be modeled. For fibers strength and durability, the Weibull distribution appears to be a solid choice, while the Gaussian distribution is more relevant for characterizing the morphological properties and continuous measurements of natural fibers.

This study provides crucial guidance for the appropriate use of statistical methods in the analysis of mechanical properties of natural fibers, thereby helping to optimize their use in various industrial and technical fields.

References

[1] Torra V, Domingo-Ferrer J, Mateo-Sanz J M, et al. Regression for ordinal variables without underlying continuous variables. Information Sciences, 2006, 176(4): 465-474. DOI: 10.1016/j.ins.2005.07.007.

[2] Harrell Jr F E. Binary Logistic Regression. Regression Modeling Strategies: With Applications to Linear Models, Logistic and Ordinal Regression, and Survival Analysis, 2015: 219-274.

[3] De Neve J, Thas O, Ottoy J P, et al. An extension of the Wilcoxon-Mann-Whitney test for analyzing RT-qPCR data. Statistical Applications in Genetics and Molecular Biology, 2013, 12(3): 333-346. DOI: 10.1515/sagmb-2012-0003.

[4] Zimmerman D W, Zumbo B D. The Relative Power of Parametric and Nonparametric Statistical Methods. In A Handbook for Data Analysis in the Behaviorial Sciences: Methodological issues. New York: Psychology Press, 2014: 481-517.

[5] Zimmerman D W. Invalidation of parametric and nonparametric statistical tests by concurrent violation of two assumptions. The Journal of Experimental Education, 1998, 67(1): 55-68. DOI: 10.1080/00220979809598344.

[6] Fay M P, Proschan M A. Wilcoxon-Mann-Whitney or t-test? On assumptions for hypothesis tests and multiple interpretations of decision rules. Statistics Surveys, 2010, 4: 1-39. DOI: 10.1214/09-SS051.

[7] Hoekstra R, Kiers H A, Johnson A. Are assumptions of well-known statistical techniques checked, and why (not)? Frontiers in Psychology, 2012, 3: 137. DOI: 10.3389/fpsyg.2012.00137

[8] Mahachie John J M, Van Lishout F, Gusareva E S, et al. A robustness study of parametric and non-parametric tests in model-based multifactor dimensionality reduction for epistasis detection. BioData Mining, 2013, 6(1): 1-17. DOI: 10.1186/1756-0381-6-9.

[9] Schreiber J B. Issues and recommendations for exploratory factor analysis and principal component analysis. Research in Social and Administrative Pharmacy, 2021, 17(5): 1004-1011. DOI: 10.1016/j.sapharm.2020.07.027.

[10] Mvududu N H, Sink C A. Factor analysis in counseling research and practice. Counseling Outcome Research and Evaluation, 2013, 4(2): 75-98. DOI: 10.1177/2150137813494766.

[11] Yang B. Factor Analysis Methods. Research in Organizations: Foundations and Methods of Inquiry. Swansor R, ed. 2005: 181-199.

[12] Abdelhussein A, Yang G, Hussein E K, et al. Investigation of fracture behavior and mechanical properties of epoxy composites supported with MWCNTs microscopically. Vibroengineering Procedia, 2024, 54: 193-201. DOI: 10.21595/vp.2024.23924.

[13] Aldriasawi S K, Hasein A N, Anead A M, et al. Investigation the effect of surface treatment on the mechanical properties of coating. Pollack Periodica, 2024, 19(2): 138-145. DOI: 10.1556/606.2024.00955

[14] Aldriasawi S K, Ameen N H, Fadheel K I, et al. An experimental artificial neural network model: Investigating and predicting effects of quenching process on residual stresses of AISI 1035 steel alloy. Journal of Harbin Institute of Technology (New Series), 2024, 31(5): 78-92. DOI: 10.11916/j.issn.1005-9113.2023090.

[15] Aldeen A W, Mahdi D Y, Chen Z, et al. Effect of isothermal and isochronal aging on the microstructure and precipitate evolution in beta-quenched N36 Zirconium alloy. Facta Universitatis-Series: Mechanical Engineering, 2023, 23(1): 49-63. DOI: 10.22190/FUME230405019A.

[16] Al-Abboodi H, Fan H, Al - Bahrani M, et al. Mechanical characteristics of nano-crystalline material in metallic glass formers. Facta Universitatis - Series: Mechanical Engineering, 2023, 22(2): 315-328. DOI: 10.22190/FUME230128016A.

[17] Abdelhussien A, Yang G, Hussein E K, et al. Analysis of the mechanical characteristics of date seed powder-based composite carbon fiber reinforced polymers. Facta Universitatis - Series: Mechanical Engineering. Online first. DOI: 10.22190/FUME230728040A.

[18] Elanchezhian C, Ramnath B V, Ramakrishnan G, et al. Review on mechanical properties of natural fiber composites. Materials Today: Proceedings, 2018, 5(1, Part 1): 1785-1790. DOI: 10.1016/j.matpr.2017.11.276.

[19] Ari A, Karahan M, Kopar M, et al. Comparative analysis of natural fibres characteristics as composite reinforcement. Industria Textila, 2023, 74(4): 403-411. DOI: 0.35530/IT.074.04.2022110.

[20] Ngoup T, Efeze N D, Kanaa T, et al. Physical, chemical and mechanical characterization of sida rhombifolia fibers from the center region of cameroon for their potential use in textiles and composites. Journal of Natural Fibers, 2024, 21(1): 2294478. DOI: 10.1080/15440478.2023.2294478.

[21] de Queiroz H F M, dos Santos N V, Neto J S S, et al. Mechanical characterization of novel natural fibre-reinforced composites via a three-dimensional fibre architecture. Composites Science and Technology, 2025, 261: 110996. DOI: 10.1016/j.compscitech.2024.110996.