Mechanical and Thermal Behavior Analysis of Chicken Feather/*Sesbania grandiflora* Fibers-based Hybrid Epoxy Composites

Shankar Kannan Paramasivam,[a,]* Muthukannan Marimuthu,[a] Arun Sakthivel,[b] Janani Rajasekar,[c] Sivasubramanian Palanisamy,[d] Kuwar Mausam,[e] Aravindhan Alagarsamy,[f] Quanjin Ma,[g] and Saleh A Al-Farraj [h]

The mechanical and thermal properties of epoxy hybrid composites reinforced with natural fibers were studied, addressing the growing demand for eco-friendly materials. Fibers from chicken feathers (CF) and *Sesbania grandiflora* (SG) were used together with epoxy resin in composites, which were fabricated using the compression molding technique. Both the CF and SG fiber ratios ranged from 1:2 to 2:1, while fiber-to-resin weight proportions were set at 30:70 and 40:60. The composites were evaluated for mechanical and thermal characteristics in adherence to ASTM standards, with thermal properties assessed using thermogravimetric analysis (TGA). Surface morphology was examined using scanning electron microscopy (SEM). Process parameters were optimized using mathematical modeling, employing Analysis of Variance (ANOVA) and Response Surface Methodology (RSM). The hybrid composite with a 30:70 fiber/matrix ratio and a 2:1 CF/SG fiber combination demonstrated superior mechanical and thermal properties while showing reduced water absorption. A 30% fiber loading with a 2:1 CF/SG fiber ratio considerably enhanced the composite's overall performance. The optimal blending ratio for hybrid composites was a 2:1 weight proportion of CF to SG fibers, offering a promising approach to developing sustainable materials with improved characteristics. This research highlights the potential of natural fibers in creating environmentally friendly composites.

DOI: 10.15376/biores.20.4.8591-8610

Keywords: Chicken feather; Hybrid composite; Natural fibers; Mathematical modeling; Mechanical properties; Resin; SEM; Sesbania grandiflora

Contact information: a: Department of Mechanical Engineering, SSM Institute of Engineering and Technology, Dindigul-624002, Tamil Nadu, India; b: Department of Thermal Engineering, SSM Institute of Engineering and Technology, Dindigul-624002, Tamil Nadu, India; c: Department of Mathematics, SSM Institute of Engineering and Technology, Dindigul-624002, Tamil Nadu, India; d: Department of Mechanical Engineering, PTR College of Engineering and Technology, Austinpatti, Madurai – Tirumangalam Road, Madurai - 625008, Tamil Nadu, India; e: Department of Mechanical Engineering, GLA University, Mathura, India; f: Department of Electronics and Communication Engineering, Koneru Lakshmaiah Education Foundation Vaddeswaram, Guntur District - 522 302 Andhra Pradesh, India; g: School of Automation and Intelligent Manufacturing, Southern University of Science and Technology, Shenzhen 518055, China; h: Department of Zoology, College of Science, King Saud University, P.O. Box 2455, Riyadh, Saudi Arabia;
** Corresponding author: sankar7862@gmail.com*

INTRODUCTION

Reducing the use of products made from petroleum and developing biomass-based goods from environmentally friendly and renewable resources are of vital importance and gaining popularity worldwide. In all developing countries, numerous such initiatives are being undertaken and implemented. Such efforts are required to meet fundamental demands of the upcoming generation in terms of nourishment, clothing, pharmaceuticals, transportation, cosmetics, and materials (Robertson 2005; Ilyas *et al.* 2021). Utilizing byproducts of agriculture and supplementary products as a substitute in commercial uses has become more popular recently, mainly because of the scarcity of petroleum-based products. These products are made from renewable materials that are both affordable and less damaging to the environment, and they can be used to produce bio-based goods (Baiano 2014; Subagyo *et al.* 2023). The valorization of scrap and byproducts of the production process is being encouraged by laws worldwide. This waste may be valorized by extracting key components, such as amino acids, polymers, favor mixtures, and chemical compounds, which may then be employed again in the pharmaceutical, textiles, beauty products, nourishment, and composite materials multifunctional businesses (Ambrose and Clanton 2004).

Composite materials are developed by integrating several elements with radically different chemical and mechanical characteristics with the purpose of executing a function that neither of the individual components alone could do effectively. Modern society relies heavily on composite materials because relatively few materials can be utilized in their natural, unaltered condition (Alvarez-Vera *et al.* 2022; Kar *et al.* 2023; Muthukannan *et al.* 2023). The composite materials made from organic fiber-reinforced polymers are inexpensive, readily accessible, reusable, and they possess an excellent specific strength and rigidity. The components made form waste poultry feathers are potentially useful as reinforcement elements in polymeric composite materials, although few studies have attempted to explore feather fibers for bio-based composite materials applications (Khosa *et al.* 2013; Gokul *et al.* 2024; Miriţoiu 2024). Keratin fiber has the potential to serve as a substitute for synthesized reinforcement compounds in this area. The improper handling of waste poultry chicken feathers is an impact of the release of greenhouse gases from waste materials applied in the slaughtering industry, which deteriorate the ecosystem. Producing composite materials from polymers can contribute to their value. Keratin is resistant to degradation because of its strong binding forces and substantial cross linking across the molecules. (Barone and Schmidt 2005; Cheng *et al.* 2009; Gogoi *et al.* 2019; Sumesh *et al.* 2024). No fibers, synthetic or natural, can match the morphology and characteristics of chicken feathers. Feather barbs are special fibers due to their relatively low density, exceptional softness and resilience, thermal persistence, and unusual geometric form (Karthik *et al.* 2024). The overall weight of chicken feathers is higher than that of any commonly accessible synthetic or natural material. For a variety of purposes, chicken feathers are preferred due to their special qualities. Aside from their distinct composition and characteristics, chicken feathers are inexpensive, widely accessible, and a sustainable source of protein fibers (Kiew *et al.* 2013; Reddy and Yang 2007; Anjumol *et al.* 2023).

The commonly accessible Indian herbal remedy *Sesbania grandiflora*, also referred by the name agathi, is a member of the plant family Fabaceae. All portions of *Sesbania grandiflora* act like plant-based antioxidants, giving it special therapeutic qualities (Savitha *et al.* 2019). According to research experiments conducted by

Venkatesan *et al.* (2022), *Sesbania grandiflora* fiber has a greater α-cellulose quantity along with a smaller proportion of hemicellulose, lignin, and wax material, making it a viable reinforcement alternative for the polymer matrix in composite materials.

The findings of Carrillo *et al.* (2013) demonstrated that adding chicken feathers to thermoplastic layer causes a slight improvement in stiffness when only a small proportion of the feathers have been included to the composite materials. As the volume of chicken feathers was increased, the breaking strength at the highest loading, deformation at break, and resilience qualities dropped. A number of different types of fiber are combined in a single matrix to develop hybrid composites, which are being given more attention in an attempt to enhance physical properties. Compared to composites made of a single type of fiber, these exhibit a number of positive effects (Carrillo *et al.* 2013; Savitha *et al.* 2019; Venkatesan *et al.* 2022). The majority of the research was conducted using a combination of artificial and organic fibers. The behavior of hybridized composite materials is the summation of the individual parts, where the benefits and drawbacks of the constituents utilized in the composite material appear more favorably balanced (Sreekala *et al.* 2002; Venkateshwaran *et al.* 2012; Athith *et al.* 2018; Jose *et al.* 2023; Palaniappan *et al.* 2024). The characteristics of the fiber-matrix interface, the quantity, type, and orientation of the fibers contained in the composite materials, as well as the manufacturing method, all influence the behaviors of hybrid composite materials (Idicula *et al.* 2010; Jawaid *et al.* 2011; Aruchamy *et al.* 2023).

According to earlier research studies, using CF fiber alone to develop composite material would not be feasible because the physical attributes of the final composite material would deteriorate as its weight percentage increased from 10 to 15% (Dittenber and GangaRao 2012; Prasanth *et al.* 2021; Gogoi *et al.* 2022). The addition of SG fiber with CF reinforced composite is expected to enhance the mechanical and thermal characteristics of hybrid composite because it has higher cellulose content, better mechanical qualities, and better water absorption capabilities than okra, *Prosopisjuliflora*, sisal, bamboo, kenaf, coconut, and other natural fibers (Savitha *et al.* 2019; Venkatesan *et al.* 2022). The intended purpose of this study was to determine the ideal combinations (in weight %) of CF and SG fibers to enhance the properties of final hybrid composite materials so to identify uses for non-toxic, cost-effective, and sustainable materials for constructional components and other common household products for which thermal and mechanical characteristics are essential.

