Research Article

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Sustainable cocoon waste epoxy composite solutions: Novel approach based on the deformation model using finite element analysis to determine Poisson's ratio

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Abstract: Poisson's ratio is essential in composite analysis and design. This study presents a novel method for determining the modulus of elasticity and Poisson's ratio of cocoon waste epoxy composites (CWECs) using FEA, validated through tensile testing. The deformation curve was first established experimentally, followed by Latin Hypercube Sampling (LHS) in MATLAB to generate 20 data pairs, enhancing result reliability. In the subsequent phase, detailed structural models of CWEC were constructed using PowerShape, and simulations were performed in ANSYS to analyze mechanical behavior. Validation was achieved by comparing the simulated deformations with empirical test data, with RMSE used as the primary accuracy metric. The results yielded an RMSE of 0.2181, indicating a strong correlation between the FEA model and experimental observations. This confirms the reliability of the derived values for modulus of elasticity (565.57 MPa) and Poisson's ratio (0.4564). Further validation of Poisson's ratio for CWEC was conducted by comparing the simulation outcomes with experimental data in accordance with ASTM standards. The findings revealed a high degree of correlation between the two methods, with a similarity of 94.21%.

Keywords: Poisson's ratio, modulus of elasticity, cocoon waste epoxy composites, FEA, LHS

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1 Introduction

Natural fiber-reinforced epoxy resin composites have garnered significant attention as a viable alternative to conventional synthetic fiber composites in engineering and structural applications. These composites, which consist of an epoxy resin matrix reinforced with natural fibers such as hemp fiber [1], Piassava fiber [2], Bamboo cellulose fiber [3], Ramie faber [4], Kenaf fiber [5], and flax fiber [6], offer enhanced mechanical properties, positioning them as suitable candidates for a wide range of industries, including automotive [7], aerospace [8], and construction [9,10]. The increasing interest in these materials is largely attributed to their environmental sustainability [11,12], cost-efficiency, and their potential to provide lightweight and high-strength solutions, thereby addressing the growing demand for sustainable engineering materials [13].

Poisson's ratio is a key parameter in fiber-reinforced epoxy composites, indicating the material's ability to deform transversely under longitudinal stress [14]. It is influenced by the properties of both the fiber and matrix, their volume fractions, and fiber orientation [15]. For unidirectional composites, Poisson's ratio typically ranges from 0.20 to 0.50, depending on the materials used [16–18]. This ratio is crucial for predicting mechanical behavior and designing materials with specific properties [19]. Mechanical properties, including Poisson's ratio, are assessed using micromechanical and experimental methods. Models account for the contributions of fiber and matrix, while techniques like tensile testing and digital image correlation validate these predictions. Understanding these properties is vital for industries such as aerospace [15], automotive [20], and civil engineering [21]. Recent advancements have led to hybrid composites that combine different fibers to optimize mechanical properties. These hybrids can achieve unique Poisson's ratios, offering tailored solutions for specific applications [22]. Such innovations drive the development of next-generation composites with improved performance and reliability.

Accurate testing of Poisson's ratio in fiber-reinforced epoxy composites necessitates the use of precise methodologies. One widely adopted approach involves the application of strain gauges to measure longitudinal and transverse strains under uniaxial loading, with Poisson's ratio calculated as the negative ratio of these strains. The reliability of this method is contingent upon the quality of the strain gauges and the precision of the data acquisition system [23]. Digital image correlation, a non-contact optical technique, provides a detailed assessment of strain distribution by capturing and analyzing images of the specimen during deformation [24]. This method is particularly well-suited for complex loading scenarios and mitigates the risk of altering the specimen's behavior by eliminating the need for physical sensors. Dynamic mechanical analysis is employed to evaluate Poisson's ratio in viscoelastic composites, measuring the material's response to oscillatory stress. By analyzing the phase lag between applied stress and resulting strain, dynamic mechanical analysis provides insights into the temperature and frequency dependence of Poisson's ratio [25]. Each testing method presents distinct advantages and limitations, with the selection of technique determined by factors such as the type of composite and the specific loading conditions. Continued advancements in testing technologies will further enhance the accuracy of Poisson's ratio measurements in fiber-reinforced epoxy composites [26].

