



Investigation of Mechanical and Thermal Properties of Novel Hybrid Composites Based on Areca Nut Shell and Pineapple Leaf Powder Reinforced Vinyl Ester Matrix

R. K. Sathish Kumar

Research Scholar, Department of Mechanical Engineering, Vinayaka Mission's Kirupananda Variyar Engineering College, Vinayaka Mission's Research Foundation (Deemed to Be University), Salem, 636308, Tamil Nadu, India

E-mail: sathishrk1982@gmail.com

ABSTRACT

Renewability, cheap cost, and sustainability have recently made eco-friendly materials popular. As a result, both academic and industrial fields are paying great attention to seeking bio-based filler materials for the creation of composites. The study is intended to investigate the utilisation of solid biomass waste in the hybrid form of Areca Nut Shell Powder (ASP) and Pineapple Leaf Powder (PLP) as fillers in vinyl ester-based composites. This process has been investigated for the first time using the hand lay-up technique. These filler substances are agricultural by-products that can be obtained from renewable sources at a low cost. Their mechanical and thermal properties were assessed for hybrid fillers included in the matrix at filler contents from 0 to 20 wt.%. Usually, adding hybrid fillers improved mechanical properties but had a small effect on thermal ones. The hybrid filler-reinforced composites showed notable increases in flexural, impact, and Shore D hardness characteristics in comparison to the neat vinyl ester resin, with improvements of 1.53 times, 1.66 times, and 1.35 times, respectively, at 16 wt.% filler loading, while the tensile strength displayed a steady decline. Using TGA and HDT techniques, thermal stability was evaluated, revealing an HDT value as high as 112°C. Given the results, these hybrid filler-reinforced composites could be appropriate for use in sectors including transportation and building, where moderately tough and thermally stable composites are required and where cost is a major concern.

Keywords: Agricultural waste composites, Areca Nut Shell Powder (ASP), Pineapple Leaf Powder (PLP)

Copyright © 2025. The Author(s). This is an open access preprint (not peer-reviewed) article under [Creative Commons Attribution-NonCommercial 4.0 International](https://creativecommons.org/licenses/by-nc/4.0/) license, which permits any non-commercial use, distribution, adaptation, and reproduction in any medium, as long as the original work is properly cited. **However, caution and responsibility are required when reusing as the articles on preprint server are not peer-reviewed.** Readers are advised to click on URL/doi link for the possible availability of an updated or peer-reviewed version.

How to Cite:

R. K. Sathish Kumar, "Investigation of Mechanical and Thermal Properties of Novel Hybrid Composites Based on Areca Nut Shell and Pineapple Leaf Powder Reinforced Vinyl Ester Matrix" *AIJR Preprints*, 704, Version 1, 2025. DOI: <https://doi.org/10.21467/preprints.704>

1 Introduction

Natural fillers have received considerable attention as reinforcements for polymer composite materials owing to their renewability, environment-friendliness, as well as biodegradability. With its potential for contributing to a greener economy, recent developments in the area have concentrated on using agricultural waste as an economically feasible and sustainable source of these natural fillers, meeting the increasing demand for environmentally friendly substitutes for industrial production [1]. With industries aiming to minimise their dependence on artificial and non-renewable resources, agricultural homogeneous waste products have opened doors to being good alternatives. These materials are suitable for many technical uses since they have appealing mechanical qualities and are ecologically safe at once.

Synthetic filler manufacturing worldwide has resulted in major financial and environmental effects. This results in a large carbon footprint, mostly from the usage of non-renewable resources needed in the manufacturing of synthetic materials utilised to reach great mechanical performance. Furthermore, non-biodegradable synthetic materials contaminate the environment and contribute to our landfills' filling. Another plentiful but underappreciated resource is agricultural waste, particularly that from crops. Burning it on a field poisons the air, damages the ecosystem, and emits greenhouse gases. Making composite materials from such agricultural wastes is a good way to minimise waste and lessen the environmental impact of these farming operations in order of efficiency in disposal [2]. Natural filler composites are increasingly being investigated as advanced material alternatives for automotive usage because of their low cost, lightweight, and ecologically friendly properties [3]. For vehicle interior components, including dashboards, door panels, and seat backs where modest strength and impact resistance are required, these composites are particularly appropriate. Additionally, these materials are under consideration for use in non-structural component and insulation panel applications in construction, whose environmental benefits would greatly reduce carbon footprint [4]. The growing demand for biocomposites highlights the need to cut waste and reduce resource use. Thereby supporting environmentally friendly technologies and sustainable materials and offering workable solutions for world waste management issues. Making use of this abundant resource promotes the development of sustainable replacements and helps to lessen the impact of agricultural waste on the surroundings..

Originally thrown away and burned, Areca Nut Shell waste has recently shown significant promise as a rich, underused resource [5]. With around 2.6 to 3 million tonnes yearly, Areca

nut is India's fourth most often grown commercial crop [6]. Shell makes about 60–80% of this production's weight; almost 1.5 to 2 million tonnes of Areca Nut shell trash are generated yearly. About 1.5 million tonnes of Areca nut shells are produced in India yearly from this large-scale agricultural activity, mostly unappreciated outside traditional burning [7]. From water treatment and construction to bioenergy and composite materials, Areca Nut Shell waste has become a flexible and sustainable supply for many industrial uses [8–10].

Another main agricultural waste that has attracted interest in its application in composite materials is pineapple leaf waste. Pineapple culture produces up to 250 metric tons of wet plant residues per hectare, mainly made up of leaves. This means that globally, we get around 20,000-25,000 tons of pineapple leaf residues per dry acre available after pineapple harvesting. [11]. For all that waste, most of it is either burned in the open or thrown away, causing serious environmental pollution. These leaves can be further converted into utilitarian materials, such as PLP, which in fact can provide an excellent avenue toward sustainable material development as well as waste reduction.

Besides synthetic fillers, the use of natural fillers is increasing due to their availability and renewability. In particular, Areca Nut Shell Powder (ASP) and Pineapple Leaf Powder (PLP) have different properties, which is why they could be used effectively in polymer composites. ASP's high lignin and natural silica content improve its thermal properties and can be an effective reinforcement material. The husk of the Areca nut's breakdown of cellulose (53.2%), hemicellulose (32.98%), and lignin (7.2%) counts as a natural filler, adding evidence of mechanical performance and durability [12]. Similarly, PLP with a cellulose content of 70-82% affords good specific strength, which reinforces composites, making them suitable for the automotive industry [13].

Recently, hybrid composites have emerged as an interesting research area where two or more natural fillers can be combined to improve mechanical features, including tensile, flexural, and impact strengths [14,15] and thermal properties [16]. In biocomposite development, choosing a matrix for hybrid natural fillers is a key choice since it affects the mechanical characteristics, sustainability, and application possibilities of the end product. The desired balance between performance, cost, and environmental effect often guides the selection of matrix material.