EXPERIMENTAL

Collection, Preparation, and Chemical Pretreatment of Fibers

The required quantity of chicken feathers was obtained from a local city market of Dindigul district (Tamilnadu, India). Collected chicken feathers were sorted out, washed, and dried in the sun for 10 days and then trimmed to the required size as shown in Fig.1 (b). For the chemical treatment of chicken feather fibers in the present study, a solution containing 0.1 M sodium hydroxide was applied. This process was performed in an agitated water bath at 50 ºC for a few hours. Then the material was washed with water to achieve normal conditions. Finally, the chemically treated chicken feather fiber was dried in sunlight (Álvarez-del-Castillo *et al.* 2022; Gogoi *et al.* 2022).

The plants were dehydrated and preserved to acquire the fibers from the stalk of SG. For the tank retting, the dried-out stalks of SG were chopped to a small size, as reported by Singh and Rani (2013) and wrapped into tiny bunches. The bunches of the stalk were removed away from the corresponding containers after the retting period (15 days) was over. After that, the fibers extracted from the stalks of SG were manually separated, soaked in 0.1 M sodium hydroxide solution for 48 h, washed with normal water several times, and allowed to air dry on a level area, as represented in Fig. 1 (A through F) (Singh and Rani 2013; Gogoi *et al.* 2022).

Fig. 1. Preparation of *Sesbania gradiflora* fiber and chicken feather fiber: A. Raw plant; B. Stem separation; C. Fiber extraction; D. Fiber for composite after drying and treatment; E. Raw chicken feathers after cleaning and drying; F. Chicken feathers after chemical treatment

Fiber Characteristics

More than 80% of chicken feathers are composed of keratin, a scleroprotein category that is incredibly resistant to chemical, biological, and structural perturbations. Because keratin contains disulfide bonds, bonding of hydrogen, salt links, and cross-links, it is mechanically stable and highly resistant to proteolytic destruction (Misra and Kar 2003; Sun *et al.* 2022). In essence, a chicken feather is made up of certain β-sheet and α-helical configurations. Its outermost twigs are composed of a small number of α-helical configurations and nearly all β-sheet configurations (Tesfaye *et al.* 2017).

Disulfide (S-S) bonds, which connect neighboring keratin proteins, are significantly more prevalent in rigid β-sheet keratins due to the larger cysteine composition than softer α-helix keratins. Multidimensional protein structures are stabilized by their content of robust disulfide connections, which are extremely challenging to destroy (Santhosh *et al.* 2024; Saravanan and Dhurai 2012). The chemical, mechanical and thermal properties of both chicken feather fibers and SG fibers used in the present research work are presented in Tables 1 and 2. Cellulose, the primary component of structural stability, strength and stiffness, is more abundant in SG fiber. This fiber has a higher level of lignin than other organic fibers, and the presence of this ingredient is regarded to be contributing factor of its rigidity.

Table 1. Chemical Composition of Fibers (Tan *et al.* 2017; Sobucki *et al.* 2019)

Parameters	Chicken Feather (%)	*Sesbania grandiflora* (%)
Cellulose	-	72.75
Crude keratin protein	82.36	-
Hemicellulose	-	8.01
Crude lipid	0.83	-
Lignin	-	15.91
Ash	1.49	1.52
Moisture	12.33	4.58
Wax	-	0.17
Crystallinity Index	20.55	69.11

Table 2. Mechanical and Thermal Properties of Fibers (Tan *et al.* 2017; Sobucki *et al.* 2019; Sah *et al.* 2021)

Parameters	Chicken Feather	*Sesbania grandiflora*
Tensile strength (MPa)	220	439
Young modulus (GPa)	3.96	42.83
Elongation at break (%)	7	21.24
Maximum thermal stability (°C)	250 to 350	375

Hybrid Composite Development

The physical laying-up approach and compression molding operation were employed for developing hybrid composite materials in the present investigation. The LY556 Epoxy resin (density of 1.1 g/cm^3 and viscosity 12,000 to 13,000 cP) to hardening agent (HY951) ratio of 10:1 was applied to produce the matrix in tandem with the approach suggested by Dev *et al.* (2025). Table 3 provides a clearer representation of the experimental design details depending on the fibers (CF and SG) and matrix formulation (resin and hardening agent).

Table 3. Experimental Design Based on Composition of Matrix and Fibers (Based on Weight %)

Sample Code	Matrix (%)	Matrix Composition (%)		Fiber (%)	Fiber Composition (%)		Size of the Laminate (in mm^3)
		Resin	Hardener		CF	SG	
1EX/CF1/SG2	70	90	10	30	10	20	290 × 290 × 3
1EX/CF2/SG2	70			30	15	15	
1EX/CF2/SG1	70			30	20	10	
2EX/CF1/SG2	60			40	10	30	
2EX/CF2/SG2	60			40	20	20	
2EX/CF2/SG1	60			40	10	30	

As shown in Fig. 2, for maintaining the hybrid composite materials as dense as possible, the fibers (CF and SG) were distributed in a random manner in the bottom mould inside an enclosure. Once the necessary layers were laid, matrix materials (resin and hardener) were poured across the layers, and the head portion of mould was sealed. For aiding in the course of curing, a temperature 140 °C and a pressure of 35 MPa were maintained for 3 h (Senthil Kumar *et al.* 2024). To assess the mechanical and thermal behavior, specimens were subsequently prepared using the fabricated composite laminates.

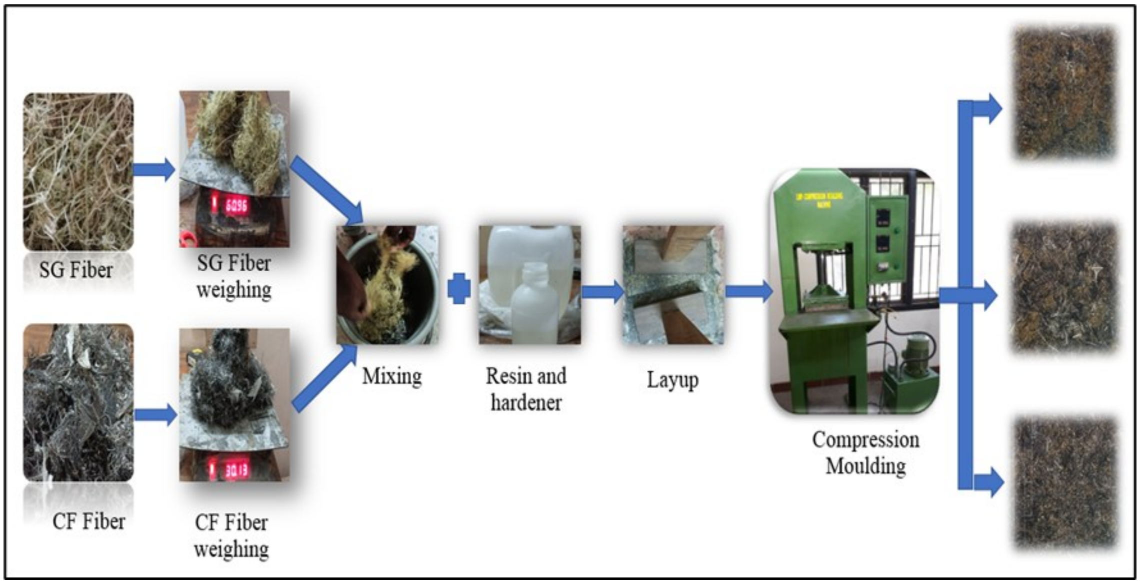

Fig. 2. Fabrication of hybrid composite

Characterization of Hybrid Composite- Mechanical Characteristics

The tensile strength and flexural strength of the hybrid composite samples 1EX/CF1/SG2, 1EX/CF2/SG2, 1EX/CF2/SG1, 2EX/CF1/SG2, 2EX/CF2/SG2, and 2EX/CF2/SG1 were evaluated by following the ASTM D638-14 (2022) and ASTM D790 (2017) standards, respectively, using a Kalpak computerized universal testing machine (Model: KIC-2-1000-C, Capacity: 100 kN). The impact strength was assessed in accordance with ASTM D256 (2023) standard in impact testing equipment (Model: QPI-IC-21 J). The interlaminar shear strength of all fabricated composite laminates was determined as per the ASTM D2344 (2022) standard. The hardness of all samples was determined by following ASTM D2240 (2021) standard using a Durometer (Model: RR12).

