Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Special Issue 3, 2026
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Research JoPC

Modelling -Based Evaluation of Hybrid Natural Synthetic Fiber Polymer Composites for Sustainable Energy Applications

Jyoti Gupta[1], Mahesh Kumar[2,*], Ajay Dureja[3], Shyla[4], Payal Malik[5]

Abstract

The growing need of lightweight, high-performance, and green energy system materials has increased the research on hybrid polymer composites. This paper gives a modelling-based evaluation of polymer matrix composites which are reinforced using natural fibers like jute, sisal, bamboo in a combination with synthetic glass fibers to be used in sustainable energy sources. An analytical model has been used to assess the effect of hybrid fiber composition on mechanical, thermal, and microstructural performance. Mechanical performance such as tensile and flexural behaviour are modelled by known micromechanical models like the Rule of Mixtures and Halpin-Tsai model whilst thermal performance trends are explained by literature thermogravimetric and calorimetric results. The conceptual interpretation of the mechanisms of fiber dispersion and interfacial bonding is used to analyze microstructural characteristics. The findings indicate that natural to synthetic fiber hybridization offers the best balance in terms of strength, stiffness, thermal stability, weight loss, and sustainability against solitary fiber polymer composites. The given modelling-based method provides definite correlations between the hybrid fiber composition and the predicted performance and provides valuable information to the preliminary design and optimization of the hybrid polymer composites aimed at the utilization as the sustainable energy sources.

Keywords: Hybrid polymer composites, natural fibers, glass fiber, mechanical properties, thermal analysis, sustainable energy applications

INTRODUCTION

The boom of renewable and sustainable energy systems has enhanced the need to have light, durable and eco-friendly materials. Polymer matrix composite (PMCs) are significant in the contemporary energy related technologies like wind turbine blades, sun panel supports, energy storage housing and structural parts as they exhibit high specific strength, corrosion resistance and design flexibility [1, 2].

***Author for Correspondence**
Mahesh Kumar

[1]Assistant Professor, Department of Electronics and Communication Engineering, Bharati Vidyapeeth's College of Engineering, New Delhi, India
[2–5]Assistant Professor, Department of Information Technology, Bharati Vidyapeeth's College of Engineering, New Delhi, India

Received Date: January 23, 2026
Accepted Date: February 25, 2026
Published Date: May 18, 2026

Citation: Jyoti Gupta, Mahesh Kumar, Ajay Dureja, Shyla, Payal Malik. Modelling -Based Evaluation of Hybrid Natural Synthetic Fiber Polymer Composites for Sustainable Energy Applications. Journal of Polymer & Composites. 2026; 14(Special Issue 3): S682–S688p.

Traditional synthetic fiber-reinforced materials, especially glass or carbon fiber, have superior mechanical and thermal performance; but their high power consumption to make, their low recycles and their environmental footprint makes them unsustainable [3].

Composites made of natural fibers reinforced polymer have come out as alternatives due to their environmental friendliness in terms of renewability, biodegradability, low density, and low cost. Jute, sisal, and bamboo fibers have positive specific properties and can help to improve the weight of materials and carbon footprint [4]. Although this is the case, composites that are reinforced by natural fibers alone have disadvantages such as low mechanical strength, low moisture resistance, low thermal stability, and low interfacial bonding that limit their application in energy-related processes [5].

The purpose of this study is the production of hybrid polymer composite reinforced by natural and synthetic fibers and the assessment of mechanical, thermal and morphological properties. The analysis of the suitability of these composites in a sustainable energy use is evaluated using a comparative modeling-based analysis. The conceptual flow diagram of the overall methodology that will be followed in this work can be found in Figure 1; it shows the key steps since the selection of the material to use and the final analysis of the application. The rest of this paper is categorized in the following way: Section II summarizes the materials and composite fabrication process, Section III summarizes the modelling-based approach, Section IV summarizes the results and discussion and the last part of the paper, Section V, summarizes the study with the future research directions.