Cocoon waste epoxy composites (CWECs), a subset of fiber-reinforced epoxy materials, present several advantages, positioning them as promising candidates for diverse engineering applications. One of their primary benefits is sustainability, as the use of silkworm cocoon waste minimizes environmental impact and promotes the utilization of renewable resources [27]. This aligns with the increasing demand for environmentally friendly materials in sectors such as automotive and construction. In addition to their eco-friendly nature, these composites exhibit outstanding mechanical properties, including high tensile strength and impact resistance [28]. The inherent toughness of silkworm cocoons enhances the composite's durability, making them particularly well-suited for protective gear and ballistic panels. Moreover, CWECs demonstrate exceptional thermal stability, maintaining their integrity under elevated temperatures, which is advantageous in aerospace and automotive industries [29]. From an economic perspective, the use of waste materials from the silk industry significantly reduces raw material costs, making CWEC a cost-effective alternative to traditional synthetic fiber-reinforced composites. With ongoing research and development, these composites hold great potential for further optimization and broader adoption in a variety of industrial applications. Fiber-reinforced composites typically exhibit anisotropic behavior, with mechanical properties like tensile strength and modulus varying based on the direction of applied force. However, CWECs have been found to demonstrate isotropic characteristics under certain processing conditions, resulting in uniform mechanical properties in all directions. This isotropy is due to the random distribution of cocoon waste fibers within the epoxy matrix, which ensures consistent reinforcement across all orientations [30]. Strong interfacial bonding between the fibers and epoxy resin further promotes uniform stress distribution, enabling effective load transfer regardless of direction, thereby enhancing the composite's isotropic mechanical behavior [31]. Consequently, these composites are well-suited for applications requiring consistent mechanical performance, especially in structural components subjected to multi-directional loads. To assess the mechanical properties of cocoon waste-epoxy composites, an isotropic material model is often used to determine parameters like modulus of elasticity and Poisson's ratio, given their uniform response to mechanical stresses.

Poisson's ratio is a crucial parameter in the analysis of natural fiber epoxy composites, influencing their mechanical performance under various loading conditions. For example, both the modulus of elasticity and Poisson's ratio play essential roles in finite element analysis (FEA), which simulates the behavior of these composites. Micromechanical models like the Rule of Mixtures and Halpin–Tsai equations are often used to estimate elastic properties based on the fiber volume fraction and orientation. Researchers applied these models to banana, jute, and pineapple leaf fiber composites in a polylactic acid matrix, observing a general decrease in Poisson's ratio with increasing fiber content, except in sisal composites [32]. However, due to fiber morphology and interfacial variability, experimental calibration is often required. Tensile testing, especially according to ASTM D3039, remains essential for validating such models. Empirical data [33] highlight the importance of fiber alignment and stiffness on transverse response and reinforce the value of combining theoretical and experimental methods. FEA enables detailed simulations of natural-fiber composites using realistic geometries and material properties. Simulations conducted using ANSYS Workbench facilitated a comparative analysis between banana fiber/polylactic acid composites and polyethylene terephthalate composites, highlighting the promising potential of natural fiber-reinforced materials for environmentally sustainable applications [32]. Advanced FEA techniques, including representative volume elements and multiscale modeling, have proven effective in capturing anisotropic behavior [34]. Hybrid approaches integrating FEA and experimental data,

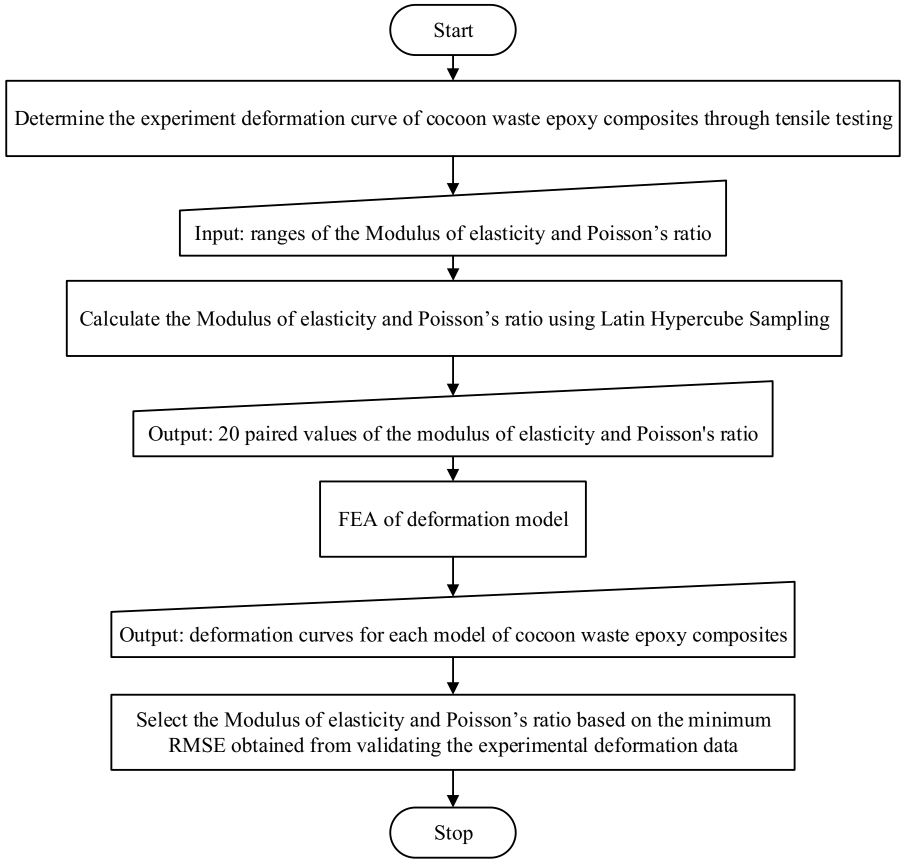

Figure 1: Workflow for the novel methodology based on the deformation model and utilizing FEA.

such as the numerical homogenization method used by Adeniyi *et al.* [35], offer reliable predictions and now serve as benchmarks. Therefore, any new method must demonstrate improved accuracy, efficiency, or applicability.