Out of the widely used polymer matrices for these natural filler composites, epoxy resins stand out because of their exceptional adhesiveness, ease of processing, and remarkable chemical resistance. Their cost, biodegradability, and dependency on non-renewable resources are clear

negatives, though [17,18]. Under such circumstances, Vinyl ester resins prove to be excellent substitutes for epoxy resins, providing a balance of characteristics and cost-effectiveness for composite construction while still preserving environmental friendliness and the possibility for biodegradability [19]. Recent studies by several researchers point to vinyl ester resins improving the properties of hybrid natural filler composites, so providing a good replacement for epoxy resins. Moreover, as vinyl ester resins have better properties, such as minimal shrinkage, good thermal characteristics, and strong chemical resistance [20–22], they can be considered the ideal matrix for hybrid composites.

Both the thermal and mechanical characteristics of areca nut shell powder (ASP) and Pineapple Leaf Powder (PLP) as a hybrid have not yet been completely investigated. The knowledge gaps highlight the requirement of a comprehensive evaluation of both the thermal and mechanical features of hybrid filler-reinforced composites with vinyl ester resin based on several influencing parameters. Particularly in sectors like automotive and civil engineering, the results of this study will likely offer insightful analysis for the creation of next-generation hybrid filler composites. The study aims to identify the best filler mix to improve composite performance and support sustainable material development and efficient waste management. The suggested method's use of commonly accessible agricultural waste provides a reasonably priced solution that lowers the environmental impact of composite products and enhances their applications in industry.

2 Materials and methods

2.1 Materials

Due to their plentiful availability in the area, 3 kg of areca nut shells and pineapple leaves were used as reinforcement fillers for this experimental study, obtained from local agricultural suppliers near Madurai, Tamil Nadu, India. Regionally common are areca nut shells, a byproduct of areca palm cultivation, and pineapple leaves, from pineapple farming. GSRR Resins and Polymers, Madurai, India, sourced the matrix material, Vinyl Ester (VE) resin (styrene content–45%), density 1.12 g/cm³, viscosity 350–400 cps, and specific gravity 1.08. Curing agents N-dimethylaniline (C₈H₁₁N—promoter), methyl ethyl ketone peroxide (C₈H₁₈O₆—catalyst), and cobalt 6% naphthenate (C₂₀H₃₄CoO₄—accelerator) [23] Were also acquired from GSRR Resins and Polymers in the advised amounts to assist the curing process.

2.2 Fabrication of composites

The ASP was finely ground and milled into fine powders of particle size in the range 50 μm - 150 μm [24]. Similarly, the PLP was prepared through mechanical processing and sieving with a sieve grid of 0.3 mm to achieve a comparable distribution of fine powders of size close to 75 μm [25]. Maintaining uniformity in the fine powders is crucial for obtaining a composite with consistent mechanical and thermal properties across a large area, as the general performance of the composite material is much influenced by the powder properties.

2.2.1 Material Characteristics

- ASP Density: 1.25 g/cm³ [26]
- PLP Density: 0.97 g/cm³ [27,28]
- ASP Composition: Cellulose (35-65%), Lignin (15-35%), Natural silica content [29,30]
- PLP Composition: Cellulose (70-82%), Lignin (10%), Moisture (12%) [31]

To ensure uniformity, all composites were prepared following the same protocol. The reinforcement materials were mixed evenly along with the vinyl ester matrix using a systematic approach. The hand lay-up process was selected due to its simplicity and ability to produce consistent laminates at a controlled fiber content. For mechanical and thermal properties enhancement of the composites, the resin system was optimised with respect to the curing process, and a post-curing process was applied at high temperatures. [32,33]. Total filler loading remained in between 0-20 wt.% with varying ASP: PLP ratios while keeping vinyl ester content at 100-80 wt.%, resulting in six different combinations. These blends were chosen particularly to evaluate how variations in filler fraction and ratio influence the performance of the composites. We have implemented this method to investigate equal and different ratios of ASP/PLP and to determine the most ideal mix in terms of mechanical strength and thermal stability. To find the threshold at which the composite qualities begin to decline, both fillers were equally added at weight fractions of 0, 4, 8, 12, 16, and 20%. Composites were produced by the hand lay-up method and cured over 24°C at room temperature. Table 1 shows the detailed configuration of various combinations. The processing parameters were maintained constant for all combinations to ensure consistency in the fabrication process.

Table 1. Different Combinations of ASP-PLP with Vinyl Ester

Combination	Total Filler (wt.%)	ASP: PLP Ratio	Vinyl Ester (wt.%)
C1	0	0	100
C2	4	2:2	96
C3	8	4:4	92
C4	12	6:6	88
C5	16	8:8	84
C6	20	10:10	80

2.2.2 Manufacturing

We selected a varied weight percentage of filler combinations to produce composite materials with total filler content varying from 0-20 wt.% of reinforcement materials (ASP and PLP) and 80-100 wt.% of Vinyl Ester (VE) as matrix. We used the hand lay-up method for the hybrid composite manufacturing. The matrix material, along with the hardener and catalyst, was purchased from Vasavibala Resins, K.K. Nagar, Madurai, Tamil Nadu.

Initially, the blending was carried out with Catalyst - Methyl ethyl ketone peroxide (MEKP) at 1.5 wt.%, hardener (Cobalt naphthenate) at 2 wt.%, and thinner was poured into the the matrix container and evenly mixed with the help of mechanical stirrer for about 5-10 minutes to aid the initiation of the reaction to occur. As the initial blending was completed, the pre-weighed quantities of ASP and PLP were gradually added to the resin mixture while continuing mechanical stirring at 400 rpm for another 5-10 minutes for proper dispersion to take place.

Wood material was used to prepare the mold cavity based on the ASTM Standards. We cleaned the mold using isopropyl alcohol to remove any contaminants. Then, three coats were made with carnauba wax to act as a release agent. Subsequently, the hand lay-up method was used to fill the mold with a blended mixture of the reinforcement materials and lower matrix material. After being dried at ambient temperature ($27\pm 2^{\circ}\text{C}$) for 24 hours, the hybrid composite specimens were post-cured at 80°C for roughly four hours. Six different combinations—C1 through C6—were produced under constant processing conditions for all the samples. For mechanical and thermal testing, the specimens were thus sized and shaped in line with ASTM guidelines.

3 Experimental work

3.1 Tensile testing

Tensile testing following ASTM D638 was performed using a Universal Testing Machine (UTM). Tensile testing reveals the deformation resistance of the material and failure under uniaxial tension, thereby guiding the choice of the composites for load-bearing uses. Measuring 165 mm in length by 13 mm by 3 mm by thickness, the specimen was These specimens were evaluated under a speed of cross-head ranging 2 mm/minute under room temperature ($27\pm 2^{\circ}\text{C}$) according to ASTM D3039 / D3039M-17 standards. The specimen was set with its ends into the clamping grips of the testing equipment, then the weight was raised gradually until it failed.