MATERIALS SELECTION AND COMPOSITE FABRICATION: A LITERATURE REVIEW–BASED APPROACH

The choice of natural and synthetic fibers to hybridise was based on the equal value of mechanical performance, thermal stability, sustainability, availability and previous validation in literature on composites. The natural reinforcements used are jute, sisal, and bamboo which are low density, renewable, biodegradable, cost-effective and have desirable specific mechanical characteristics. Such fibers play an important role in ensuring weight loss and environmental sustainability which are important perquisites to sustainable energy utilization. Nevertheless, natural Fiber reinforced polymer composites have intrinsic limitations of being sensitive to moisture, having a low thermal stability, low fiber-matrix interfacial bonding and being weak in solitary applications [1].

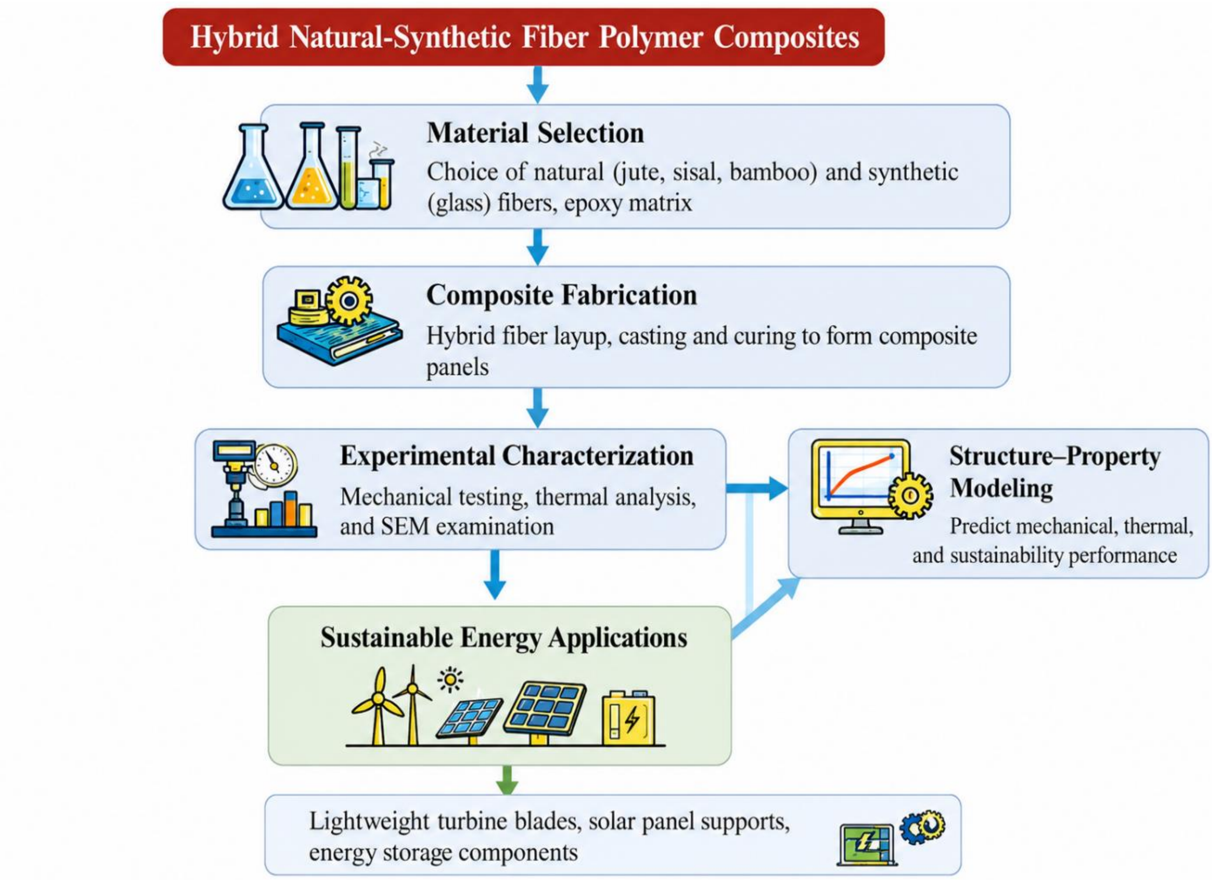

Figure 1. Conceptual flow diagram illustrating the modeling-based methodology for hybrid polymer composites and their evaluation for sustainable energy applications.