This study presents an innovative methodology for determining Poisson's ratio of CWEC. The proposed approach employs foundational models to predict the mechanical behavior of these composites by integrating empirical data with theoretical analysis. These models indicate that Poisson's ratio can be tailored by modifying cell geometry, such as the cell wall thickness and angle of hexagonal cells. Advanced numerical techniques, particularly FEA, are utilized to perform detailed simulations that accommodate complex geometries and material behaviors under various loading conditions. In addition, experimental methods were employed to validate the theoretical and computational models, with results providing critical insights and confirming model accuracy. Overall, these integrated approaches underscore the significance of combining theoretical, computational, and experimental methodologies to achieve a comprehensive understanding and optimization of the mechanical properties of CWEC.

2 Materials and methods

2.1 Procedure

The structured workflow procedure is designed to achieve specific objectives efficiently through the systematic integration of various components and adherence to established protocols. This organized approach facilitates the effective completion of tasks. A thorough explanation of the process requires identifying its key phases and dependencies, which is essential for improving both understanding and operational efficiency. Initially, the deformation curve of CWEC was determined through tensile testing. Subsequently, the study utilized LHS implemented *via* MATLAB software (The MathWorks, Inc., Natick, MA, USA) to calculate key mechanical properties, including the modulus of elasticity and Poisson's ratio. In the third phase, detailed CWEC structural models were generated using PowerShape software, developed by Autodesk Inc. (San Rafael, CA, USA). Following model generation, the simulation process was conducted using ANSYS Workbench, a sophisticated computational tool developed by ANSYS Inc. (Canonsburg, PA, USA). The

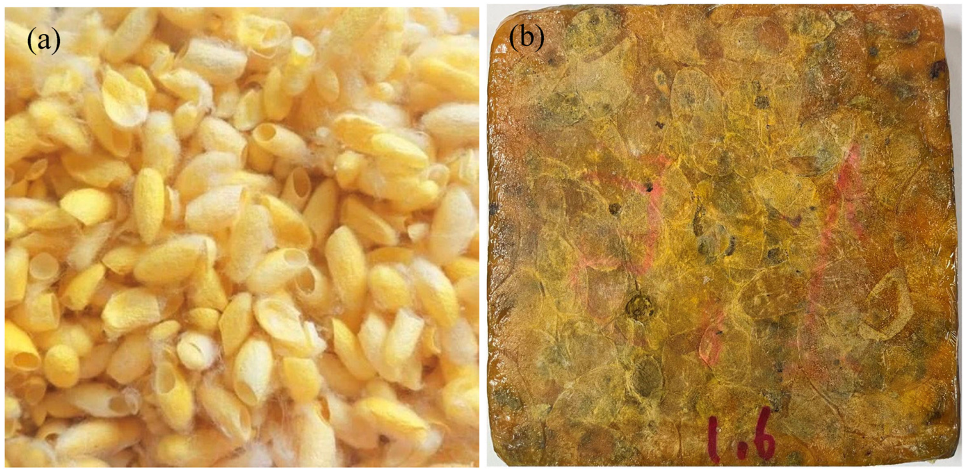

Figure 2: The general macroscopic view of (a) raw cocoon waste materials and (b) CWEC panels.

research placed particular emphasis on FEA and its consistency with experimentally validated data from CWEC, as demonstrated in Figure 1.

2.2 Tensile testing

The cocoon waste used in this study, sourced from the Nang Noi Sisaket-1 silkworm breed in Sisaket Province, consists of discarded or defective cocoons unsuitable for reeling due to irregular morphology. Typically, the waste has a pointed end, blunt head, a fibrous texture, and averages 3 cm in length and 1.5 cm in width, as shown in Figure 2(a). Its average weight is 6.47–6.55 g per 10 cocoons, with silk lengths ranging from 280 to 950 m. The epoxy resin (CYD-128) used as the matrix has a density of 1,200 kg/m^3, and the hardener, EPAMINE PA53, was sourced locally in Thailand. The cured epoxy composites exhibit a hardness exceeding 85 Shore A. The composite plate was fabricated using compression molding. Epoxy resin and hardener were mixed in a 4:1 ratio, producing 50 g of matrix solution, which was degassed to remove air bubbles. Initially, 10 g of the solution was poured into the base of a 15 cm × 15 cm × 20 cm mold. Approximately 50 g of cocoon waste was then evenly distributed, and the remaining resin was poured to fully cover the material.

Figure 3: The configuration for the tensile testing of CWEC panels.

The mold was sealed and compressed at 1.5 MN for 2 h at 25°C. After compression, the specimen was removed and cured at 25°C for 72 h, resulting in fully formed composite panels, as shown in Figure 2(b).

