

A general review on pineapple leaf fiber as a building block for composite materials

Abstract

Pineapple leaf fiber (PALF) has attracted increasing attention as an agricultural residue for the development of composite and functional materials. This review examines PALF from its composition and fundamental characteristics to its modification, processing, applications, and environmental implications. The chemical composition, morphology, crystallinity, thermal behaviour, and mechanical characteristics of PALF are discussed in relation to its performance in material systems. Particular attention is given to modification methods, including hot water, alkali, acid hydrolysis, bleaching, silane, calcium hydroxide, and combined treatments, and their effects on non-cellulosic constituents, fiber structure, and interfacial behaviour. The review further covers the fabrication of PALF-based composites using different polymer matrices and emerging applications involving aerogels and carbon-based materials. Available environmental evidence is also examined to identify the influence of fiber extraction and processing on carbon emissions and the potential environmental benefits associated with the utilization of agricultural residues and PALF biodegradability. By bringing these aspects together, this review provides an updated assessment of the factors governing the processing and performance of PALF-based materials and identifies areas requiring further investigation.

Keywords: Pineapple leaf fiber, natural fiber, lignocellulosic materials, polymer composites, aerogels

Volume 12 Issue 5 - 2026

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Received: September 13, 2026 | **Published:** October 27, 2026

Introduction

Growing environmental concerns, restrictions on unsustainable materials, and the finite nature of petroleum resources have increased interest in materials derived from renewable sources. Petroleum, natural gas, and coal remain major raw materials for conventional plastics and related polymeric products, creating a strong need for alternative materials with lower dependence on non-renewable resources.¹ Natural materials have therefore gained increasing attention in material development, particularly for products associated with resource efficiency and the broader objectives of sustainable production and consumption.² In polymer composites, reinforcement with fibers and other fillers provides an important route for modifying material strength and stiffness while reducing reliance on fully petroleum-based reinforcement systems.¹

Plant-based fibers have become important reinforcement materials because of their availability and compatibility with composite manufacturing. Jute, flax, kenaf, ramie, and pineapple leaf fiber (PALF) are among the natural fibers investigated for this purpose. Among them, PALF has attracted particular attention because of its high cellulose content, relatively high fiber strength, availability, and low cost.³ Pineapple leaves are widely available in tropical regions and are often treated as agricultural residues, with disposal by burning reported in pineapple-producing areas. Their utilisation as a fiber source can therefore create additional value from an underused biomass resource. PALF has long been used for textile applications, while its use has expanded to products including sporting goods, luggage, automotive components, cabinets, carpets, and industrial materials.^{1,2}

The composition and physical characteristics of PALF make it particularly relevant for composite development. Its cellulose content can reach nearly 80%, placing it among the natural fibers with high cellulose fractions.⁴ PALF also exhibits favourable tensile

properties and Young's modulus relative to several other natural fibers at comparable density. These characteristics have supported its incorporation into structural laminates and sandwich structures, with potential uses in furniture, automotive components, and building materials. Its increasing use in composite materials also extends beyond conventional structural reinforcement to other material forms, including paper-related products and emerging fiber-derived materials.

Despite these advantages, PALF contains hydrophilic constituents that promote moisture absorption and can limit its compatibility with hydrophobic polymer matrices. Poor fiber wettability and interfacial adhesion may weaken stress transfer between the fiber and matrix, resulting in non-uniform composite structures and reduced mechanical performance.⁵ Fiber extraction, degumming, and subsequent physical or chemical treatments are therefore important in determining the characteristics of PALF before composite fabrication. Surface modification can alter fiber topography and chemical functionality, thereby improving the interaction between PALF and the polymer matrix. The selection of compatible binders, compatibilisers, and coupling agents can further influence the resulting fiber-matrix interface.⁶

The growing use of PALF in composite materials has generated studies covering fiber extraction, processing, treatment, material characteristics, composite fabrication, and diverse applications. However, these aspects are often discussed separately, making it important to consider PALF as a material that undergoes a sequence of transformations before functioning as a composite reinforcement. This mini-review therefore brings together the extraction and processing of PALF, degumming, fiber characterization and treatment, composite fabrication and properties, major applications, and its environmental footprint. By presenting these interconnected stages, the article highlights the role of PALF as a building block for the development of composite materials.