3.2 Flexural testing

Flexural strength tests were performed using the three-point bending method, adhering to ASTM D790 criteria. Measured flexural strength revealed the composite's ability to withstand common bending loads in real-world uses such as cars and building materials. Examined at a 5 mm/min crosshead speed following ASTM D790 standard were the specimens. The test specimen measured 100 mm in span length, 12.7 mm in breadth, and 3 mm in thickness.

3.3 Impact Testing

The impact resistance for ASP-PLP vinyl ester composites was evaluated through Izod impact testing by the ASTM D256 standard. The test specimens had dimensions of 63.5 mm \times 12.7 mm \times 3.2 mm with a V-notch of 2.54 mm depth at a 45° angle. Using a pendulum impact tester with a 5.4 J hammer capacity, the testing was conducted at room temperature. Five specimens of varying filler compositions were tested to ensure statistical validity.

3.4 Shore D Hardness Testing

A digital durometer was used, and all measurements of Shore D hardness were performed according to ASTM D2240. The Shore D hardness testing method was used to determine the composites' surface hardness, which indicates their wear resistance. Specimens were produced with 6 mm thickness. Between the two measurements, there was a spacing of 6 mm, and five measurements were not measured at the same location of the specimen. An indenter was applied to the specimen while maintaining its parallelism to the surface, and readings were averaged after one second of firm contact.

3.5 Thermogravimetric Analysis (TGA)

A Perkin Elmer TGA analyser was used to conduct TGA under a nitrogen atmosphere. The samples, weighing between 5 and 10 mg, were selected and heated starting from room temperature to 800°C while keeping the heating rate constant at 10°C/min. Over the experiment, weight loss was noted to vary with temperature.

Heat Deflection Temperature (HDT)

The HDT measurements followed the ASTM D648 standard, and an HDT/Vicat testing machine was used to carry out the testing. The specimen dimensions were 127 mm × 13 mm × 3 mm, and it was subjected to a load of 1.82 MPa. The HDT was recorded at the temperature where it took the deflection by 0.25 mm under the applied load, marking the standard deflection during the flexural testing process.

4 Results and discussions

4.1 Tensile Properties

The tensile characteristics of the manufactured composites were examined, as illustrated in Figure 1. The pure vinyl ester resin (C1) revealed a tensile strength of 58.25 MPa, with the composite containing 20 wt.% total filler (C6) reporting the lowest tensile strength of 38.45 MPa, the tensile strength decreased progressively as the filler content increased.

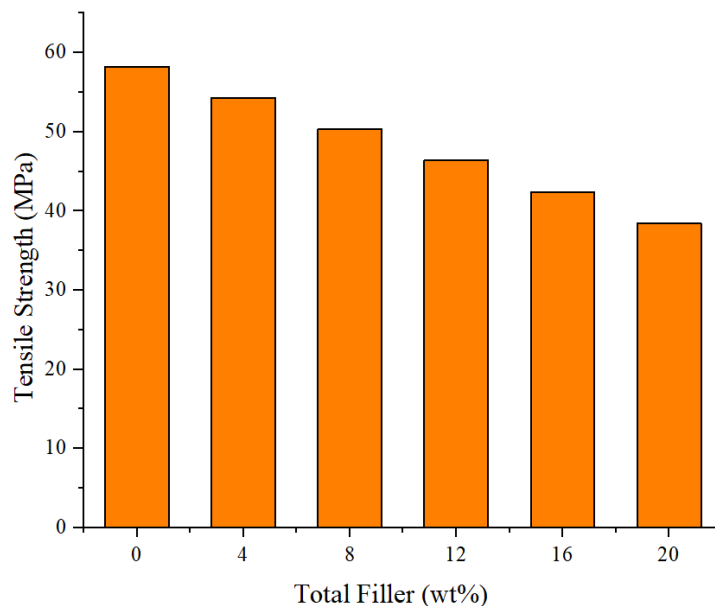


Fig. 1. Tensile Strength of Vinyl Ester Composites as a Function of Total Filler Content (ASP and PLP)

Particle agglomeration and weak interfacial bonding between the hybrid filler and the vinyl ester matrix were likely responsible for the drop in tensile strength observed with increasing filler concentration. Higher filler loads show more natural filler, which seems to encourage poor dispersion and causes microvoids and compromised filler-matrix interactions. Particularly clear in composites with higher filler material, where particle agglomeration aggravates the drop in mechanical performance, these elements taken together help to explain the decline in tensile strength [34].

4.2 Flexural Properties

Unlike their tensile characteristics, the flexural properties of the vinyl ester composites exhibited a clear trend, as shown in Figure 2. With filler loadings of up to 16 wt.%, flexural strength improved; however, beyond this point, it fell noticeably. The flexural strength from the pure vinyl ester at lower filler concentrations enhanced to a maximum at 16 wt.%, which may be ascribed to better stress transfer and more robust hybrid filler and the vinyl ester matrix interfacial adhesion. This development implies that a balanced filler composition at these levels allows efficient load distribution, therefore improving the capacity of the composite to resist bending forces. But, as filler content surpassed 16 wt.%, a drop in flexural strength became clear, probably caused by filler agglomeration and weakened interfacial bonding. Higher filler loadings seem to be affected by particle clustering and greater void creation, which seem to reduce the load transfer efficiency and cause a decline in flexural performance.

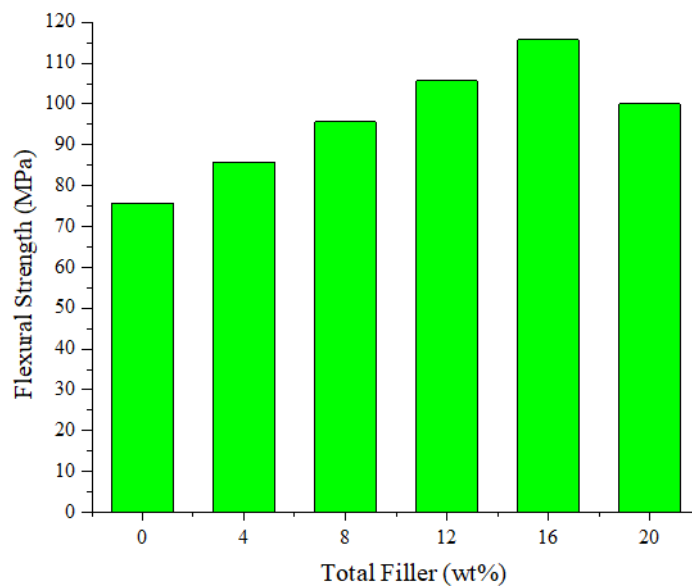


Fig. 2. Flexural Strength of Vinyl Ester Composites as a Function of Total Filler Content (ASP and PLP)