Tensile testing was conducted at a displacement rate of 5 mm/min until the specimen reached the load cutoff, in accordance with ASTM D638 standards [36]. The experiment utilized the Bluehill software, version 3 (INSTRON Co., Ltd., High Wycombe, Bucks, UK). In experimental tensile tests, the load–extension relationship plays a crucial role in determining the mechanical properties of materials. This method consists of applying tensile force to the specimen and accurately recording the resulting elongation or displacement, as illustrated in Figure 3. These measurements provide the foundation for evaluating the material's behavior under external forces, contributing to a deeper understanding of its mechanical properties. The experimental deformation curve, derived from these measurements, is subsequently employed to validate the deformation curve generated through FEA models, ensuring consistency between empirical and simulated results. The deformation curve was derived through testing a set of ten specimens in the experimental setup.

2.3 LHS

LHS is a valuable tool in materials science for investigating the properties and behavior of CWEC structures [37]. When applying LHS to CWEC structures, the goal is to systematically explore the parameter space, encompassing design variables and manufacturing conditions that influence the material's properties. This process begins with identifying the key design variables, such as geometric parameters, material properties, or manufacturing conditions, that affect the CWEC structure. Crucial to this step is defining the ranges and discretization levels for each variable, including the minimum and maximum values for parameters such as cell size and the number of intervals within each range. Based on this defined parameter space, a Latin hypercube design is generated. The LHS algorithm ensures that the sampling of design variables is both even and representative, allowing for a diverse exploration of CWEC structure configuration.

For each experimental run or simulation, specific values are assigned to the design variables according to the Latin hypercube design, creating unique combinations of design parameters for each trial. These parameter sets are then used to either simulate the behavior of CWEC structures through computational methods or to fabricate physical prototypes with varying parameter combinations. Once the physical prototypes are fabricated, measurements of material properties, such as mechanical strength, stiffness, or thermal conductivity, are conducted. In parallel, simulations provide relevant material property data derived from computational results. The collected data from both experiments and simulations are analyzed to assess the material properties corresponding to each set of design variables. Statistical analysis and data visualization techniques are then employed to identify trends and correlations between the design parameters and material properties. By utilizing LHS in the study of CWEC structures, researchers can efficiently explore the influence of various design variables, optimize structural performance, balance trade-offs between different properties, and gain valuable insights into the behavior of these unique cellular materials.

The exit is divided into M sub-intervals, resulting in the occurrence of the jth sub-interval for the ith design variable X_i:

$$\left[L_{ij} = L_i + \frac{(j-1)(U_i - L_i)}{M}\right] \le X_{ij} \le \left[U_{ij} = L_i + \frac{j(U_i - L_i)}{M}\right]. \tag{1}$$

The points within each sub-range were subsequently generated through uniform random sampling of a point X_{ij} within the jth sub-interval corresponding to the ith design variable, employing the Monte Carlo method:

$$X_{ij} = L_{ij} + (U_{ij} - L_{ij})\cdot\text{rand}. \tag{2}$$

After obtaining X_{ij}, which represents the elements of the design matrix, the elements X are randomly swapped within the rows to generate the final design matrix using the LHS method. Here, L_{ij} represents the lower bound of the jth sub-interval for design variables, while U_{ij} denotes the upper bound of the same sub-interval. The term rand refers to a random number sampled from a uniform distribution over the interval [0, 1].

2.4 Finite element analysis (FEA)

FEA is a powerful numerical technique widely used in engineering to simulate the physical behavior of structures and materials [34]. This approach involves dividing complex geometries into smaller, more manageable elements, which facilitates detailed analysis of behavior under various conditions. FEA has demonstrated effectiveness in predicting stress, strain, and deformation, providing engineers with critical insights into structural performance prior to the construction of physical prototypes. Moreover, this methodology is applicable across a diverse range of engineering disciplines, including mechanical, civil, aerospace, and biomedical engineering. When applying FEA to model the CWEC structure, it is essential to establish an appropriate mathematical framework. This framework is characterized by specific equations that depend on key model details, including material properties, geometry, and loading conditions. A simplified representation of the finite element formulation for the CWEC structure can be articulated through a general structural equation based on force equilibrium, particularly within the context of linear elastic analysis:

$$K \cdot U = F. \tag{3}$$

In this discussion, K (N/mm) is referred to as the stiffness matrix, U (mm) represents the displacement vector, and F (N) signifies the force vector. The stiffness matrix encompasses material properties, such as the modulus of elasticity (E), measured in MPa, and Poisson's ratio (υ), which are crucial for understanding how the material reacts under various loading scenarios. The constitutive matrix (D), also expressed in MPa, for isotropic, linear elastic materials is represented by the subsequent expression:

$$D = \frac{E}{(1+\upsilon)(1-2\upsilon)} = \begin{bmatrix} 1-\upsilon & \upsilon & \upsilon & 0 & 0 & 0 \\ \upsilon & 1-\upsilon & \upsilon & 0 & 0 & 0 \\ \upsilon & \upsilon & 1-\upsilon & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\upsilon}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\upsilon}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\upsilon}{2} \end{bmatrix}. \tag{4}$$