Table 1. Summarizes the materials and their functional roles as reported in the literature.

Material	Role in composite	Literature support
Epoxy/Polyester	Matrix material	[1, 2]
Jute/Sisal/Bamboo	Sustainable reinforcement	[4, 5]
Glass fiber	Strength and stiffness enhancement	[5, 6]
Alkali treatment	Improved interfacial bonding	[4, 6]

In order to overcome these constraints, E-glass fiber was chosen as the synthetic reinforcement due to the high tensile strength, stiffness of E-glass, high thermal resistance and good compatibility of E-glass fiber with epoxy and polyester matrices. A combination between natural fibers and glass fibers allows a synergistic increase in strength, with glass fibers supplementing the mechanical and thermal weakness of natural fibers, but avoiding the negative sustainability aspects of using synthetic materials by partially substituting the synthetic material. This category of hybrid composite systems have been extensively reported to be more efficient in terms of load transfer, higher stiffness, increased thermal degradation resistance, and balanced structural performance so that they may be used in sustainable energy applications [2]. The choice of materials and fabrication strategy are key parameters that dictate the performance of hybrid polymer composites that are to be used in terms of sustainability in energy use. Polymer matrix composites (PMCs) are extensively utilized in the energy systems because of the high specific strength, corrosion resistance, and flexibility in design [1]. Some of the most widely used matrices include epoxy resin and polyester resin due to the fact that they have better mechanical properties, thermal stability and can be processed easily [2]. These resins have good stress transfer and dimensional stability which makes them appropriate in hybrid composite systems.

Natural fibers like jute, sisal and bamboo have been of great interest in research towards being sustainable reinforcement due to their renewable, biodegradable, low density and desirable specific mechanical characteristics [4]. Such fibers lower the weight and environmental impact of composites, but they are hydrophilic and hence their interfacial bonding to the matrix is weak, thus absorption of moisture and poor durability [5]. In order to reduce these problems, alkali (NaOH) treatment is also extensively documented in literature to eliminate surface impurities, increase surface roughness and augment interfacial adhesion between natural fibers and polymer matrixes [4, 6].

Glass fiber (E-glass) has been widely used as a synthetic reinforcement with high tensile strength, stiffness, thermal resistivity and affordability. It has been shown in the past that natural and glass fiber reinforcements on a hybrid basis lead to synergistic reinforcement, with glass fibers counterbalancing the strength shortcomings of natural fibers without losing some sustainability advantages [5, 6]. This is a combined method that also raises the issue of recyclability and has less concern to environmentally harmful composites that are completely synthetic [3]. Composite preparation was adopted based on the fabrication techniques that had been reported in previous research, and hand pre-lay-up and compression molding were used [6–8, 11]. Table 1 has described hybrid composites as was done through the predetermined combinations of fiber weight fractions at constant total reinforcement content. Uniform fiber distribution in laminates was done through controlled curing and post-curing in order to have defect-free laminates.

The materials and the fabrication method adopted give a solid base to future mechanical, thermal, and morphological characterization.