4.3 Impact Properties

With the neat vinyl ester resin (C1) exhibiting an impact strength of 12.5 kJ/m², the impact strength of the ASP and PLP-reinforced vinyl ester composites demonstrated a remarkable dependence on filler content, as illustrated in Figure 3. The impact resistance rose while adding areca nut shell powder (ASP) and pineapple leaf powder (PLP), reaching 18.2 kJ/m² for the composite with 16 wt.% filler loading (C5). Observed up to 16 wt.%, this improvement indicates a better energy absorption capacity, probably resulting from the hybrid fillers' effective contribution, which strengthens the matrix and enables more efficient dissipation of impact forces. The increase in strength, which is 1.46 times greater than the neat resin, implies that the fillers improve the composite's capacity to withstand sudden loads at these concentrations. Beyond this ideal filler level, though, its impact strength fell to 15.8 kJ/m² for the 20 wt.% filler composite (C6). Filler agglomerates forming causes this decline as they compromise uniform load distribution and create stress concentration sites, reducing the general toughness. The trend suggests that 16 wt.% is the ideal filler concentration to obtain balanced mechanical performance in these hybrid composites.

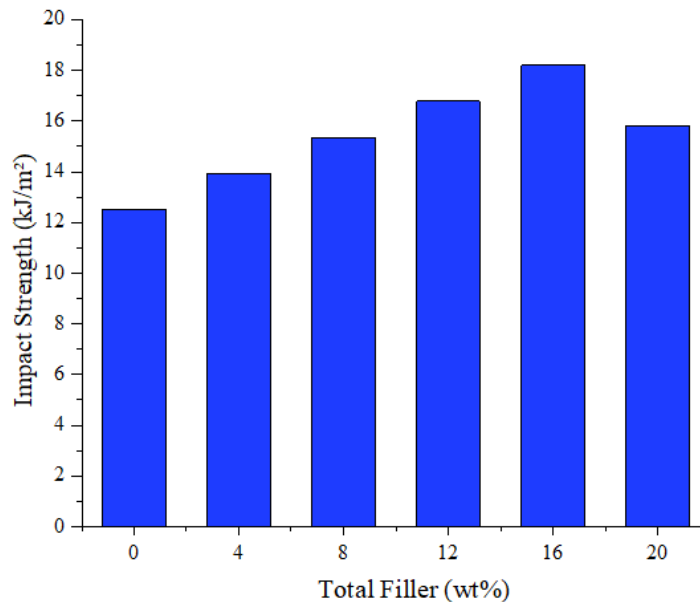


Fig. 3. Impact Strength of Vinyl Ester Composites as a Function of Total Filler Content (ASP and PLP)

4.4 Shore D Hardness

Figure 4 shows the steady rise in Shore D hardness values under filler loading. The rise in Shore D hardness with rising filler content points to the fillers' reinforcing action. The composite gets harder and more indelible as the filler content rises. Applications where resistance to wear and surface deformation is vital, such those involving automotive and industrial components, benefit especially from this increase in hardness. However, a slight decrease in hardness was observed at 20 wt.% filler content, which could be attributed to the reduced quality of the filler dispersion. The neat vinyl ester (C1) exhibited a hardness value of 82, which increased to 88 for C5 (16 wt.% filler) and slightly decreased to 86 for C6 (20 wt.% filler). The enhanced hardness can be attributed to the hard particulate nature of ASP and the reinforcing effect of PLP.

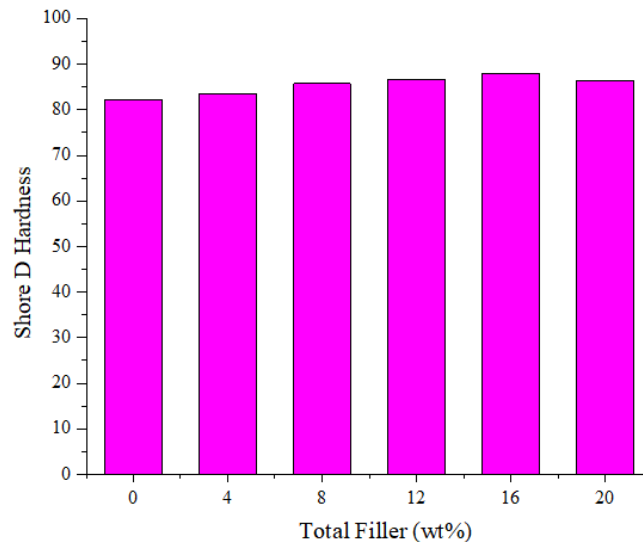


Fig. 4. Shore D Hardness of Vinyl Ester Composites as a Function of Total Filler Content (ASP and PLP)

Unlike tensile strength, which shows a continuous decrease, both impact strength and Shore D hardness show improvement up to 16 wt.% total filler loading (C5) before declining at higher filler content, following the trend observed in flexural properties.

4.5 Morphological Analysis

Scanning electron microscopy (SEM) on a JEOL instrument model JSM-5300LV, operating at 10 kV, was used to perform morphological analysis of vinyl ester composites reinforced with Areca Nut Shell Powder (ASP) and Pineapple Leaf Powder (PLP), examining the fractured

surfaces from tensile, flexural, and impact tests. Figure 5 presents the SEM micrograph of the tensile-tested fractured surfaces for the C5 composite sample with 16% total filler (ASP, PLP 8:8). The addition of ASP and PLP fillers to the vinyl ester matrix resulted in uneven filler distribution, clusters, agglomeration, and voids, which in turn contributed to the decline of tensile strength consistently while comparing to the neat vinyl ester resin. In the C5 sample (16 wt.% filler), the micrographs revealed clusters of fillers with inconsistent dispersion, leading to a tensile strength of 42.41 MPa. This represents a notable decline compared to the typical tensile strength of commercial-grade, neat vinyl ester resin, which is approximately 80 MPa [35]. The C6 sample (20 wt.% filler) exhibited even more pronounced agglomeration and void formation, further reducing the tensile strength to 38.45 MPa. These observations indicate that the incorporation of fillers disrupted the matrix integrity, causing poor interfacial bonding and stress concentration points, which contributed to the diminished tensile properties relative to the neat resin.

For the flexural-tested samples, as shown in Figure 6, the C5 composite exhibited a fracture surface with minimal cracks and strong filler-matrix adhesion, supporting the peak flexural strength of 115.75 MPa. The uniform dispersion of ASP and PLP particles prevented extensive crack propagation, enhancing the composite's ability to resist bending forces. Conversely, the C6 sample showed increased crack formation and agglomeration, correlating with the reduced flexural strength (100.00 MPa). The SEM images highlighted regions where the matrix failed to encapsulate the fillers fully, leading to stress concentration points and a decline in performance. The impact-tested samples in Figure 7 further corroborated these findings. The C5 composite displayed a tougher fracture surface with evidence of energy dissipation through filler-matrix interaction, consistent with its peak impact strength of 18.2 kJ/m². The micrographs showed fewer voids and a more cohesive structure. In the C6 sample, however, the presence of agglomerates and detached fillers indicated reduced toughness, reflected in the lower impact strength of 15.8 kJ/m². The increased filler content appeared to hinder the matrix's ability to absorb and distribute impact energy effectively.