Thermogravimetric Analysis

The thermogravimetric analyzer (Model: TGA 55, TA Instruments, New Castle, DE, USA) was employed to assess the thermal character of the fabricated hybrid composite laminates in accordance with the concept described by Rafi *et al.*(2024). The heat rate during analysis was 20ºC/min from 20 to 950 ºC in nitrogen atmosphere having mass flow rate 30 mL/min.

Water Absorption Study

Following the ASTM D570 (2022) guideline, as in the earlier investigations (Rafi *et al.* 2024; Chowdhury *et al.* 2025), samples were prepared for the water absorption experiment. After the composites were cut into samples measuring 62 x 62 x 1.8 mm^3, they were prepared to dry. Water absorption was measured by weighing the samples on a weighing machine before and after soaking them in water for a set duration. To assess the amount of water absorption, each specimen's mass was calculated using the ASTM D570 (2022) guideline prior to its immersion in distilled water. The percentage of water absorbed by hybrid composite was calculated using Eq. 1,

$$W_A = [(W_w - W_d) \div W_d] \times 100 \quad (1)$$

where W_A is the water absorbed by specimen (%), W_w is the weight of specimen after immersion in water (g), and W_d is the weight of specimen before immersion in water (g).

Surface Morphology

The surface morphology of the fiber samples was examined using a high-resolution TESCAN Scanning Electron Microscope (TESCAN ORSAY HOLDING, Brno, South Moravian Region, Czech Republic). Imaging was conducted at an accelerating voltage of 10 kV and a working distance of 10 to 15 mm. SEM images were taken at different magnifications to closely observe the fiber structure and surface characteristics.

Statistical Analysis

An analysis of variance (ANOVA) was employed to analyze each response variables, and a regression test was performed to validate the framework and determine the statistical value of the coefficient.

RESULTS AND DISCUSSION

Effect of Process Parameters on Mechanical Characteristics

Figure 3 illustrates the tensile, flexural, impact, and interlaminar shear strengths of hybrid composite materials developed using CF/SG fibers. It is evident that their mechanical characteristics were enhanced by the integration of CF/SG fibers. In comparison to the hybrid composite with 40% fiber loading, the composite with 30% fiber loading performed better in every mechanical property. The tensile, flexural, impact and shear properties of 30% fiber loaded hybrid composite shows an increasing trend with respect to quantity of CF fiber as shown in Fig. 3a, 3b, 3c, and 3d, respectively, and the 2:1 (CF/SG) combination hybrid composite yielded the greatest tensile strength of 12.194 MPa, maximum flexural strength of 101.76 MPa, highest impact energy of 0.3 J, and optimum interlaminar shear strength of 9.1 MPa. The stress strain diagram of well performed sample is represented in Fig. 4

The greatest tensile and flexural strengths achieved in the present research were 31.4% and 80.1% higher than the tensile and flexural property values of chicken feather fibers reinforced composites (Prasanth *et al.* 2021). Even though the highest tensile strength of CF/Betel Nut fibers-based hybrid composite was 42.6% more than the maximum tensile strength found in the present research, the highest flexural property value attained in this study was 36.5% higher than those found in CF/Betel nut fiber-based hybrid composite (Gogoi *et al.* 2022). The maximum flexural property value obtained in this study was 51.6% greater than those found out in banana/coir natural fiber-based hybrid composite, despite the fact that the tensile strength of the hybrid composite based on banana/coir natural fibers was 29.2% higher than the maximum tensile strength observed in the present investigation (Senthil Kumar *et al.* 2024). Even though the chemically modified CF fiber reinforced high density polyethylene composite's maximum tensile strength was 61.1% greater than the highest tensile strength obtained in this investigation, the flexural strength achieved in this study was

84.1% greater than those attained in the chemically modified CF fiber reinforced high-density polyethylene composite (Oladele *et al.* 2018).

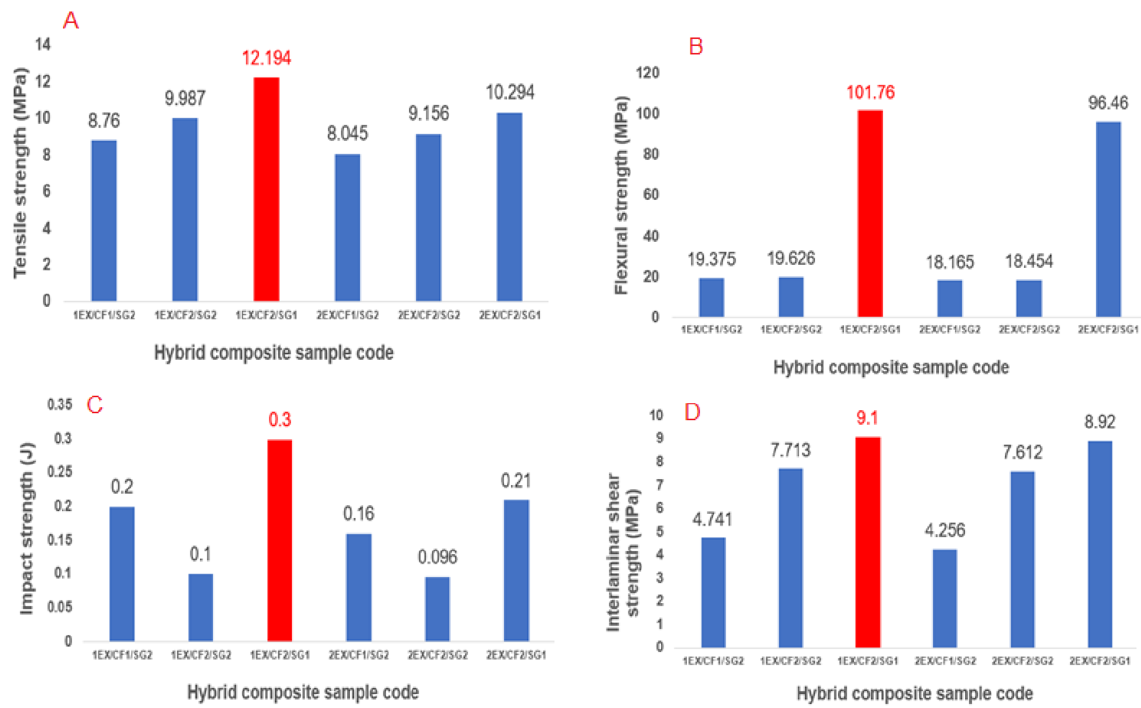

Fig. 3. Effect on mechanical properties (a. Tensile strength, b. Flexural strength, c. Impact energy, and d. Interlaminar shear strength) in changing process variables