2.5 Verification of experimental results

To validate the simulation results, an experimental investigation of Poisson's ratio was conducted in accordance with the ASTM D3039 standard [38]. The experiment involved testing ten specimens, and the standard error was calculated to compare the experimental findings with the simulation data. For fiber-reinforced polymer composite materials, the determination of Poisson's ratio follows the ASTM D3039 standard, which outlines the procedures for assessing the tensile properties of reinforced polymer composites under controlled conditions. In this study, an Instron Electropulse E10000 (INSTRON Co., Ltd., High Wycombe, Bucks, UK) was used, equipped with a dynamic extensometer featuring a 12.5 mm gauge length, ±5 mm travel, and 0.01 mm accuracy. Poisson's ratio testing process comprised several steps. First, dog-bone-shaped test specimens were fabricated from the composite material according to specific dimensions and geometry. Second, strain gauges or extensometers were attached to the specimen in both axial (loading) and transverse directions to measure longitudinal and lateral strains during the tensile loading process. Next, the prepared specimen was mounted in a tensile testing machine and subjected to uniaxial tensile loading until failure, with load and strain data continuously recorded throughout. Finally, Poisson's ratio was determined by calculating the negative ratio of lateral strain to axial strain, focusing on the elastic region of the stress–strain curve.

3 Results and discussion

The CWEC specimen model was developed using PowerShape software to assess its mechanical properties through tensile testing. The specimen's dimensions, shown in Figure 4, were carefully predefined to ensure accurate evaluation of the material's behavior under tensile loading. These dimensions, along with the specific testing conditions, were intentionally designed to enable a precise analysis of the material's response to tension. Additionally, these parameters enhance the overall tensile testing process, allowing for a more comprehensive assessment of the CWEC's mechanical properties.

3.1 LHS modulus of elasticity and Poisson's ratio

The LHS method has gained widespread adoption in research due to its effectiveness and ease of

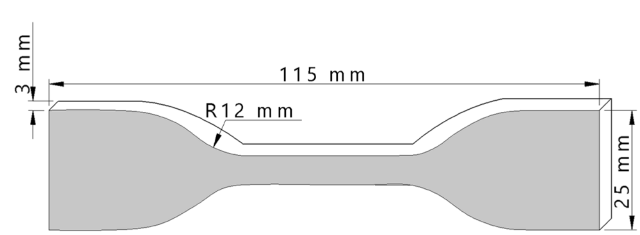

Figure 4: Dimensions of the CWEC specimen model used for FEA.

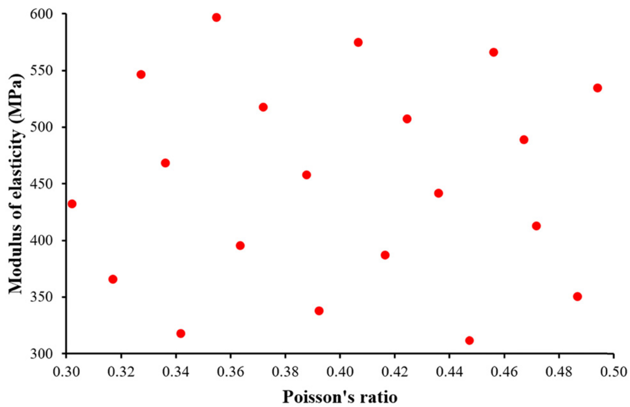

Figure 5: The findings obtained using the LHS technique, utilizing 20 pairs of input variables.

implementation. To support this approach, an experimental program was developed in MATLAB, allowing for the assignment of 20 distinct values to each design variable. The range for modulus of elasticity was set between 300 and 600 MPa, while Poisson's ratio was defined between 0.3 and 0.5. These values were derived from the deformation analysis of the tensile test conducted on CWEC, in conjunction with the findings reported by Gere and Goodno [16] and Chowdary *et al.* [17]. These values were subsequently analyzed using the FEA to calculate the deformation for the 20 models presented in Figure 5. In this figure, the modulus of elasticity is plotted on the vertical axis, and Poisson's ratio is plotted on the horizontal axis, offering a clear visual representation of the normal data distribution within the specified ranges. The randomization process employed in this study is based on a uniform data distribution.

The results obtained from incorporating the modulus of elasticity and Poisson's ratio parameters into the computation of 20 FEA models are presented in Table 1.

3.2 FEA simulation

The boundary conditions applied during the tensile testing of CWEC are critical for accurately capturing the material's mechanical behavior. At the fixed end of the specimen, displacement is constrained to zero, while at the moving end, the applied force is either controlled or measured, providing essential input load data for the tensile test. This configuration ensures that the test reliably reflects the actual mechanical response of the CWEC material. Figure 6 illustrates the boundary conditions employed in the simulation. The finite element mesh consists of 9,000 elements and 46,602 nodes. The element size in finite element models of specimens varies depending on the region

Table 1: Optimization results for determining the modulus of elasticity and Poisson's ratio using a surrogate model