The morphological analysis clearly illustrates that the mechanical properties of ASP-PLP-reinforced vinyl ester composites are strongly influenced by filler dispersion and interfacial bonding. For tensile properties, the addition of fillers led to agglomeration and uneven distribution, significantly reducing strength compared to the neat vinyl ester resin's commercial benchmark of ~80 MPa. However, at 16 wt.% filler loading (C5), the hybrid composite achieved an optimal balance for flexural and impact properties, with minimal voids and

effective filler-matrix adhesion, resulting in superior performance in these tests. At 20 wt.% (C6), the increased filler concentration exacerbated agglomeration and void formation and reduced mechanical performance across all tests. These observations emphasise the importance of optimising filler content to balance the reinforcing effect of ASP and PLP in vinyl ester composites.

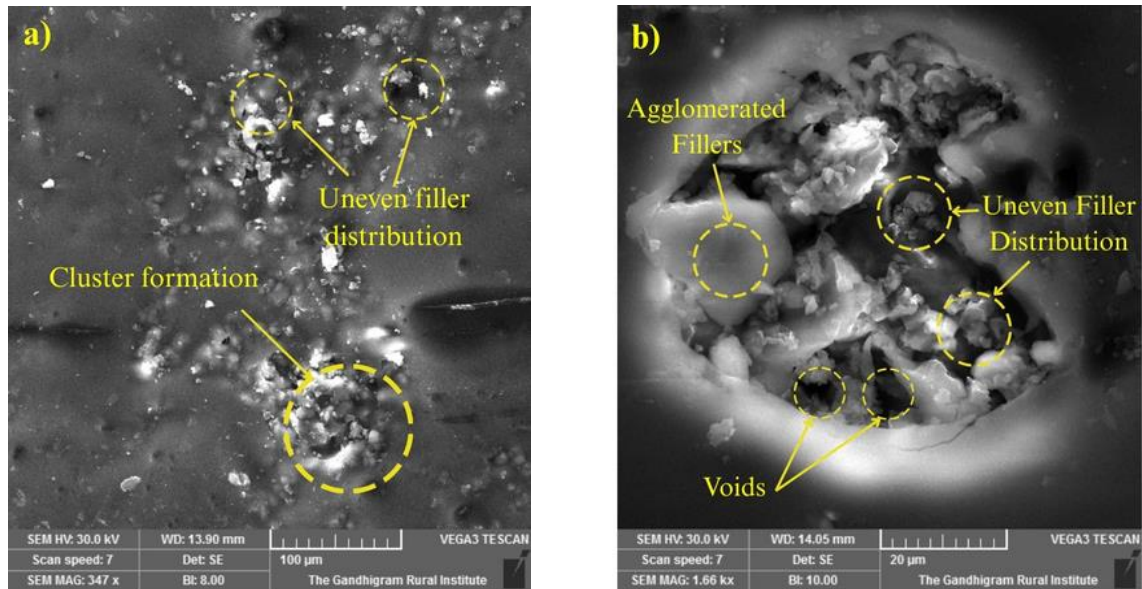


Fig. 5. Fractured surface morphology of tensile tested sample containing a) C5 16% b) C6 20 wt.% of hybrid filler

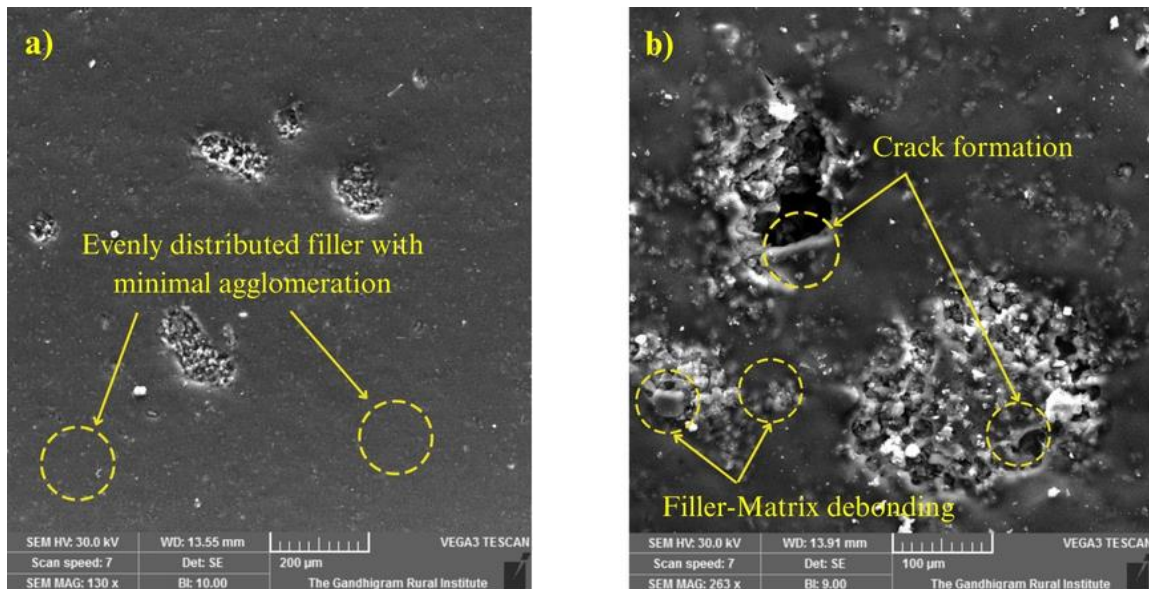


Fig. 6. Fractured surface morphology of flexural tested samples, a) C5 16 wt.% of hybrid filler b) C6 20 wt.% of hybrid filler