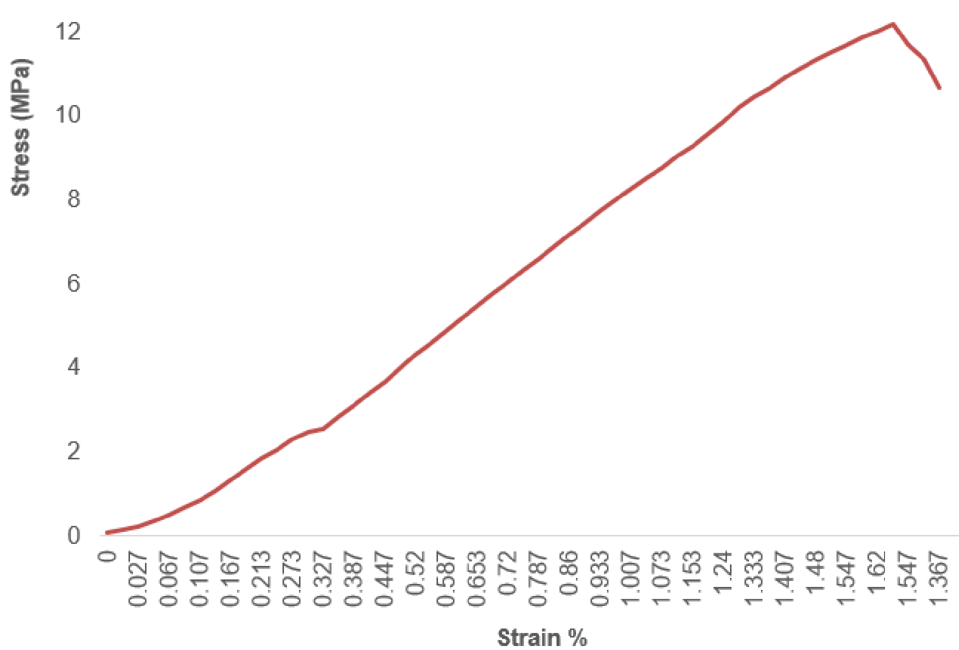

Fig. 4. Stress-strain curve of hybrid composite

The composite comprising of 2:1 (CF/SG) fiber combination (30% fiber loading) had the highest average impact strength, assessing 0.3 J. The type of fiber, matrix, and their adherence all exhibited significant effects on the impact strength (Chowdhury *et al.* 2025). As fiber loading rises, the composite might become equipped to withstand higher energy levels due to improved and stronger adhesion between the fiber and matrix. Thus, it is evident that the impact strength had been enhanced. Employing a shore D hardness testing machine, the hardness character of the manufactured composite specimens was examined, and three points were selected on the sample for conducting the test measurements. The maximum average hardness of 82 shore D scale was attained with the hybrid composite having 1:1 (CF/SG) fiber combination in 30% fiber loading. The tendency of a material to modify its shape over stress is represented by its hardness, which is based on the arrangement of fibers in the matrix. The present experiment found that hardness increased up to 30 wt% of fiber loading, as represented in Table 4; however, as fiber loading increased, the hardness property slightly decreased. The existence of voids identified *via* SEM image evaluation in Fig. 7 could be the reason for this behavior.

Table 4. Shore D Hardness

Sample No.	Shore D Hardness
1EX/CF1/SG2	73
1EX/CF2/SG2	82
1EX/CF2/SG1	74
2EX/CF1/SG2	74
2EX/CF2/SG2	76
2EX/CF2/SG1	79

For the establishment of hybrid composites based on natural fibers that have superior rigidity and strength, a minimal weight percentage is preferable. The results indicated that employing 30 wt% fiber content was the most efficient way to increase tensile property. The clumps of fiber inside the matrix without adequate bonding between those fibers may be the source of the poor interfacial bonding that is likely to occur from a high level of fiber application. The fiber-matrix interface, which is determined by the fiber’s surface topography, resin characteristics, and chemical reliability, has a significant impact on the overall performance of any fiber-reinforced polymer composite (Gogoi *et al.* 2022). Numerous studies have shown that flexural property decreases as fiber loading increases (Uzun *et al.* 2011; Tesfaye *et al.* 2017). Low interfacial strength, poor fiber distribution in the matrix, and increased fiber–fiber engagement were the reasons given for this phenomenon, which led to a decrease in load-transferring performance as fiber loading increased (Uzun *et al.* 2011; Choudhry and Pandey 2012; Reddy *et al.* 2014).

Thermogravimetric Analysis

The TGA test was performed to determine the deterioration properties of CF- and SG- based composites (for samples 1EX/CF1/SG2, 1EX/CF2/SG2, and 1EX/CF2/SG1). The material’s stable thermal behavior can be assessed by the weight drop across a specified temperature band (23 °C to 930 °C), which is measured as a percentage of the specimen’s weight loss when heated. The results of TGA of CF- and SG-based composites are presented in Table 5 and the best performed sample’s TGA graph is represented in Fig. 5. The disappearance of moist matter was the reason for the samples' initial loss of weight in the temperature range of 23 to roughly 150 °C. The reduction in weight between 250 to 450 °C was caused by the breakage of disulfide bonds and the removal of hydrogen sulfide from cysteine present in CF fiber, while deterioration above 450 °C was attributed to keratin breakdown (Gogoi *et al.* 2019).

For SG fiber, the weight loss was due to deterioration and decomposition of cellulose, hemicellulose, and lignin contents (Rafi *et al.* 2024). The sample 1EX/CF2/SG1 hybrid composite performed the best out of all the composites, and the initial decomposition temperature demonstrated a rising pattern as the CF fiber percentage of hybrid composite increases. This could be due to the hybrid composite's stronger network configuration connecting the functionalities of the resin, SG fiber, and CF fiber. The TGA results of the present research are consistent with the thermal stability behavior of chicken feather/betel nut fibers-based hybrid composite and oil palm/sugarcane bagasse fibers-based hybrid composite, as reported by Gogoi *et al.*(2022) and Ramlee *et al.*(2021), respectively.

Table 5. Thermograms of Hybrid Composites

<table>
<tr><th rowspan="2">Sample Code</th><th rowspan="2">Initial Decomposition Temperature (T_i)</th><th colspan="2">Maximum Pyrolysis Temperature (Tm)</th><th colspan="4">Decomposition Temperature (Td) at Different Weight % Loss</th><th rowspan="2">Residual Weight % at 930°C</th></tr>
<tr><th>1st step</th><th>2nd step</th><th>20</th><th>40</th><th>60</th><th>80</th></tr>
<tr><td>1EX/CF1/SG2</td><td>140</td><td>360</td><td>450</td><td>318</td><td>361</td><td>393</td><td>525</td><td>10.81</td></tr>
<tr><td>1EX/CF2/SG2</td><td>223</td><td>320</td><td>410</td><td>350</td><td>382</td><td>405</td><td>442</td><td>14.39</td></tr>
<tr><td>1EX/CF2/SG1</td><td>232</td><td>360</td><td>430</td><td>347</td><td>374</td><td>394</td><td>428</td><td>10.60</td></tr>
</table>

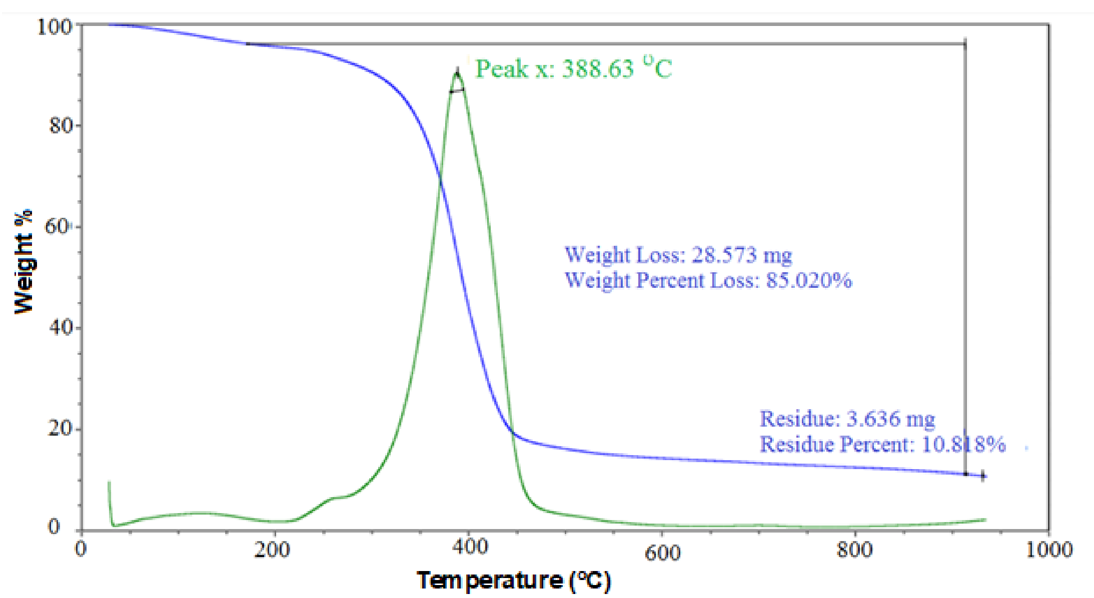

Fig. 5.TGA curve of hybrid composite

Effect on Water Absorption Characteristics

The water absorption properties of fabricated hybrid composite materials comprised of 2:1, 1:1, and 1:2 (CF/SG) fiber ratios in 30% and 40% fiber loadings were studied for 24 h, and their values are illustrated Fig. 6. The 24-hour water absorption test period was chosen since the literature and preliminary results showed that the materials approach saturation equilibrium during this time and had little additional uptake after that. This period of time is in line with established testing procedures (such as ASTM D570) and concentrates on the key preliminary absorption behaviour, which is most important for evaluating performance in the short term. The hydroxyl molecules and micro voids presence in the fibers ingest an additional quantity of water as the duration of their contact to water increases. The CF and SG fibers-based hybrid composite materials with the highest fiber loading (40 wt%) exhibited the highest level of hydroxyl groups, since they absorbed additional water during an extended contact time. Both the amount of cellulose and the quantity of hydrogen bonds that exist among the fibers and water molecules expand with increased fiber loading (Rafi *et al.* 2024; Savitha *et al.* 2019).