Model	Modulus of elasticity (MPa)	Poisson's ratio	Validated RMSE Mean ± SEM	95% CI
Model 1	350.24	0.4870	0.8465 ± 0.0706	0.7867–0.9062
Model 2	387.00	0.4166	0.6563 ± 0.0824	0.6022–0.7103
Model 3	311.25	0.4473	1.1079 ± 0.0765	1.0232–1.1927
Model 4	546.41	0.3273	0.2257 ± 0.0741	0.2090–0.2424
Model 5	565.57	0.4564	0.2181 ± 0.0718	0.2024–0.2337
Model 6	365.26	0.3172	0.7682 ± 0.0776	0.7086–0.8279
Model 7	517.50	0.3720	0.2560 ± 0.0804	0.2354–0.2766
Model 8	457.50	0.3880	0.3897 ± 0.0694	0.3626–0.4167
Model 9	318.00	0.3420	1.0622 ± 0.0760	0.9815–1.1430
Model 10	574.91	0.4067	0.2181 ± 0.0734	0.2021–0.2341
Model 11	337.50	0.3926	0.9284 ± 0.0716	0.8619–0.9949
Model 12	441.66	0.4362	0.4381 ± 0.0699	0.4075–0.4687
Model 13	507.00	0.4246	0.2721 ± 0.0772	0.2511–0.2931
Model 14	412.50	0.4720	0.5435 ± 0.0786	0.5008–0.5862
Model 15	395.11	0.3637	0.6206 ± 0.0814	0.5701–0.6712
Model 16	432.00	0.3021	0.4742 ± 0.0801	0.4363–0.5122
Model 17	468.00	0.3362	0.3609 ± 0.0771	0.3331–0.3887
Model 18	534.43	0.4942	0.2340 ± 0.0688	0.2179–0.2501
Model 19	488.94	0.4674	0.3067 ± 0.0726	0.2845–0.3290
Model 20	596.47	0.3550	0.2250 ± 0.0784	0.2074–0.2426

SEM = standard error of mean; CI = confidence interval.

of interest. Accurate stress analysis in the gauge and fillet transition areas, where stress gradients peak, necessitates the use of fine mesh elements with edge lengths near 0.5 mm. Conversely, in less critical regions such as the grip sections, a coarser mesh with element edge lengths of 1.0 mm is generally sufficient. To ensure numerical accuracy and minimize distortion, it is essential to maintain an element aspect ratio close to unity. The use of a structured mesh with a gradual transition between fine and coarse regions is recommended to achieve an optimal balance between computational efficiency and solution fidelity. In particular, localized mesh refinement should be applied in the fillet regions, where geometric discontinuities can lead to elevated stress concentrations. Capturing these localized effects accurately is crucial for evaluating mechanical performance and predicting failure. To ensure the reliability of simulation results, mesh convergence studies should be systematically performed. This involves refining the mesh and monitoring the variation in stress or strain at key locations within the model. A variation of less than 3% between successive mesh refinements is accepted as an indicator of adequate mesh convergence and model stability.

FEA will be performed on each model, applying load values ranging from 10 to 300 N to calculate the corresponding elongation distances. The results from the elongation phase tests for each model will then be compared with data obtained from actual tensile test experiments. To validate the tensile test results for CWEC using FEA, the root mean square error (RMSE) will be used as a key statistical measure to evaluate how accurately the simulation represents the material's deformation behavior. RMSE quantifies the discrepancies between experimental data and simulated results by assessing the differences between observed and predicted values. A lower RMSE indicates a closer alignment between FEA predictions and experimental observations [39], suggesting that the simulation effectively reflects the real-world deformation behavior of CWEC under tensile loading, as illustrated in Figure 7. Calculating RMSE allows for the evaluation of agreement between experimental and simulated results. For example, a low RMSE value indicates that the FEA model successfully captures the deformation patterns observed in physical tests. Therefore, RMSE is a reliable metric for comparing deformation behavior in tensile testing with FEA predictions [39]. Minimizing RMSE is essential for validating the FEA model and ensuring its accuracy in representing the mechanical performance of CWEC under tensile stress [40]. This validation is critical for both material research and design applications. The minimum RMSE observed for Model 5 is 0.2181, as shown in Table 1, with corresponding modulus of elasticity and Poisson's ratio values of 565.57 MPa and 0.4564, respectively.

A total of ten specimens were employed in the experimental procedure. Given the limited sample size, the confidence interval (CI) for RMSE of CWEC was calculated using the *t*-distribution rather than the normal distribution due to the increased statistical uncertainty inherent in small datasets. For a 95% confidence level with a sample size of ten, the CI is computed using the following equation:

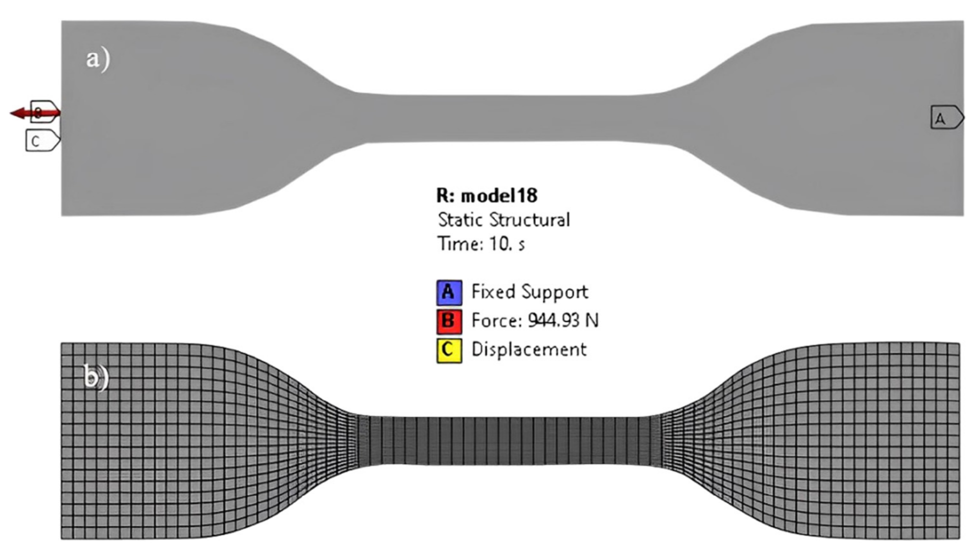

Figure 6: Boundary conditions applied in the analysis: (a) distributed load with a fixed support, and (b) meshing of the tensile model using the quadratic hexahedral element.

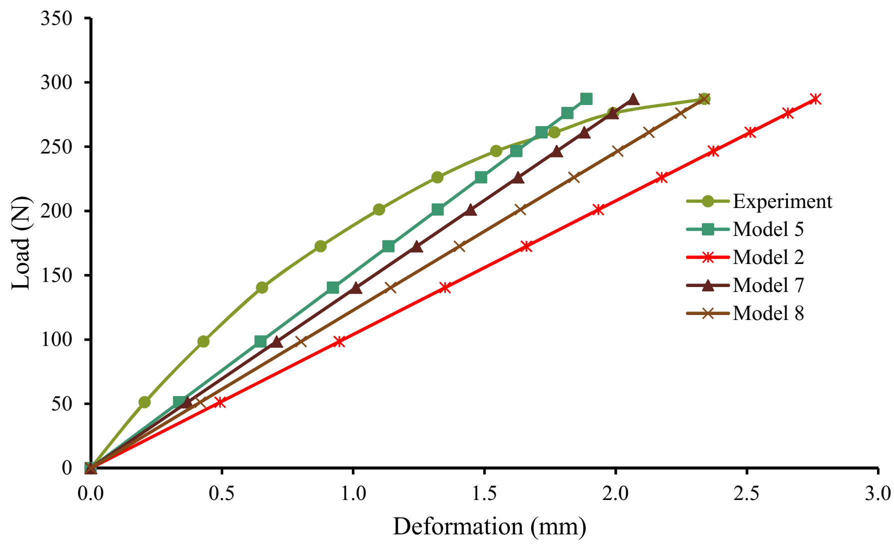

Figure 7: Deformation comparison between the results of the experiment and some simulation data.

$$\mathrm{CI} = \bar{X} \pm t_{\frac{\alpha}{2},n-1}\left(\frac{s}{\sqrt{n}}\right), \quad (5)$$

where $\bar{X}$ represents the sample mean, s is the sample standard deviation, n is the sample size, and $t_{\frac{\alpha}{2},n-1}$ is the critical t-value corresponding to the desired confidence level.

This approach is widely adopted in the analysis of composite materials due to its robustness in handling small sample sizes. The calculated CI values are presented in Table 1, with SEM ranging from 0.0694 to 0.0824. The relatively wide CI indicates a higher degree of uncertainty in the mechanical behavior of the material. This variability is