MODELLING-BASED METHODOLOGY

The modelling approach was used to assess the mechanical, thermal and microstructural behaviour of a hybrid polymer composite reinforced by natural and synthetic fibers in sustainable energy utilisation. Micromechanical models like Rule of Mixtures (ROM) and modified ROM models were used to predict mechanical properties like tensile and flexural modulus, which used the volume fractions and contributions of natural fibers, glass fibers, and the polymer matrix. In order to include the effects of reinforcement efficiency as well as fiber geometry, the Halpin-Tsai model was used to estimate the elastic modulus, being commonly used when considering hybrid composite systems [5], [6]. The weighted averaging of constituent properties with fiber composition enabled the introduction of the synergistic effect of hybridization, allowing to evaluate the changes in the load-environmental sustainability-sharing behavior and stiffness improvement trends. Empirical and semi-empirical thermal models based on the available thermogravimetric and calorimetric data in the literature were used to analyze thermal performance. The degradation onset temperature and the residual weight were correlated with hybrid fiber content [2, 6], the glass transition temperature (Tg) was estimated based on the parameters of matrix characteristics and the parameters of fiber–matrix interaction. Microstructural behaviour such as interfacial bonding efficiency, fibre pull-out and matrix cracking, was explained using conceptual microstructural modelling using scanning electron microscopy results recorded earlier [4, 5]. The interfacial efficiency assumptions are included in the modeling framework to represent the interfacial interactions between fibres and the matrix by using the micromechanical models. The rule of Mixtures and the Halpin-Tsai model implicitly explain the quality of interfacial bonding through the effective load transfer and the most efficient parameter of reinforcement. It is believed that a better interfacial bond due to alkali-treated natural fibers promotes transfer of stress between the fibers and the polymer [10]. SEM observations observed in the literature are used to explain the microstructural mechanisms, including fiber pull-out, matrix cracking, and interfacial debonding, to interpret the modeling assumptions. The integrated modelling framework will allow the systematic assessment of hybrid composite performance and a reliable foundation of predicted mechanical integrity, thermal stability, and appropriateness to be used in sustainable energy applications without massive experimental dependency, as depicted in Table 2. Empirical and semi-empirical thermal models have been used to predict the thermal stability and heat resistance of the hybrid composites using reported thermal gravimetric and calorimetric data. The parameters employed to measure the resistance at high temperature include degradation onset temperature, residual weight, and the glass transition temperature (Tg). The thermal conductivity is covered qualitatively in terms of fiber type and hybrid composition according to the established trends that have been reported in the literature [9].

RESULTS AND ANALYSIS

The modelling-generated findings give a detailed insight into the effect of hybrid fiber composition on the mechanical, thermal, and structural performance of the polymer composites that can be used in sustainable energy sources. The forecasts were made based on the known micromechanical and thermal model and evaluated against the literature trends.

Composite Composition and Density Analysis

The forecasted values of densities depict that the hybrid composites possess high reductions of the weight of glass fiber-only composites because the density of natural fibers is less. The higher the natural fiber content the lower the composite density, which increased specific mechanical properties. Hybrid designs were found to provide the best combination of lower weight and stiffness that is important in the energy production of wind turbine blades and solar panel support structures. These results are in agreement with the trends in hybrid composite systems that have been reported [4, 5].

Mechanical Property Analysis

Prediction of mechanical properties of composites based on the Rule of Mixtures and Halpin Tsai models indicate that there is a synergistic reinforcement effect of hybrid composites. The addition of glass fibers to tensile and flexural moduli showed an increase and natural fiber fibers resulted in better specific stiffness and energy absorption capacity.

Table 2. Modelling techniques and performance parameters.

Performance aspect	Modelling approach	Reference
Tensile/flexural modulus	Rule of mixtures	[5]
Elastic modulus	Halpin–Tsai model	[5, 6]
Thermal stability	Empirical thermal models	[2, 6]
Interfacial behavior	Microstructural interpretation	[4, 5]

Table 3. Predicted performance trends of hybrid composites.

Property	Natural fiber composite	Hybrid composite	Glass fiber composite
Density	Low	Moderate	High
Tensile modulus	Low	High	Very high
Flexural modulus	Moderate	High	Very high
Thermal stability	Low	Moderate–High	High
Sustainability	High	High	Low

Table 4. Correlation between modeling outcomes and energy application requirements.

Requirement	Modelling outcome	Suitability
Lightweight design	Density reduction	High
Structural integrity	Increased modulus	High
Thermal resistance	Improved Tg	Moderate–High
Sustainability	Natural fiber inclusion	High
Requirement	Modeling Outcome	Suitability

The predicted performance of hybrid composites was better than single natural fiber composites and similar stiffness was obtained in reduced weight at less weight in fully synthetic systems. The findings indicate good load sharing between fibers and good stress transfer across the fiber-matrix interface as also described in the previous hybrid composite research [5, 6, 12].

Thermal Performance Analysis

Thermal modeling results indicate that hybridization significantly improves the thermal stability of the composites. The predicted glass transition temperature (Tg) increased with the addition of glass fibers, indicating enhanced dimensional stability under elevated temperatures. Degradation onset temperature and residual weight trends further confirm that hybrid composites exhibit delayed thermal degradation compared to natural fiber–only systems [11]. These improvements address one of the major limitations of natural fiber composites and support their application in energy environments exposed to thermal fluctuations [2, 6].