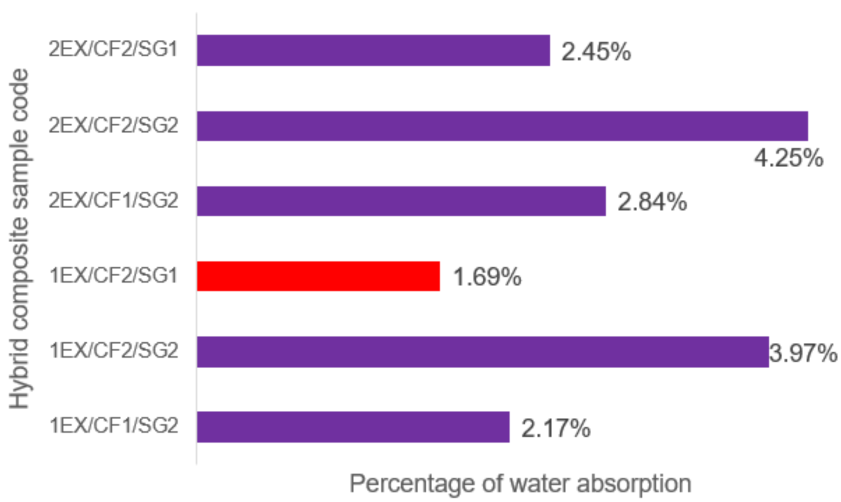

Fig. 6. Effect on water absorption

Surface Morphological Properties

Improved adhesion at the fiber-matrix interface is demonstrated by the surface features of the broken-down sample in Fig. 7. Evidence of pull-out *vs.* breakage indicated that improved adhesion had been achieved when using the ideal process variable set. The technique of fiber agglomeration may be applied to identify regions of stress in the framework caused by fiber reinforcement flaws. Although an incorrect distribution of the fiber loading might lead to the development of stress level changes, dense clustering improves fiber connections. The ability of fibers to transmit loads may be hampered by interfacial contacting. However, matrix fracture or fiber cluster stress affects how load is transferred. Fiber pullout and stretch are minimal because the natural fibers and epoxy matrix have formed good physical contact. This is also evident from fiber breaking, which indicates that the fibers' capacity to separate from the matrix is diminished. This improved the matrix's ability to effectively transmit the stresses to the CF and SG fibers.

The hybrid epoxy composites' mechanical properties were shown to be improved in comparison because of enhanced stress transmission under these conditions.

Furthermore, because the hybrid fibers were evenly distributed throughout the epoxy matrix, alternative causes of failure, such as cracking in the matrix, were barely noticed. The epoxy matrix and chemically treated CF and SG fibers worked in concert to improve the hybrid composites' interfacial reliability, which increased their mechanical property. This resulted from the natural fibers being treated with alkali, which formed rough fiber surfaces. A similar finding has been noted by numerous past researches (Balaji *et al.* 2019; Senthil Kumar *et al.* 2024; Sharath *et al.* 2024). In order to best resolve specific microstructural aspects pertinent to the investigation (such as morphology and porosity), several SEM magnifications were selectively used. In accordance with typical SEM procedures and the objective of the research, greater magnifications captured precise information, while lower magnifications offered contextual examines. Scale bars are included in every image to ensure appropriate comprehension.

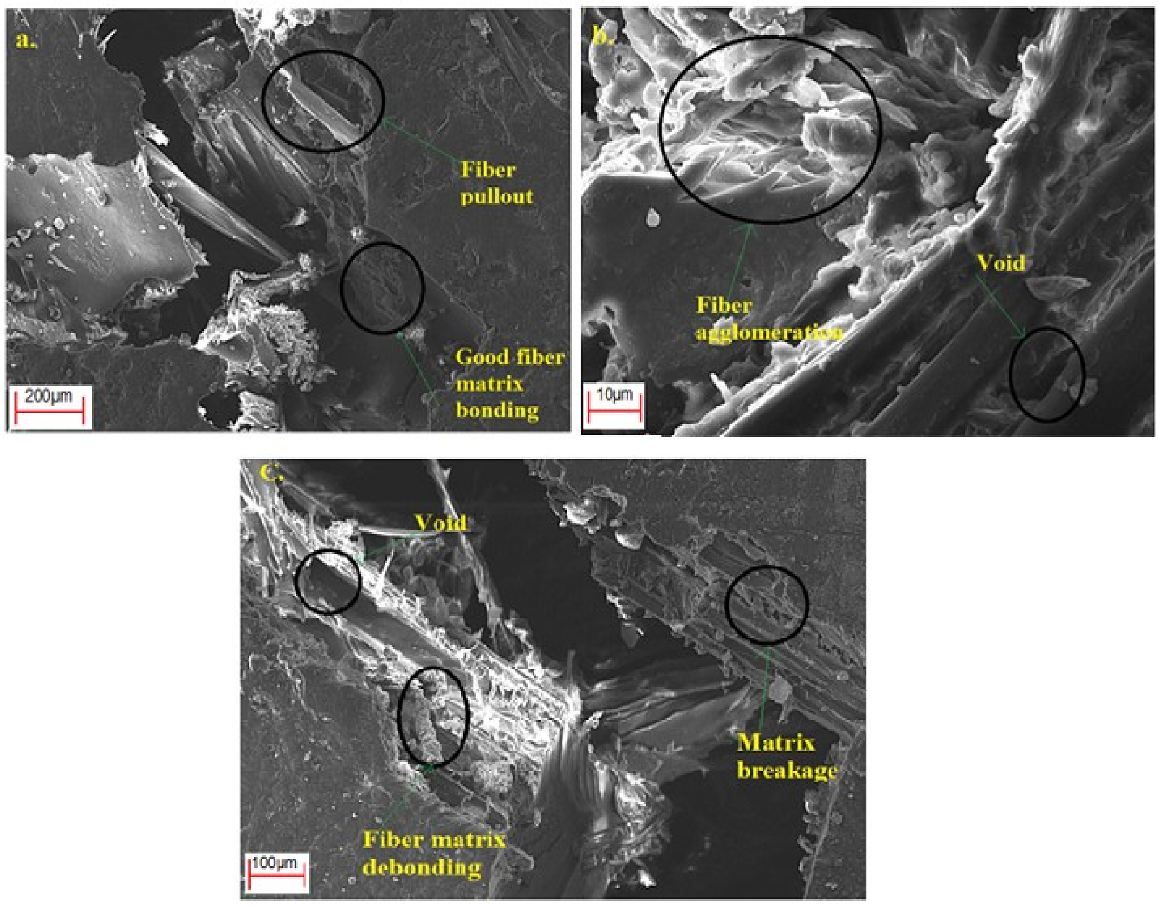

Fig. 7. SEM images of 1EX/CF2/SG1 hybrid composite

Responses Analysis and Confirmation of Experiments

A statistical method commonly used to ascertain the relevance of several variables on a dependent variable is the assessment of variance. Tables 6 and 7 display the results of the ANOVA performed using the mechanical features. P-values, with a 0.05 confidence level, indicate the statistically significant nature of the process variable under consideration. The findings showed that with the exception of fiber proportion for flexural strength, all process variables had P-values less than 0.05, indicating their significance in comparison to the response under consideration. Therefore, the factor having a significant overall effect was fiber concentration. Both the type and fraction of fibers employed were found to have a significant effect on the mechanical characteristics of the hybrid composite.