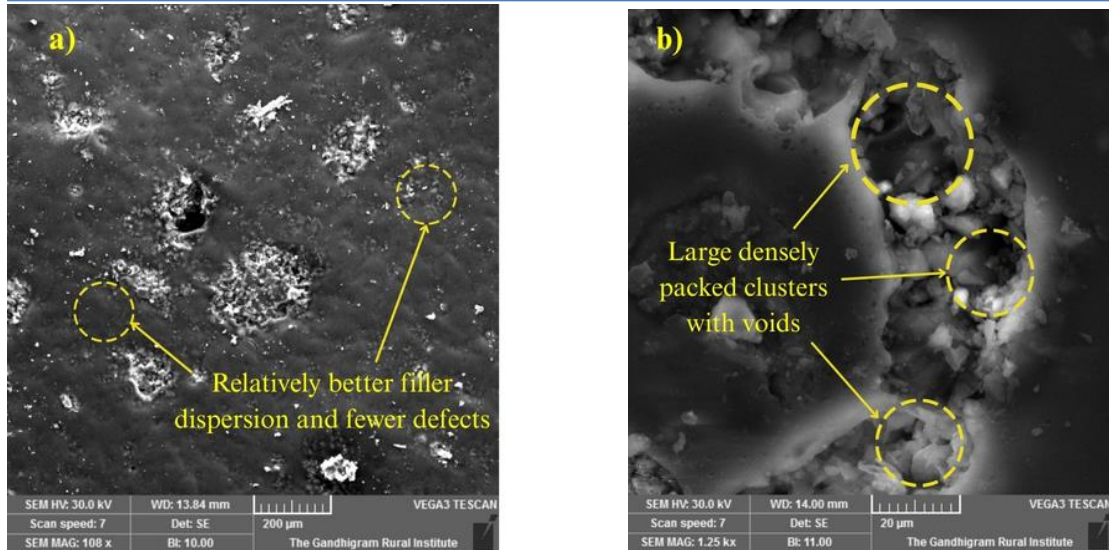


Fig. 7. Fractured surface morphology of impact tested samples, a) C5 16 wt.% of hybrid filler b) C6 20 wt.% of hybrid filler

4.6 TGA analysis

The thermal properties of Areca Nut Shell Powder (ASP) and Pineapple Leaf Powder (PLP) reinforced vinyl ester composite (C5) were evaluated under a nitrogen atmosphere using Thermogravimetric Analysis. At a constant heating rate of 10°C/min, the samples, weighing 5-10 mg, were heated from room temperature to 800°C, with weight loss being recorded as a function of temperature. As shown in Figure 8 (a), the TGA results revealed that the C5 composite (16 wt.% total filler, ASP: PLP = 8:8) exhibited a significantly higher initial degradation temperature of 348°C and a maximum degradation temperature of 412°C. This enhancement, approximately 23°C higher than the neat resin, demonstrates the reinforcing effect of the hybrid ASP and PLP fillers. It is evident from Figure 8 (b) the improved thermal stability is attributed to the lignocellulosic composition of the fillers which is cellulose (35-65% in ASP, 70-82% in PLP), lignin (15-35% in ASP, 10% in PLP), and natural silica in ASP for those collectively enhance resistance to thermal degradation.

Additionally, the composite showed a higher char residue of 18% at 800°C, indicating reduced mass loss and greater thermal resistance. This increased char formation suggests that the hybrid fillers contribute to a protective layer during decomposition, further supporting the material's suitability for applications requiring lightweight, thermally stable materials, such as automotive under-hood components or construction elements exposed to elevated temperatures.

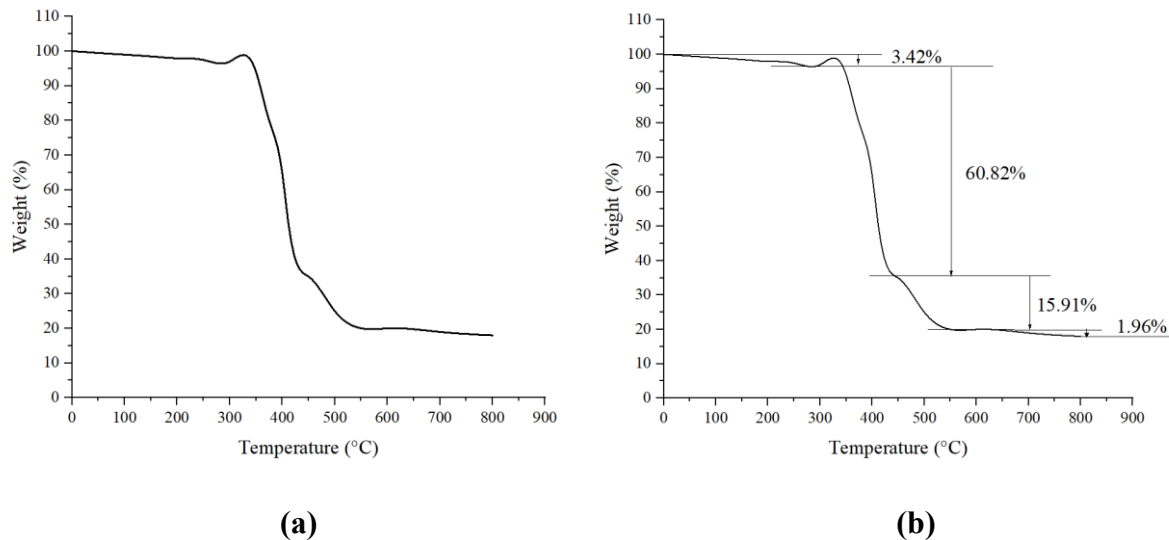


Fig. 8. a), b) TGA Curve of ASP-PLP Reinforced Vinyl Ester Composite C5 Showing Weight Loss as a Function of Temperature.

4.7 Heat deflection temperature tests

To determine the thermal resistance under load of areca nut shell powder (ASP) and pineapple leaf powder (PLP) reinforced vinyl ester composites, their Heat Deflection Temperature (HDT) was evaluated over a spectrum of filler loadings as shown in Figure 9. Serving as the baseline for comparison, the neat vinyl ester resin (C1) showed an HDT of 89°C. The HDT values revealed a steady rise up to a filler concentration of 16 wt.% with the addition of ASP and PLP fillers. At this level, the composite with 16 wt.% total filler (C5) reached a maximum HDT of 112°C, signifying a 1.26-fold increase over the pure resin. This development highlights the role of the hybrid fillers in enhancing thermal stability, most likely by restricting polymer chain mobility and so increasing the structural stiffness of the composite. But as the filler concentration climbed from 16 wt.% to 20 wt.% (C6), the HDT did drop considerably to 108°C. Higher filler loadings reveal a decline that points to filler agglomeration, which could cause thermal weak spots and damage the composite's capacity to tolerate deformation under combined heat and mechanical stress. The observed trend, an initial rise followed by a reduction, highlights the critical need to optimise filler content to reach optimal thermal performance. Reaching 112°C, the improved HDT of up to 16 wt.% shows how efficiently ASP and PLP stabilise vinyl ester composites thermally. This implies they are suitable materials for use in demanding resilience to high temperatures, like structural components subjected to intense heat.