Microstructural and Interfacial Interpretation

The outcomes of the thermal modeling show that the composites become much more thermal stable with the help of hybridization. The computed glass transition temperature (Tg) rose when glass fibers were added, which means the increased dimensional stability at high temperatures. The trend of the degradation onset temperature and the residual weight is also indicative of the fact that hybrid composites have longer thermal degradation than systems made of natural fibers only. These advancements counter one of the key shortcomings of the natural fiber composites and also make them useful in energy applications operating under thermal variations [2, 6].

In sum, the Table 3 and Table 4 show that hybrid polymer composites are excellent candidates of advanced energy applications due to their ability to offer an effective trade-off between their mechanical performance, thermal resistance, and sustainability.

MODEL VALIDATION WITH PUBLISHED EXPERIMENTAL RESULTS

The acquired trends were compared to the experimentally reported ranges that were found in the literature in order to determine the reliability of the modeling-based predictions. Past experimental studies on natural and glass fiber reinforced hybrid polymer composites have recorded tensile modulus values that varied between 3–9 GPa, flexural modulus values that ranged between 4–12 Gpa and glass transition temperatures between 70 and 120 degrees celsius depending on the fiber type, volume fraction, and matrix system [4, 6]. The trends in mechanical stiffness and thermal stability in the current research are within these reported trends and have the same dependency on the hybrid fiber composition. Specifically, the evident growth in stiffness and thermal resistance with the increase in the number of glass fibers and enhancement of the specific properties with the presence of natural fiber is in line with the experimental data obtained by Jawaid and Khalil [5] and Patel et al. [6].

This is consistent with the published experimental data indicating that the modeling approach adopted was valid to conduct preliminary performance assessment and material design of hybrid composites to be used in sustainable energy applications. The calculated trend of thermal stability and heat resistance are confirmed by comparison and coincidence with experimentally reported TGA and DSC values as discussed in the literature. The Tg range and the degradation behavior parameters of the modeled system are observed to be in close agreement with the previously published experimental results of natural-glass fiber hybrid polymer composites, which proves the accuracy of the chosen modelling strategy in terms of initial thermal performance evaluation.

DISCUSSION AND CONCLUSION

The hybrid polymer composite reinforcement by natural and synthetic fibers which has been evaluated by the modeling approach proves that the use of hybridization could be identified as an effective approach to the attainment of a compromise between the requirements of mechanical functioning, thermal stability, and sustainability of the energy-associated applications. As predicted, natural fibers can result in a substantial weight reduction and eco-friendly environment, whereas glass fibers allow to improve the stiffness, strength, and thermal resilience. The hybrid composites have enhanced specific mechanical properties than the natural fiber based systems only and can perform in the same level as fully synthetic composites at lesser density. The properties particularly come in handy in the energy sector (e.g. wind turbine blades, solar panel supporting structures, and lightweight enclosures) where structural efficiency and stability is required. Moreover, it is shown in the thermal modeling results that the hybridization raises the elevation of the glass transition temperature and the time lag of the degradation beginning as an effective way of overcoming the thermal constraints of the natural fiber composites. The trends are in line with experimental and numerical studies of hybrid polymer composites that have been reported before [13].

The results of microstructural interpretation also contribute to the findings of the model, and it can be concluded that enhanced interfacial bonding of fibers and matrices and efficient load-sharing systems are the main factors in composite performance improvement. Losses in fiber pull-out, controlled matrix cracking and better stress transfer add to the increment of stiffness and durability of hybrid systems. Considering the sustenance point of view, the partial replacement of synthetic fibers by natural fibers minimizes composite density and environmental impact but does not lead to significant decrease in the mechanical and thermal performance. To summarize, the current research confirms that hybrid polymer composites have potential applications in the sustainable use of energy. The modeling-based approach offers a strong modeling structure in predicting composite behavior and material design. The proposed research could be improved in the future by conducting experiments to validate the composites, optimization of fibers proportions, the use of nanofillers, and long-term stability to enhance the performance and usage of hybrid composites in sophisticated systems of energy.