Table 6. ANOVA of Flexural Test Outcomes

Source	Degrees of Freedom (DOF)	Sum of Squares (SS)	Mean of Squares (MS)	F-value	P-value
Regression	2	7638.5	3841.73	12.68	0.034
A	1	9.84	9.84	0.03	0.869
B	1	7673.62	7673.62	25.32	0.015
Error	3	909.20	303.07		
Total	5	8592.66			

Table 7. ANOVA of Tensile Test Outcomes

Source	Degrees of Freedom (DOF)	Sum of Squares (SS)	Mean of Squares (MS)	F-value	P-value
Regression	2	10.0745	5.0373	30.84	0.01
A	1	1.9792	1.9792	12.12	0.040
B	1	8.0954	8.0954	49.56	0.006
Error	3	0.4900	0.1633		
Total	5	10.5645			

The ANOVA operator R^2 and adjusted R^2 values are listed in Table 8. The R^2 values can be used to evaluate the established RSM model's estimation ability. The capacity of the model for predicting the responses is greater if its magnitude is nearer to unity. As a result, all the outcomes' R^2 and adjusted R^2 values were seen to be nearer to unity, indicating the established RSM regression model's ability to predict responses despite the process factors taken into consideration.

Table 8. R^2 and Adjusted R^2 of Formulated Model

Response	R^2	Adjusted R^2
Flexural strength	0.8942	0.8236
Tensile strength	0.9536	0.9227

A regression model was established for predicting the outcomes of the study based on RSM. The regression model for flexural strength (FS) and tensile strength (TS) is shown in Eqs. 2 and 3, respectively. Both the equations made a substantial contribution to the process variables prediction based on values of Tables 6 and 7. Furthermore, the improved predictable patterns of the established models are indicated by R^2 values in Table 8. Equations 2 and 3 are as follows:

$$FS = -15.4 - 3.1\ A + 57.3\ B \tag{2}$$

$$TS = 10.216 - 1.384\ A + 1.863\ B \tag{3}$$

The validation studies were then used to verify the regression equations' accuracy. The most appropriate variable setup was selected for confirmation, and the projected and observed outcomes were contrasted as indicated in Fig. 8.

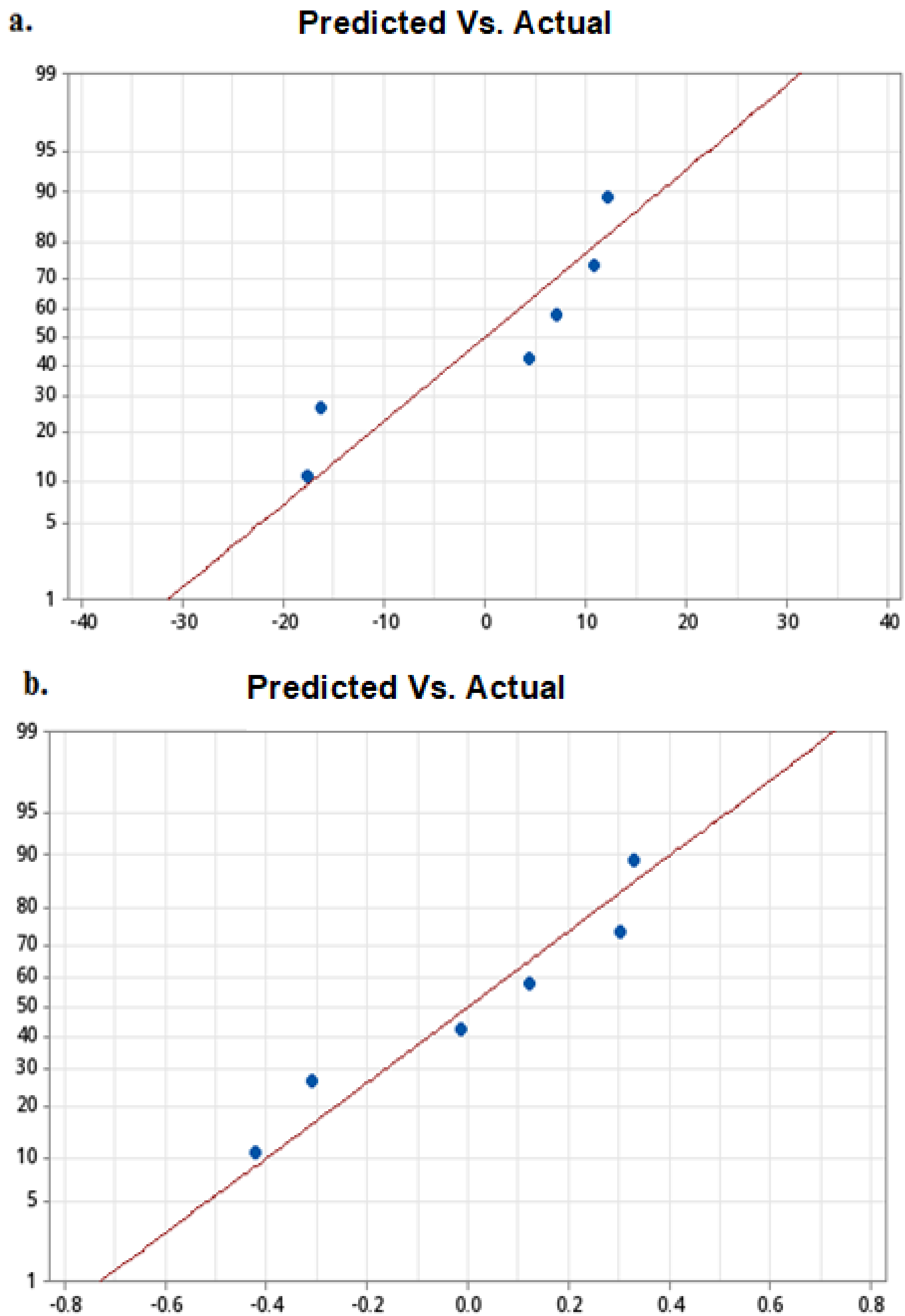

Fig. 8. Experimental and model values of A. Flexural strength; B. Tensile strength

CONCLUSIONS

1. The research findings conclusively demonstrated that simultaneous usage of chicken feather (CF) and *Sesbania grandiflora* (SG) fibers with epoxy resin could improve the composites' characteristics. In comparison to earlier experimental studies, the hybrid composites with 30% fiber loading containing 2:1 (CF/SG) fibers ratio were found to be improved.
2. Additionally, a study of thermogravimetric analysis (TGA) and water absorption demonstrated improved thermal stability and reduced water absorption property in the composite prepared with a 2:1 weight ratio of CF and SG fibers.
3. The scanning electron microscope (SEM) analysis of the composite materials' surface morphological behavior revealed that the hybrid composites had reduced roughness of the surface.
4. A response surface model was established to forecast the outcomes, and it was noticed that the regression coefficient R^2 of the model was close to unity, indicating the significant predictability of the developed model. As demonstrated by the response surface findings, the developed model's prediction ability was extremely high. Responses and the important process variables were found to have a linear correlation.
5. Therefore, it can be reported that the optimal combination for composites loaded with 30% fiber containing weight ratio of CF to SG is 2:1, exhibiting a significant overall enhancement in all characteristics.
6. The results of this study indicate that hybrid fibers might be a suitable reinforcement material for composites. Additionally, these composites may prove to be environmentally beneficial materials in the future.
7. Hybrid composites made from CF and SG fibers are the important milestone towards sustainable material development and circular economy principles. Low weight and non-structural applications (such as automotive industries, furniture, and home decors) where biodegradability, cost-effectiveness, and lightweight are sought are where they show the most promise.

ACKNOWLEDGMENTS

This project was supported by Ongoing Research Funding program, (ORF-2025-7), King Saud University, Riyadh, Saudi Arabia.

Data Availability Statement

Data will be made available on request from the authors

Ethical Approval

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

REFERENCES CITED

Álvarez-del-Castillo, M. D., Garrido-Soriano, N., Casadesús, M., Macanás, J., Molins-Duran, G., and Carrillo-Navarrete, F. (2022). "Environmental impact of chicken feathers based polypropylene composites developed for automotive and stationary applications and comparison with glass-fibre analogues," *Waste and Biomass Valorization* 13(11), 4585-4598. DOI: 10.1007/s12649-022-01810-0

Alvarez-Vera, M., Vázquez, J., Fernández, D. and Reinoso, R. (2022). "Poultry feathers and offal treatment by using beneficial microorganisms," *BioResources* 17(1), 64-74. DOI: 10.15376/biores.17.1.64-74

Ambrose, C. G., and Clanton, T. O. (2004). "Bioabsorbable implants: Review of clinical experience in orthopedic surgery," *Annals of Biomedical Engineering* 32, 171-177. DOI: 10.1023/B:ABME.0000007802.59936.fc

Anjumol, K. S., Sumesh, K. R., Vackova, T., Hanna, J. M., Sabu, T., and Spatenka, P. (2023). "Effect of plasma treatment on the morphology, mechanical, and wetting properties of polyethylene/banana fiber composites," *Biomass Conversion and Biorefinery* 14, 30239-30250. DOI: 10.1007/s13399-023-04884-5

Aruchamy, K., Palaniappan, S. K., Lakshminarasimhan, R., Mylsamy, B., Dharmalingam, S. K., Ross, N. S., and Pavayee Subramani, S. (2023). "An experimental study on drilling behavior of silane-treated cotton/bamboo woven hybrid fiber reinforced epoxy polymer composites," *Polymers*15(14), article 3075. DOI: 10.3390/polym15143075

ASTM D256-23e1 (2023). "Standard test methods for determining the Izod pendulum impact resistance of plastics,"ASTM International, West Conshohocken, PA, USA.