Methodology

Relevant literature was reviewed using keywords and combinations of the terms “pineapple leaf fiber,” “PALF,” “fiber extraction,” “surface treatment,” “mechanical properties,” “polymer composites,” “industrial applications,” and “environmental sustainability.” The review primarily focused on studies published between 2015 and 2026, while earlier publications were considered where relevant. The selected literature was analyzed to evaluate PALF extraction methods, fiber properties, surface modification techniques, composite performance, and potential industrial applications.

Extraction and processing of PALF

Retting of PALF

Retting is used to separate PALF from the surrounding non-fibrous components of pineapple leaves. Small bundles of scratched PALF are immersed in water at a material-to-solution ratio of 1:20, and 0.5% urea can be added to accelerate the retting process. The fibers are checked periodically by hand as they loosen, allowing the removal of constituents such as lignin, fats, waxes, pectin, and other extractable materials. The separated fibers are then washed with water and air-dried.⁷ Further mechanical processing using ball and disk mills can produce smaller fiber sizes and improve fiber yield from finely chopped fresh pineapple leaves, although these methods are more complex than conventional extraction techniques.

Mechanical extraction and processing

Manual scraping extracts PALF by crushing the soft green portions of pineapple leaves and washing away the non-fibrous materials. Traditionally, the process is carried out on a long workbench using a small knife-like tool, a clamshell, or a broken porcelain plate. This method produces two distinct fiber fractions. Approximately 75% by weight consists of larger vascular bundles obtained from the upper lamina, whereas the remaining 25% consists of finer fiber strands from the lower lamina.⁸ The high-quality PALF obtained through manual scraping has been used to produce piña fabric in the Philippines. However, the method requires considerable skill, patience, and manual labor, which limits its productivity for large-scale fiber extraction.

Mechanical extraction has increased the processing capacity of PALF compared with manual scraping. A semi-automatic decorticating machine developed by KVIC uses high-speed blades mounted on rollers to disrupt the waxy leaf surface and remove impurities. Later developments included a machine equipped with fixed rollers and a raspator rotor, where the rotor spacing could be adjusted according to leaf dimensions. This system processed pineapple leaves at 5.24 kg h⁻¹ and reduced processing time by 52.08% compared with earlier semi-automatic machines.⁹ Improvements in conventional scraping machines have also focused on the feeding, scraping, and combing rollers. One electrically powered system could process four green leaves simultaneously, with a capacity of 30 kg of leaves per hour and an average production of 1 kg of dry fiber per hour.¹⁰ Automatic decorticator systems with capacities exceeding 1000 kg of leaves per hour have also been developed, although variations in leaf thickness can affect their performance.¹¹ More recent computer-assisted systems use intelligent sensing and flexible clamping to accommodate leaf thickness, curvature, and flexibility. Such systems have been reported to improve fiber recovery and reduce material loss compared with traditional extraction methods.

Mechanical milling provides another route for obtaining PALF with smaller dimensions. Fresh pineapple leaves containing approximately 80% water are first chopped into pieces of 5–8 mm and then subjected

to wet milling using either a ball mill or a disc mill. The ball mill contains 50 steel balls with a diameter of 25.4 mm, whereas the disc mill uses a circular plate with a diameter of 150 mm.¹² These milling processes produce approximately 2.8–3.0% fiber yield, with fiber diameters ranging from 3 to 194 µm. Milling dried leaves produces a slightly higher yield and thicker fibers than fresh leaves. The resulting short fibers can be further classified using steel wire meshes and are suitable for use as fillers or reinforcements in polymer composites.¹²

Despite improvements in mechanical extraction, the large-scale production of PALF still requires further optimization. Reported processing capacities are not directly comparable because some studies report the mass of leaves processed, whereas others report the amount of dry fiber produced. Therefore, fiber yield, quality, energy consumption, and processing conditions should be evaluated together to determine the practical efficiency of different extraction systems. Variations in leaf thickness, moisture content, and morphology also present challenges for consistent fiber extraction. Future studies should prioritize standardized performance evaluation and integrated processing systems that improve fiber recovery while reducing labor, energy consumption, and material losses.