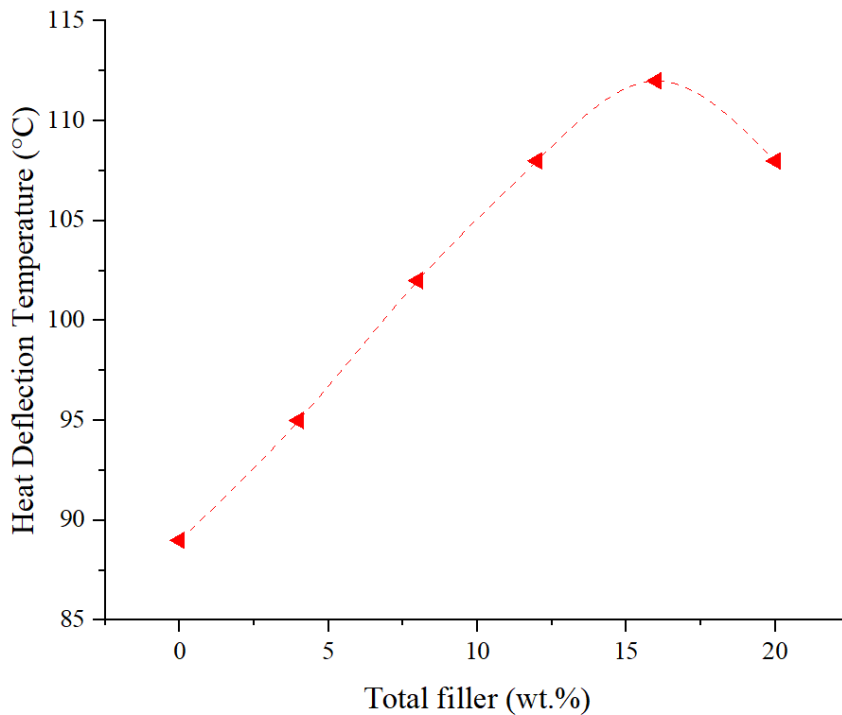


Fig. 9. Heat deflection temperature against total filler wt. % of ASP-PLP loaded VE composite

5 Conclusion

Fabricated using the hand lay-up process, the present research examined the mechanical and thermal characteristics of hybrid composites reinforced with areca nut shell powder (ASP) and pineapple leaf powder (PLP) in a vinyl ester matrix. Using static mechanical tests, including tensile, flexural, impact, hardness, and thermal analyses (TGA, HDT), the performance of these composites throughout filler loadings ranging from 0 to 20 weight percent was assessed. The following results were observed.

1. The composite with 16 wt.% total filler (C5, 8 wt.% ASP and 8 wt.% PLP) showed best flexural strength (115.75 MPa), impact strength (18.2 kJ/m²), and Shore D hardness (88), representing improvements of 53%, 46%, and 7%, respectively, over the clean vinyl ester resin. These qualities were better than those of the 20 wt.% filler composite (C6, 10 wt.% ASP and 10 wt.% PLP) by 15.75%, 15.19%, and 1.92%, respectively. Due to particle agglomeration and lower interfacial bonding, tensile strength fell with rising filler content from 58.25 MPa for the neat resin (C1) to 38.45 MPa at 20 wt.% filler (C6).

2. The C5 composite showed improved thermal stability with an initial degradation temperature rise to 348°C and a heat deflection temperature (HDT) of 112°C. Attributed to the lignocellulosic character of the fillers improving matrix stability, these changes show better resistance to thermal degradation and deformation under load when compared to 325°C and 89°C for the neat resin.
3. Scanning electron microscopy (SEM) revealed that the C5 composite exhibited low voids and high filler-matrix adhesion, which corresponded to its optimal mechanical performance. By contrast, the C6 composite revealed more agglomeration and void creation, which lowered its properties and underlined the need for ideal filler distribution.
4. At 16 wt.% total filler loading (ASP: PLP, 8:8), these composites strike a good balance between mechanical strength and thermal stability, which makes them appealing for applications in transportation, such as automotive interiors and construction of non-structural panels in the construction industry. By utilising agricultural waste of approximately 1.5–2 million tonnes of Areca Nut shells and 20,000–25,000 tonnes of pineapple leaves, these materials present a sustainable and cost-effective alternative to synthetic reinforcements, thereby promoting waste management and environmental preservation.

Future studies could explore surface modification strategies to enhance filler-matrix adhesion, thereby reducing the loss of tensile strength, and investigate long-term durability to increase the practical applications of these hybrid biocomposites.

Declaration of competing interest

The author declare that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data used for the research described in the article will be available upon valid request.

References

- [1] Sathish Kumar RK, Sasikumar R, Dhilipkumar T. Exploiting agro-waste for cleaner production: A review focusing on biofuel generation, bio-composite production, and environmental considerations. *J Clean Prod* 2024;435. <https://doi.org/10.1016/j.jclepro.2023.140536>.

- [2] Bharath KN, Basavarajappa S. Applications of biocomposite materials based on natural fibers from renewable resources: A review. *Science and Engineering of Composite Materials* 2016;23:123–33. <https://doi.org/10.1515/secm-2014-0088>.
- [3] Volpe V, Pantani R. Natural fiber-reinforced light composites for the automotive industry. *Polym Compos* 2025. <https://doi.org/10.1002/pc.29518>.
- [4] Mital'ová Z, Litecká J, Duplák J. Agro-Fiber Based Composites With Use in Automotive Industry. *TEM Journal* 2024;2429–35. <https://doi.org/10.18421/TEM133-70>.
- [5] McNeill DC, Pal AK, Nath D, Rodriguez-Urbe A, Mohanty AK, Pilla S, et al. Upcycling of ligno-cellulosic nutshells waste biomass in biodegradable plastic-based biocomposites uses - a comprehensive review. *Composites Part C: Open Access* 2024;14. <https://doi.org/10.1016/j.jcomc.2024.100478>.
- [6] World Food and Agriculture – Statistical Yearbook 2024. 2024. <https://doi.org/10.4060/cd2971en>.
- [7] Katipalla A, Ballal P, Shivanna NK. Areca Nut Husk: A Burning Issue? *Indian Journal of Respiratory Care* 2024;13:140–1. <https://doi.org/10.5005/jp-journals-11010-1108>.
- [8] Lalmunsiam, Lee SM, Choi SS, Tiwari D. Simultaneous removal of Hg(II) and phenol using functionalised activated carbon derived from Areca nut waste. *Metals (Basel)* 2017;7. <https://doi.org/10.3390/met7070248>.
- [9] Sharma SR, S SS. Use of areca-nut husk ash (AHA) in brick preparation and its impact analysis 2022. <https://doi.org/10.21203/rs.3.rs-1578847/v1>.
- [10] Mishra RK, Gariya B, Savvasere P, Dhir D, Kumar P, Mohanty K. Thermocatalytic Pyrolysis of Waste Areca Nut into Renewable Fuel and Value-Added Chemicals. *ACS Omega* 2024;9:25779–92. <https://doi.org/10.1021/acsomega.3c10184>.
- [11] Fouda-Mbanga BG, Tywabi-Ngeva Z. Application of Pineapple Waste to the Removal of Toxic Contaminants: A Review. *Toxics* 2022;10. <https://doi.org/10.3390/toxics10100561>.
- [12] Sangma ARW, Joshi SR. Areca nut: Traditional processing, uses and products potential of the husk. n.d.
- [13] Azhar Ekoputra F, Ismail I. Effect a Chemical Treatment of Pineapple Leaf Fiber (PALF) for Mechanical Properties as a Reinforced Composite Matrix Polyesters. n.d.
- [14] Nagaprasad N, Vignesh V, Karthik Babu NB, Manimaran P, Stalin B, Ramaswamy K. Effect of green hybrid fillers loading on mechanical and thermal properties of vinyl ester composites. *Polym Compos* 2022;43:7928–39. <https://doi.org/10.1002/pc.26925>.
- [15] Babu NBK, V V, Arun Balasubramanian K, S KD, Khan A, Hashem M, et al. Effect of natural hybrid fillers reinforced vinyl ester composites on mechanical and physical properties. *Mater Res Express* 2024;11:105504. <https://doi.org/10.1088/2053-1591/ad8105>.
- [16] Jagadeesh P, Puttegowda M, Thyavihalli Girijappa YG, Rangappa SM, Siengchin S. Effect of natural filler materials on fiber reinforced hybrid polymer composites: An