ASTM D570-22 (2022). "Standard test method for water absorption of plastics," ASTM International, West Conshohocken, PA, USA.

ASTM D638-14 (2022). "Standard test method for tensile properties of plastics," ASTM International, West Conshohocken, PA, USA.

ASTM D790-17 (2017). "Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials," ASTM International, West Conshohocken, PA, USA.

ASTM D2240-15 (2021). "Standard test method for rubber property—Durometer hardness,"ASTM International, West Conshohocken, PA, USA.

ASTM D2344/D2344M-22 (2022). "Standard test method for short-beam strength of polymer matrix composite materials and their laminates," ASTM International, West Conshohocken, PA, USA.

Athith, D., Sanjay, M. R., Yashas Gowda, T. G., Madhu, P., Arpitha, G. R., Yogesha, B., and Omri, M. A. (2018). "Effect of tungsten carbide on mechanical and tribological properties of jute/sisal/E-glass fabrics reinforced natural rubber/epoxy composites," *Journal of Industrial Textiles* 48(4), 713-737. DOI: 10.1177/1528083717740765

Baiano, A. (2014). "Recovery of biomolecules from food wastes—A review," *Molecules* 19(9), 14821-14842. DOI: 10.3390/molecules190914821

Balaji, A., Sivaramakrishnan, K., Karthikeyan, B., Purushothaman, R., Swaminathan, J., Kannan, S., Udhayasankar, R., and Haja Madieen, A. (2019). "Study on mechanical and morphological properties of sisal/banana/coir fiber-reinforced hybrid polymer composites," *Journal of the Brazilian Society of Mechanical Sciences and Engineering* 41, article 386. DOI: 10.1007/s40430-019-1881-x

Barone, J. R., and Schmidt, W. F. (2005). "Polyethylene reinforced with keratin fibers obtained from chicken feathers," *Composites Science and Technology* 65(2), 173-181. DOI: 10.1016/j.compscitech.2004.06.011

Carrillo, F., Rahhali, A., Canavate, J., and Colom, X. (2013). "Biocomposites using waste whole chicken feathers and thermoplastic matrices," *Journal of Reinforced Plastics and Composites* 32(19), 1419-1429. DOI:10.1177/0731684413500546

Cheng, S., Lau, K., Liu, T., Zhao, Y., Lam, P.-M., and Yin, Y. (2009). "Mechanical and thermal properties of chicken feather fiber/PLA green composites," *Composites Part B: Engineering* 40(7), 650-654. DOI:10.1063/5.0235884

Choudhry, S., and Pandey, B. (2012). "Mechanical behaviour of polypropylene and human hair fibres and polypropylene reinforced polymeric composites," *International Journal of Mechanical and Industrial Engineering* 2(1), 118-121.

Chowdhury, T., Ahmed, M., Mahdi, E., Haque, M. R., Haque, M. M., Gafur, M. A., and Hasan, M. (2025). "An experimental study on mechanical, physical, and thermal properties of waste hair-rattan hybrid fiber-reinforced composite," *Biomass Conversion and Biorefinery* 15(3), 3789-3802. DOI: 10.1007/s13399-023-05179-5

Dev, B., Rahman, M. A., Rahman, M. Z., Turjo, S. M., Adib, R. J., Jeem, M. H., and Nasim, N. (2025). "Mechanical properties of unidirectional banana/snake plant fiber-reinforced epoxy hybrid composites: Experimental and numerical analyses," *Polymer Bulletin* 2025, Available Online. DOI: 10.1007/s00289-025-05658-x

Dittenber, D. B., and GangaRao, H. V. S. (2012). "Critical review of recent publications on use of natural composites in infrastructure," *Composites Part A: Applied Science and Manufacturing* 43(8), 1419-1429. DOI: 10.1016/j.compositesa.2011.11.019

Gogoi, G., Chowdhury, C., and Maji, T. K. (2022). "Hybrid bio-based composites from waste chicken feather and betel nut fiber: A study on the mechanical and thermal properties," *Journal of Bionic Engineering*19(1), 268-277. DOI: 10.1007/s42235-021-00122-8

Gogoi, G., Mandal, M., and Maji, T. K. (2019). "Study of properties of modified soybean oil based composite reinforced with chicken feather," *Fibers and Polymers* 20, 1061-1068. DOI: 10.1007/s12221-019-8843-x

Gokul, S., Ramakrishnan, T., Manickaraj, K., Devadharshan, P., Mathew, M. K., and Prabhu, T. V. (2024). "Analyzing challenges and prospects for sustainable development with green energy: A comprehensive review," in: *AIP Conference Proceedings* 3221, article ID 020043 DOI:10.1063/5.0235884

Idicula, M., Joseph, K., and Thomas, S. (2010). "Mechanical performance of short banana/sisal hybrid fiber reinforced polyester composites," *Journal of Reinforced Plastics and Composites* 29(1), 12-29. DOI: 10.1177/0731684408095033

Ilyas, R. A., Azmi, A., Nurazzi, N. M., Atiqah, A., Atikah, M. S. N., Ibrahim, R., Norrrahim, M. N. F., Asyraf, M. R. M., Sharma, S., Punia, S., *et al.* (2021). "Oxygen permeability properties of nanocellulose reinforced biopolymer nanocomposites," *Materials Today: Proceedings* 52(Part 5), 2414-2419. DOI: 10.1016/j.matpr.2021.10.420

Jawaid, M., Khalil, H. P. S. A., and Bakar, A. A. (2011). "Woven hybrid composites: Tensile and flexural properties of oil palm-woven jute fibres based epoxy composites," *Materials Science and Engineering: A* 528(15), 5190-5195. DOI:10.1016/j.msea.2011.03.047

Jose, S., George, J. S., Jacob, T. A., Vijayan P, P., Bhanu, A. V. A., Nedumpillil, N. N., and Thomas, S. (2023). "Nanosilica incorporated coarse wool-epoxy hybrid biocomposites with improved physico-mechanical properties," *Frontiers in Materials* 10, 1-8. DOI: 10.3389/fmats.2023.1140602

Kar, A., Saikia, D., Palanisamy, S., Santulli, C., Fragassa, C., and Thomas, S. (2023). "Effect of alkali treatment under ambient and heated conditions on the physicochemical, structural, morphological, and thermal properties of *Calamus tenuis* cane fibers," *Fibers*11(11), article 92. DOI: 10.3390/fib11110092

Karthik, A., Bhuvaneshwaran, M., Senthil Kumar, M. S., Palanisamy, S., Palaniappan, M., and Ayrilmis, N. (2024). "A review on surface modification of plant fibers for enhancing properties of biocomposites," *ChemistrySelect* 9(21), article ID e202400650. DOI: 10.1002/slct.202400650

Khosa, M. A., Wu, J., and Ullah, A. (2013). "Chemical modification, characterization, and application of chicken feathers as novel biosorbents," *RSC Advances* 3(43), 20800-20810. DOI:10.1039/C3RA43787F

Kiew, K. S., Hamdan, S. and Rahman, M. R. (2013). "Comparative study of dielectric properties of chicken feather/kenaf fiber reinforced unsaturated polyester composites," *BioResources* 8(2), 1591-1603.