Degumming of PALF

Degumming is used to remove gummy and non-cellulosic constituents from PALF, including pectin, hemicellulose, lignin, waxes, and other residual materials. Water retting is a conventional method in which aquatic microorganisms gradually degrade these components during prolonged immersion. Retting duration strongly affects fiber quality and yield. Water retting for 7 days produced soft, clean, and well-separated PALF with a maximum fiber yield of 2.8%, whereas extending the treatment to 13 days reduced the yield to 1.2% because of microbial degradation of the cellulosic component.¹³ Retting can also produce fibers with a diameter of 10.2 µm and favourable whiteness characteristics.¹⁴ The addition of 0.5% urea or diammonium phosphate at a substrate-to-liquor ratio of 1:20 can reduce retting time by approximately half.¹⁵ However, prolonged processing and wastewater generation remain limitations for large-scale water retting.

Chemical degumming provides faster removal of gummy materials through alkali, oxidative agents, organic solvents, and auxiliary chemicals. NaOH is widely used because it promotes fiber swelling and disrupts hydrogen bonding in amorphous regions rich in hemicellulose. Auxiliary chemicals such as Na₂SiO₃, Na₃PO₄, and Na₅P₃O₁₀ can further enhance impurity removal. Treatment with 2 wt% NaOH at 95–100 °C for 2 h produced PALF with a smooth surface and a tensile strength of 548 MPa.¹⁶ Higher treatment intensity can further reduce fiber dimensions, although excessive alkali exposure may damage lignocellulosic components and reduce fiber strength. Oxidative treatments using H₂O₂, sodium percarbonate, or NaClO₂ can further improve fiber cleanliness and fineness, while combined chemical treatments enable more extensive removal of hemicellulose and lignin.¹⁷

Biological degumming uses enzymes or microorganisms to selectively degrade non-cellulosic constituents and generally generates less harmful effluent than conventional chemical treatments. Specific bacteria and fungi can simultaneously produce enzymes and degrade gummy materials within the treatment system. Biopulping with *Pleurotus ostreatus* and *Trametes versicolor* produced PALF with fiber widths ranging from 1 to 10 µm after extended treatment periods.¹⁸ More recently, *Bacillus subtilis* XW-18 produced PALF with a residual gum content of only 3.5%, demonstrating its potential for efficient microbial degumming.¹⁹

Synergistic degumming combines chemical, biological, mechanical, or physical treatments to improve impurity removal while reducing fiber damage and processing time. Combining low-concentration alkali with compound enzymes increased PALF crystallinity from 36.5% to 46.7%.²⁰ Steam explosion combined with alkali treatment also produced highly refined PALF with a crystallinity of 85.5% and a tensile strength of approximately 25

MPa.²¹ Microwave, cryogenic, ultrasonic, and mechanical treatments can also assist degumming. Combined enzymatic and ultrasonic treatment reduced degumming time by 50% and produced PALF with a residual gum rate of 13.72% and a dry tenacity of 38.75 cN/tex. The degumming conditions and resulting fiber properties obtained using different degumming techniques are presented in Table 1.