-
- Overview. *Journal of Natural Fibers* 2022;19:4132–47. <https://doi.org/10.1080/15440478.2020.1854145>.
- [17] Zhao Y, Kikugawa G, Kawagoe Y, Shirasu K, Okabe T. Molecular-scale investigation on relationship between thermal conductivity and the structure of crosslinked epoxy resin. *Int J Heat Mass Transf* 2022;198. <https://doi.org/10.1016/j.ijheatmasstransfer.2022.123429>.
- [18] Di Landro L, Janszen G. Composites with hemp reinforcement and bio-based epoxy matrix. *Compos B Eng* 2014;67:220–6. <https://doi.org/10.1016/j.compositesb.2014.07.021>.
- [19] Bahrami M, Abenojar J, Martínez MÁ. Recent progress in hybrid biocomposites: Mechanical properties, water absorption, and flame retardancy. *Materials* 2020;13:1–46. <https://doi.org/10.3390/ma13225145>.
- [20] Sathish Kumar RK, Sasikumar R, Nagaprasad N, Ezhilvannan R, Krishnaraj R. Investigation of Mechanical and Thermal Stabilities of Tamarind Seed- and Peanut Shell Powder-Reinforced Vinyl Ester Composite. *Advances in Materials Science and Engineering* 2024;2024. <https://doi.org/10.1155/2024/8818030>.
- [21] Stalin A, Mothilal S, Vignesh V, Sanjay MR, Siengchin S. Mechanical properties of hybrid vetiver/banana fiber mat reinforced vinyl ester composites. *Journal of Industrial Textiles* 2022;51:5869S-5886S. <https://doi.org/10.1177/1528083720938161>.
- [22] Ramakrishnan M, Ramasubramanian S, Raman SS, Chinnapalanichamy J. Evaluation of the physical, mechanical, water absorption, and tribological behavior of pineapple leaf fiber/roselle fiber reinforced vinyl ester hybrid composites for non-structural applications. *Polym Compos* 2023;44:5284–95. <https://doi.org/10.1002/pc.27491>.
- [23] Stalin B, Nagaprasad N, Vignesh V, Ravichandran M. Evaluation of mechanical and thermal properties of tamarind seed filler reinforced vinyl ester composites. *Journal of Vinyl and Additive Technology* 2019;25:E114–28. <https://doi.org/10.1002/vnl.21701>.
- [24] Thangaraj S, Pradeep GM, Heaven Dani MS, Mayakannan S, Benham A. Experimental investigations on tensile and compressive properties of nano alumina and arecanut shell powder reinforced polypropylene hybrid composites. *Mater Today Proc*, vol. 68, Elsevier Ltd; 2022, p. 2243–8. <https://doi.org/10.1016/j.matpr.2022.08.442>.
- [25] Eze IO, Igwe IO, Ogbobe O, Anyanwu EE, Nwachukwu I. Mechanical Properties of Pineapple Leaf Powder Filled High Density Polyethylene. *International Journal of Engineering and Technologies* 2016;9:13–9. <https://doi.org/10.18052/www.scipress.com/ijet.9.13>.
- [26] Palanisamy S, Palanisami K, Madeshwaren V. Nano iron particles influence on mechanical properties and morphological analysis of polymer composites. *Revista Materia* 2025;30. <https://doi.org/10.1590/1517-7076-RMAT-2024-0698>.
- [27] Io E, Io I, Ogbobe O, Hc O, Ul E, Sc N, et al. Effects of Hydrogen Peroxide Treated Pineapple Leaf Powder on Mechanical Properties of High Density Polyethylene Composites. vol. 4. 2017.
-

- [28] Selamat MZ, Zhafri Tahir MS, Kasim AN, Dharmalingam S, Putra A, Yaakob MY, et al. Effect of starch sizes particle as binder on short pineapple leaf fiber composite mechanical properties. *MATEC Web of Conferences* 2018;150:04008. <https://doi.org/10.1051/mateconf/201815004008>.
- [29] Somashekhara J, Ramesh B T, Vinay Belagavi, Madhu H T. Investigation and Study of Mechanical Properties of Areca Shell Fiber and Palm Powder Natural Composites. *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)* 2018;15:62–73.
- [30] Hu C, Battampara P, Guna V, Reddy N. Effect of Alkali Treatment on the Structure and Properties of Natural Cellulose Fibers from Areca Cathechu Shells. *Journal of Natural Fibers* 2022;19:9754–64. <https://doi.org/10.1080/15440478.2021.1993405>.
- [31] Cheirmakani BM, Subburaj B, Balasubramanian V. Exploring the Properties of Pineapple Leaf Fiber and Prosopis Julifora Powder Reinforced Epoxy Composite. *Journal of Natural Fibers* 2022;19:2065–76. <https://doi.org/10.1080/15440478.2020.1798844>.
- [32] Dev S, Shah PN, Zhang Y, Ryan D, Hansen CJ, Lee Y. Synthesis and mechanical properties of flame retardant vinyl ester resin for structural composites. *Polymer (Guildf)* 2017;133:20–9. <https://doi.org/10.1016/j.polymer.2017.11.017>.
- [33] Jaswal S, Gaur B. New trends in vinyl ester resins. *Reviews in Chemical Engineering* 2014;30:567–81. <https://doi.org/10.1515/revce-2014-0012>.
- [34] Melnychuk M, Shevchuk I, Kashytskyi V, Feshcuk Y, Polivoda N. Mechanical Properties of Hybrid Composites Based on Polypropylene Modified with Natural Fillers, 2023, p. 221–9. https://doi.org/10.1007/978-3-031-32774-2_22.
- [35] Kandelbauer A, Tondi G, Zaske OC, Goodman SH. Unsaturated polyesters and vinyl esters. *Handbook of Thermoset Plastics*, Elsevier; 2022, p. 97–158. <https://doi.org/10.1016/B978-0-12-821632-3.00015-4>.