Mirițoiu, C. M. (2024). "Mechanical properties of composite materials with dammar-based matrices and reinforced with paper and chicken feathers waste," *BioResources* 19(3), 4698-4717. DOI: 10.15376/biores.19.3.4698-4717

Misra, M., and Kar, P. (2003). "Keratin fibers and structures for nanofiltration," in: *Natural Fibers, Plastics and Composites*,Springer, New York, NY, USA, pp. 83–93. DOI: 10.1007/978-1-4419-9050-1_6

Muthukannan, M., Kannan, P. S., Selwin, M., and Kathiravan, T. (2023). "Experimental investigation of mechanical properties of palm-bamboo–glass fibre composites," *Materials Today: Proceedings* (in Press, Corrected Proof). DOI: 10.1016/j.matpr.2023.01.377

Oladele, I. O., Okoro, A. M., Omotoyinbo, J. A., and Khoathane, M. C. (2018). "Evaluation of the mechanical properties of chemically modified chicken feather fibres reinforced high density polyethylene composites," *Journal of Taibah University for Science*12(1), 56-63. DOI:10.1080/16583655.2018.1451103

Palaniappan, M., Palanisamy, S., Khan, R., H. Alrasheedi, N., Tadepalli, S., Murugesan, T. mani, and Santulli, C. (2024). "Synthesis and suitability characterization of microcrystalline cellulose from *Citrus* x *sinensis* sweet orange peel fruit waste-based biomass for polymer composite applications," *Journal of Polymer Research* 31(4), article 105. DOI: 10.1007/s10965-024-03946-0

Prasanth, K., Prashanth, M., Prithivirajan, S., and Kumar, P. A. (2021). "Investigation on mechanical properties of chicken feather fibers reinforced polymeric composites," *Materials Today: Proceedings* 37, 3767-3770. DOI:10.1016/j.matpr.2020.10.877

Rafi, E. A., Aziz, M. B., Khan, M. T. R., Haque, M. R., Hasan, M., Gafur, M. A., Alam, M. F., Rahman, F., and Bhuiyan, M. S. (2024). "Effect of *Sesbania grandiflora* stem fiber reinforcement on mechanical, chemical, thermal, and physical properties of vinyl ester material," *Biomass Conversion and Biorefinery* 2024, 1-16. DOI:10.1007/s13399-024-06105-z

Ramlee, N. A., Jawaid, M., Yamani, S. A. K., Zainudin, E. S., and Alamery, S. (2021). "Effect of surface treatment on mechanical, physical and morphological properties of oil palm/bagasse fiber reinforced phenolic hybrid composites for wall thermal insulation application," *Construction and Building Materials* 276, article ID 122239. DOI: 10.1016/j.conbuildmat.2020.122239

Reddy, K. N., Chanrasekar, V., Reddy, K. T., and Hussain, S. A. (2014). "Performance evaluation of Emu feather fiber reinforced polymer composites," *International Journal of Mechanical Engineering and Robotics Research* 3(1), 272-283.

Reddy, N., and Yang, Y. (2007). "Structure and properties of chicken feather barbs as natural protein fibers," *Journal of Polymers and the Environment*15, 81-87.

Robertson, G. L. (2005). *Food Packaging: Principles and Practice*, CRC Press, Boca Raton, FL, USA. DOI: 10.1201/b21347

Sah, N., Goel, A., Chaudhary, A. K., and Verma, A. (2021). "Thermal analysis of chicken fiber augmented epoxy composites," *Materials Today: Proceedings* 44, 4409-4413. DOI: 10.1016/j.matpr.2020.10.580

Santhosh, N., Praveena, B. A., Gowda, A. C., Duhduh, A. A., Rajhi, A. A., Alamri, S., Berwal, P., Khan, M. A., and Wodajo, A. W. (2024). "Innovative eco-friendly bio-composites: A comprehensive review of the fabrication, characterization, and applications," *ReviewsonAdvancedMaterials Science* 63(1), article ID 20240057. DOI:10.1515_rams-2024-0057

Saravanan, K., and Dhurai, B. (2012). "Exploration on the amino acid content and morphological structure in chicken feather fiber," *Journal of Textile and Apparel, Technology and Management* 7(3), article 1829.

Savitha, K., Annapoorani, G. S., Sampath, V. R., and Atalie, D. (2019). "Physical characterization of cellulosic fibres from *Sesbania grandiflora* stem," *Indian Journal of Fibre & Textile Research (IJFTR)* 44(4), 437-441.

Senthil Kumar, M. S., Rajeshkumar, L., Rangappa, S. M., and Siengchin, S. (2024). "Mechanical behaviour analysis for banana/coir natural fiber hybrid epoxy composites through experimental modelling," *Journal of Polymer Research* 31(6), article 163. DOI: 10.1007/s10965-024-04018-z

Sharath, B. N., Yashas Gowda, T. G., Madhu, P., Pradeep Kumar, C. B., Jain, N., Verma, A., Sanjay, M. R., and Siengchin, S. (2024). "Fabrication of raw and chemically treated biodegradable *Luffa aegyptica* fruit fibre-based hybrid epoxy composite: A mechanical and morphological investigation," *Biomass Conversion and Biorefinery* 2024, Available Online. DOI: 10.1007/s13399-024-05570-w

Singh, N., and Rani, A. (2013). "Extraction and processing of fiber from *Sesbania aculeata* (dhaincha) for preparation of needle punched nonwoven fabric," *National Academy Science Letters* 36, 489-492. DOI: 10.1007/s40009-013-0166-7

Sobucki, L., Ramos, R. F., Gubiani, E., Brunetto, G., Kaiser, D. R., and Daroit, D. J. (2019). "Feather hydrolysate as a promising nitrogen-rich fertilizer for greenhouse lettuce cultivation," *International Journal of Recycling of Organic Waste in Agriculture* 8, 493-499. DOI: 10.1007/s40093-019-0281-7

Sreekala, M. S., George, J., Kumaran, M. G., and Thomas, S. (2002). "The mechanical performance of hybrid phenol-formaldehyde-based composites reinforced with glass and oil palm fibres," *Composites Science and Technology* 62(3), 339-353. DOI: 10.1016/S0266-3538(01)00219-6

Subagyo, Y., Priwintoko, B., Ismail, R., Fitriyana, D. F., Jujur, I. N., Setyadi, I., and Taqwatomo, G. (2023). "Development of magnesium biocomposites with hydroxyapatite or carbonate apatite reinforcement as implant candidates: A review," *Mechanical Engineering for Society and Industry* 3(3), 152-165. DOI: 10.31603/mesi.10389

Sumesh, K. R., Ajithram, A., Anjumol, K. S., and Sai Krishnan, G. (2024). "Influence of natural fiber addition and fiber length in determining the wear resistance of epoxy-based composites," *Polymer Composites* 45(4), 3029-3042. DOI: 10.1002/pc.27968

Sun, Y., Li, B., Zhang, Y., Dou, H., Fan, W., and Wang, S. (2022). "The progress and prospect for sustainable development of waste wool resources," *Textile Research Journal* 93(1–2), 468-485. DOI: 10.1177/00405175221098572

Tan, Y. H., Abdullah, M. O., Nolasco-Hipolito, C., and Zauzi, N. S. A. (2017). "Application of RSM and Taguchi methods for optimizing the transesterification of waste cooking oil catalyzed by solid ostrich and chicken-eggshell derived CaO," *Renewable Energy*114, 437-447. DOI: 10.1016/j.renene.2017.07.024

Tesfaye, T., Sithole, B., Ramjugernath, D., and Chunilall, V. (2017). "Valorisation of chicken feathers: Characterisation of chemical properties," *Waste Management* 68, 626-635. DOI:10.1016/j.wasman.2017.06.050

Uzun, M., Sancak, E., Patel, I., Usta, I., Akalın, M., and Yuksek, M. (2011). "Mechanical behaviour of chicken quills and chicken feather fibres reinforced polymeric composites," *Archives of Materials Science and Engineering* 52(2), 82-86.

Venkatesan, G., Vignesh, V., Nagarajan, K. J., Krishnaraj, R., Nagaprasad, N., and Vinayagar, K. (2022). "Extraction and characterization of agricultural discarded *Sesbania aculeata* stem waste as potential alternate for synthetic fibers in polymer composites," *Journal of Natural Fibers* 19(15), 10601-10615. DOI: 10.1080/15440478.2021.2002756

Venkateshwaran, N., Elayaperumal, A., and Sathiya, G. K. (2012). "Prediction of tensile properties of hybrid-natural fiber composites," *Composites Part B: Engineering*,43(2), 793-796. DOI:10.1016/j.compositesb.2011.08.023

Article submitted: April 20, 2024; Peer review completed: May 29, 2025; Revised version received: June 3, 2025; Accepted: July 31, 2025; Published: August 7, 2025.
DOI: 10.15376/biores.20.4.8591-8610