Table 1 Degumming conditions and resulting properties of PALF obtained using different degumming techniques

Source	Method characteristics	Pretreatment	Degumming process	Post-degumming process	Fiber properties
Jose et al. ¹⁴	Water retting • Low energy efficiency • Water pollution	Cleaning	• Dipping for 7 days • Material-to-liquor ratio = 1:15 • Retting for 7 days • Material-to-liquor ratio = 1:10 at room temperature	• Washing with water • Air drying • Bleaching with 30% H ₂ O ₂ at 85 °C and pH 10-11 for 60 min • Neutralisation with 1% CH ₃ COOH • Rinsing and air drying	• Fiber diameter = 10.2 µm • Fiber fineness = 1.3 tex • Tenacity = 22.5 cN/tex • Whiteness index = 59.5 • Fiber yield = 2.8%
Banik et al. ¹⁵			• Immersion with 0.5% urea or DAP • Substrate-to-liquor ratio = 1:20	• Washing in pond water • Air drying • Hanging from bamboo poles	• Fiber diameter = 52 µm • Fiber fineness = 3.2 tex • Tenacity = 22 cN/tex • Fiber fineness = 3.4 tex • Tenacity = 16.7 cN/tex
Munawar et al. ¹⁶	Chemical degumming • Moderate energy consumption • Environmentally harmful	Cleaning and air drying to obtain a fiber moisture content of 6-8%	• Immersion in 2% NaOH • Material-to-liquor ratio = 1:100 • 95 °C for 120 min	• Rinsing with distilled water • Neutralisation with 2% CH ₃ COOH • Rinsing with distilled water • Drying at 50 °C in a vacuum oven • Rinsing with water	• Fiber diameter = 41.5 µm • Crystallinity degree = 57.9% • Tensile strength = 548 MPa • Toughness = 9.9 MPa • Fiber diameter = 52 µm
Hazarika et al. ¹³			• 1% NaOH • Material-to-liquor ratio = 1:10 • 85 °C for 60 min • 30% H ₂ O ₂ at 85 °C and pH 10-11 for 60 min • 20 g/L NaOH at 100 °C for 240 min	• Neutralisation with 1% CH ₃ COOH • Rinsing with water	• Fiber length = 280 mm • Tenacity = 27.47 cN/tex
Lee et al. ²²		• 2 g/L H ₂ SO ₄ • 60 °C for 120 min	• 10% H ₂ O ₂ at 95 °C for 50 min	• Air drying • Oiling • Drying	• Cellulose content = 80.09% • Crystallinity degree = 61.7% • Residual rate = 9.84% • Fiber fineness = 12.3 dtex • Tenacity = 4.15 cN/dtex
Zúñiga-Arias et al. ²³	Biological degumming • High energy efficiency • Extremely eco-friendly	• Pre-soaking at 60 °C for 60 min	• 10% enzymatic depolymerisation • 0.2 mol/L Na ₅ P ₃ O ₁₀ for 5 h • 20% H ₂ O ₂ and 3% Na ₂ SiO ₃ at 100 °C for 20 min	• Oiling • Air drying	• Fiber fineness = 19.36 tex • Tenacity = 3.19-6.96 cN/dtex
Peng et al. ¹⁹		Sterilisation	• Tenfold dilution of B. subtilis XW-18 seed culture with sterile water	• Washing with clean water	• Fiber yield = 2.29%

Table I Continued...

			• In-situ inoculation on fresh pineapple leaves • Retting on a rotary shaker at 30 °C and 170 rpm for 7 days • Mass-to-volume ratio = 1:5	• Sun drying	• Residual gum rate = 3.5% • Fiber diameter = 3-110 μm • Tenacity = 4.22 cN/dtex • Whiteness = 88.03
Cherian et al. ²¹	Synergistic approaches	Chopping into 1-2 cm lengths	• 8% NaOH for 24 h • Liquid ratio = 1:10 • Washing with water • Drying	• Steam explosion at 18 MPa and 210 °C for 5 min	• Cellulose content = 77.7% • Residual gum rate = 15.3% • Crystallinity degree = 85.5% • Tensile strength = 24.8 MPa • Modulus = 1.3 GPa
Tian et al. ²⁰			• 1% NaOH, 2% Na_2CO_3, 1% $\text{Na}_5\text{P}_3\text{O}_{10}$, and 2% JFC for pre-degumming • Compound enzyme containing 0.5% laccase and 0.3% xylanase • 4 h • Material-to-liquor ratio = 1:50 • Temperature = 50-55 °C • pH = 4.6-5.0	• Rinsing to neutral pH • Drying under ambient conditions	• Cellulose content = 74.46% • Crystallinity = 46.73%