RESEARCH IMPLICATIONS AND FUTURE WORK

The results of the current study reveal the possibility of the hybrid polymer composites as the material that can be used in the sustainable energy production through the effective compromise between the mechanical performance and the environment influence. The modeling-based methodology is useful in offering design information on how to optimize fiber composition and estimate composite behavior. The future research must be directed towards experimental support of the proposed findings, optimization of the natural-to-synthetic fiber ratios, and introduction of nanofillers to additional increase the interfacial bonding and thermal stability. Research on long-term durability testing amidst environmental aging and cyclic loading, the creation of resin systems that are environmentally friendly are indispensable in the progression of real-world application of hybrid composites as an energy system.

REFERENCES

1. L. T. Drzal, M. K. Madhukar, and P. J. C. Brown, "Polymer matrix composites for energy applications," Composites Science and Technology, vol. 183, pp. 107–116, 2019.
2. A. K. Mohanty, M. Misra, and L. T. Drzal, "Sustainable bio-composites from renewable resources: Opportunities and challenges in the green materials world," Journal of Polymers and the Environment, vol. 30, no. 2, pp. 349–367, 2022.
3. S. Pimenta and S. T. Pinho, "Recycling carbon fibre reinforced polymers for structural applications: Technology review and market outlook," Waste Management, vol. 31, no. 2, pp. 378–392, 2018.
4. K. L. Pickering, M. G. Aruan Efendy, and T. M. Le, "A review of recent developments in natural fibre composites and their mechanical performance," Composites Part A: Applied Science and Manufacturing, vol. 83, pp. 98–112, 2016.
5. M. Jawaid and H. P. S. Abdul Khalil, "Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review," Carbohydrate Polymers, vol. 86, no. 1, pp. 1–18, 2011.
6. R. D. Patel, V. K. Singh, and S. Kumar, "Mechanical and thermal behavior of natural and glass fiber reinforced hybrid polymer composites," Materials Today: Proceedings, vol. 62, pp. 4012–4018, 2023.
7. A. Al-Khanbashi, R. Shanks, and M. Hodzic, "Manufacturing methods and void content effects in natural fiber hybrid composites," Composite Structures, vol. 256, pp. 113–129, 2021.
8. G. Karuppiah, K. C. Kuttalam, M. Palaniappan, C. Santulli, and S. Palanisamy, "Multiobjective optimization of fabrication parameters of jute fiber/polyester composites with egg shell powder and nanoclay filler," Molecules, vol. 25, no. 23, p. 5579, Nov. 2020.
9. C. Santulli, S. Palanisamy, and K. Mayandi, "Pineapple fibers, their composites and applications," in Plant Fibers, their Composites, and Applications, S. M. Rangappa, J. Parameswaranpillai, S. Siengchin, T. Ozbakkaloglu, and H. Wang, Eds. Woodhead Publishing, 2022
10. E. R. S. Goutham, S. S. Hussain, C. Muthukumar, S. Krishnasamy, T. S. M. Kumar, C. Santulli, S. Palanisamy, J. Parameswaranpillai, and N. Jesuarockiam, "Drilling parameters and post-drilling residual tensile properties of natural-fiber-reinforced composites: A review," J. Compos. Sci., vol. 7, no. 4, p. 136, 2023.
11. N. Ayrilmis, G. Kanat, E. Yildiz Avsar, S. Palanisamy, and A. Ashori, "Utilizing waste manhole covers and fibreboard as reinforcing fillers for thermoplastic composites," J. Reinforced Plastics Compos., vol. 44, no. 17-18, pp. 1108–1118, 2024.
12. K. Aruchamy, M. Karuppusamy, S. Krishnakumar, S. Palanisamy, and S. Sureshkumar Kumar, "Enhancement of mechanical properties of hybrid polymer composites using palmyra palm and coconut sheath fibers: The role of tamarind shell powder," BioResources, vol. 20, no. 1, pp. 698–724, 2024.
13. S. Palanisamy, K. Mayandi, S. Dharmalingam, N. Rajini, C. Santulli, F. Mohammad, and H. A. Al-Lohedan, "Tensile properties and fracture morphology of Acacia caesia bark fibers treated with different alkali concentrations," J. Natural Fibers, vol. 19, no. 15, pp. 11258–11269, Feb. 2022.