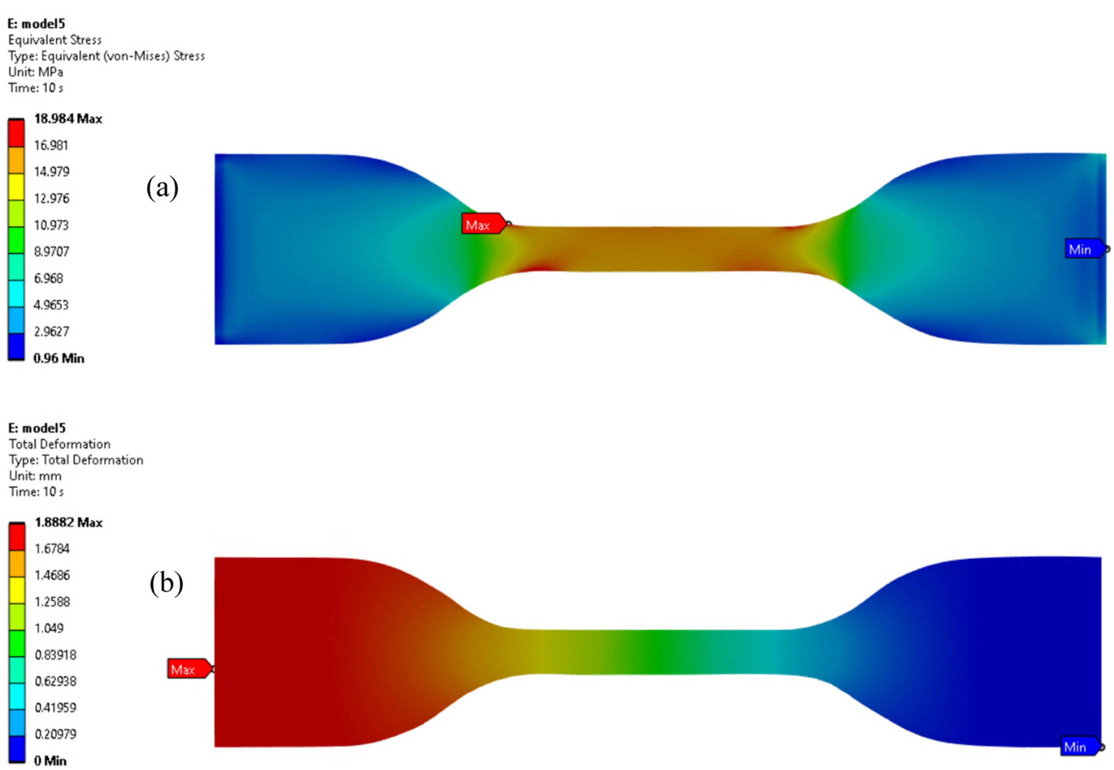

Figure 8: (a) Stress distribution and (b) deformation in CWEC subjected to load extension.

attributed to the natural heterogeneity of plant-based fibers, including variations in fiber diameter, cellulose content, and fiber–matrix interfacial bonding, which contribute to broader CIs compared to those observed in synthetic fiber composites [41–43].

The validation of numerical simulations was performed by comparing the simulation outcomes with the experimental results. Specifically, Poisson's ratio of CWEC was measured in both the numerical simulations and the experimental tests. The findings indicate a high degree of correlation between the two approaches, with a similarity of 94.21%, corresponding to an error margin of 5.79%.

FEA simulations are critical for understanding the mechanical behavior of CWEC during tensile testing. These simulations provide detailed insights into stress distribution, deformation patterns, and strain energy within the material. Several factors affect the accuracy of FEA results, including boundary conditions, material properties, geometric configuration, and the time-dependent behavior of the composite. By analyzing these variables, FEA reveals the formation of complex stress fields, especially in cases of significant deformation. Accurately modeling stress distribution is essential for predicting the mechanical performance of CWEC, identifying potential failure points, and optimizing designs that rely on its tensile properties. For example, as illustrated in Figure 8, the maximum recorded stress reached 18.98 MPa, while the peak observed deformation was 1.89 mm.

4 Conclusion

This study focuses on determining the modulus of elasticity and Poisson's ratio of CWEC using FEA, with validation achieved through comparative tensile testing. To improve the robustness and reliability of the validation process, 20 data pairs were generated utilizing the LHS method, allowing for a thorough exploration of the parameter space. The validation process involved systematically comparing the simulated deformations to empirical test results, employing RMSE as the primary measure of accuracy. The analysis yields the following conclusions:

1. The observed RMSE of 0.2181 demonstrates a strong agreement between the FEA model and experimental observations, thereby confirming the reliability of the identified values for the modulus of elasticity (565.57 MPa) and Poisson's ratio (0.4564).
2. The validation of Poisson's ratio for CWEC was accomplished by comparing simulation outcomes with experimental data. The results indicate a high degree of correlation between the two approaches, with a similarity of 94.21%, corresponding to an error percentage of 5.79%.

5 Future work

Building upon the promising outcomes of the present study, future research should extend the proposed methodology to a wider range of natural fiber and waste-derived composite materials to evaluate its generalizability. Further investigations into the influence of fiber content, orientation, and matrix composition on Poisson's ratio and the modulus of elasticity are warranted to gain a more comprehensive understanding of the mechanical behavior of such composites. Moreover, the simulation framework may be refined by incorporating dynamic loading scenarios, environmental factors (*e.g.*, temperature and humidity), and long-term degradation effects to improve its predictive accuracy. The integration of machine learning algorithms with FEA for real-time parameter optimization also represents a promising direction for advancing the design and performance prediction of composite materials.

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Author contributions: All authors have accepted responsibility for the entire content of this manuscript and consented to its submission to the journal, reviewed all the results and approved the final version of the manuscript. Sutha Loidueanchai took the lead in conceptualizing and designing the study, as well as in collecting, analyzing, and interpreting the data. Apichart Artnaseaw provided supervision, secured funding, and played a key role in drafting the manuscript. Furthermore, Apichart Artnaseaw offered

critical feedback to ensure the manuscript's accuracy, coherence, and compliance with scholarly standards. Achira Artnaseaw provided essential guidance throughout the research process, contributing significantly to refining the research questions, developing the methodology, and interpreting the findings.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: The datasets generated and/or analyzed during the course of this study are available from the corresponding author upon reasonable request.

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