Characteristics of PALF

The characteristics of PALF are governed by its crystalline structure, chemical composition, thermal behaviour, anatomical arrangement, and surface morphology. Its mechanical performance is strongly influenced by crystallinity, cross-sectional area, porosity, fiber dimensions, and structural defects. X-ray diffraction analysis generally shows characteristic reflections at 2θ values of approximately 16.8°, 22.1°, and 28.4°, while the crystallinity of PALF ranges from about 32% to 78%, depending on the pineapple variety, geographical origin, and fiber treatment conditions.^{21,24} Chemical modification can further alter this structure and mechanical performance. For example, treatment with 6 wt% NaOH increased PALF crystallinity to approximately 76%, with a crystallite size of 24 nm and a reported tensile strength of up to 1620 MPa.²⁵ Mercerization can transform cellulose I into cellulose II and increase tensile strength from 288 to 450 MPa while improving fiber elasticity.²⁶ However, crystallinity alone does not determine mechanical performance, since fiber geometry and internal defects can also substantially affect strength. Figure 1 illustrates the relationship between fiber cross-sectional characteristics and mechanical properties, demonstrating the importance of fiber structure in PALF performance.²⁷

The chemical characteristics of PALF reflect its lignocellulosic composition, which mainly consists of cellulose, hemicellulose, lignin, pectin, waxes, and other minor constituents. The FTIR spectra presented in Figure 2 show the characteristic absorption bands of raw and differently treated PALF. The broad band at 3500-3100 cm^{-1} is associated with O-H stretching vibrations of hydroxyl groups, while the absorption near 2900 cm^{-1} corresponds to C-H stretching. The

band around 1730 cm^{-1} is attributed to C=O stretching associated with hemicellulose and lignin, whereas the bands in the 1600-1500 cm^{-1} region are related to aromatic structures of lignin. The absorption bands around 1426 cm^{-1} and 1160 cm^{-1} are associated with CH_2 vibrations and C-O-C linkages, respectively. Changes in the intensity of these characteristic bands among raw PALF and samples S1-S4 indicate modifications in the relative proportions of lignocellulosic components following different treatments.²⁸

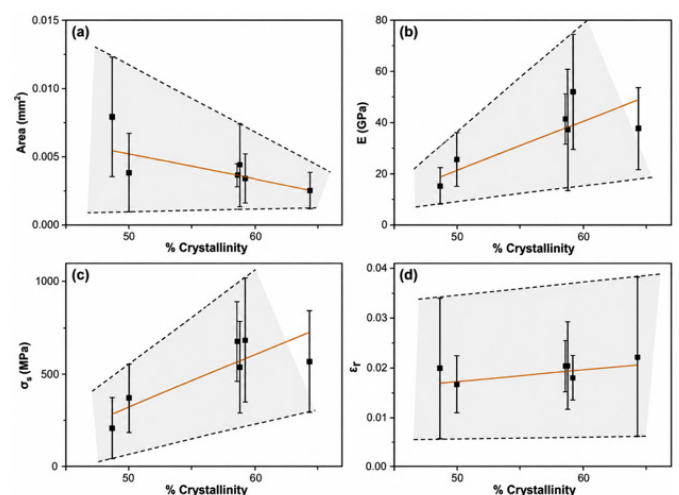


Figure 1 Mechanical properties of PALF. (a) Cross-sectional area; (b) Young's modulus; (c) tensile strength and (d) stress - strain at break. Reproduced with permission from ref. [27], copyright© 2013, Elsevier.

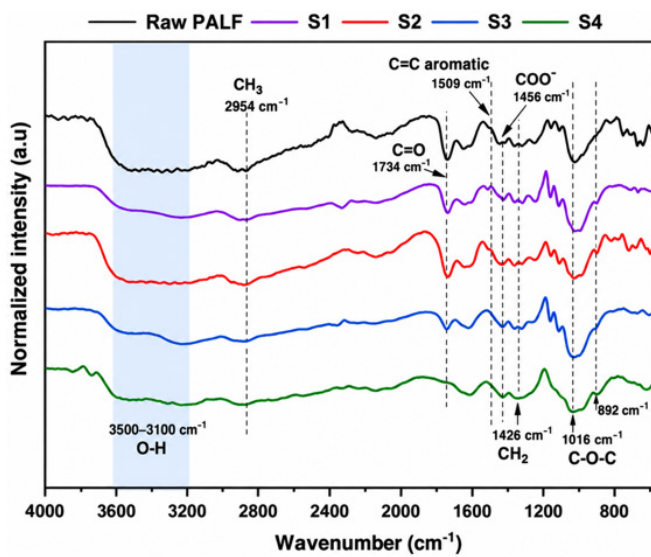


Figure 2 FTIR spectra of PALF under different treatment conditions. (a) Raw PALF; (b) S1-treated PALF; (c) S2-treated PALF; (d) S3-treated PALF; and (e) S4-treated PALF. Reproduced with permission from ref. [28], copyright © 2025, Elsevier B.V.

PALF is a non-thermoplastic lignocellulosic fiber that undergoes thermal degradation before conventional melting. Figure 3 presents the TGA curves of raw PALF and the treated samples (S1–S3 and H_{1.5}), showing differences in thermal degradation behavior. All samples exhibit a relatively small initial weight loss at lower temperatures, mainly associated with moisture removal, followed by rapid mass loss between approximately 300 and 400 °C due to the degradation of lignocellulosic constituents. The degradation temperatures varied among the samples, with characteristic transitions occurring at approximately 304 °C and 339 °C. Differences in the residual weight at higher temperatures further indicate that the treatments altered the thermal decomposition behaviour of PALF. Thermal stability varies substantially according to fiber origin and composition. PALF obtained from the Pina Plantation showed 20% and 50% weight losses at 146.68 and 401.94 °C, respectively, with a main degradation temperature of 251.06 °C and a residual mass of 39.82% at 700 °C.²⁹ In contrast, PALF from another Malaysian plantation showed 20% and 50% weight losses at 212 and 306 °C, respectively, with a residual mass of 20.29% at 700 °C, demonstrating the influence of plantation source and fiber characteristics on thermal behavior.³⁰ Treatments can further modify thermal stability. Bleaching may reduce thermal stability through fiber degradation and increased amorphous regions, whereas alkali treatment can improve thermal resistance through the removal of hemicellulose and low-molecular-weight lignin components.²⁹ Reported onset oxidation temperatures increased from 287.09 °C for raw PALF to 329.63 and 330.33 °C after NaOH and silane treatment, respectively.³¹

The thermal transitions of PALF and PALF-based composites can also be evaluated using DSC, as shown in Figure 4. A pure PALF exhibited a reported glass transition temperature of approximately 74 °C.³² Its thermal behavior can change after incorporation into polymer matrices. For example, PALF-reinforced high-impact polystyrene composites showed reported glass transition and melting temperatures of 123 and 149 °C, respectively. The influence of PALF on crystallization behavior depends on the polymer matrix, as PALF addition reduced the crystallization temperature in some composites, whereas PALF/PVA composites and pure PVA showed crystallization temperatures of 131 and 132 °C, respectively.³³

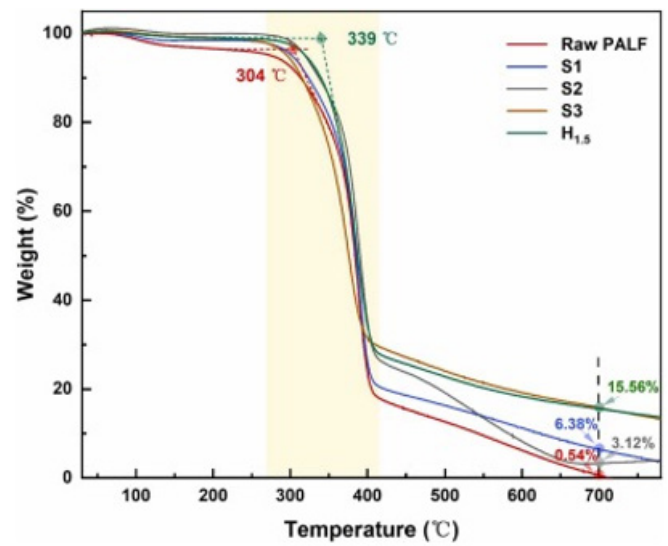


Figure 3 TGA curves of raw PALF and treated PALF samples (S1–S3 and H_{1.5}), with the corresponding degradation temperatures and residual weight percentages. Reproduced with permission from ref. [28], copyright © 2025, Elsevier B.V.

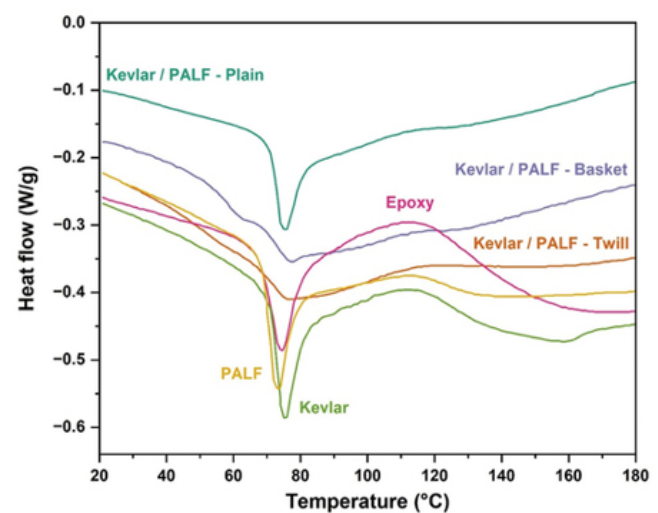


Figure 4 DSC curves of PALF and PALF-based composites. Reproduced with permission from ref. [32], copyright © 2022, Wiley.

The anatomical structure of pineapple leaves also contributes to the properties of PALF. Figure 5 illustrates the anatomical arrangement of pineapple leaves and fiber bundles, which are distributed within the vascular tissue and mesophyll regions. The fiber bundles consist of thick-walled cells bound through the middle lamella, which contains lignin, pectin, and hemicellulose. At the cellular level, each fiber consists of a primary wall and a secondary wall composed of the S1, S2, and S3 layers. Although these layers have similar major chemical constituents, their cellulose microfibril orientations differ. The S2 layer is the thickest and accounts for approximately 43–78% of the secondary wall thickness, making it particularly important for fiber strength and stiffness.³⁴

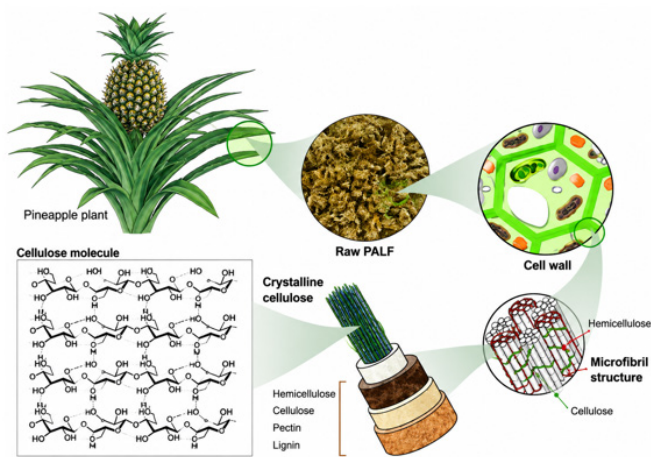


Figure 5 Hierarchical, anatomical, and structural organization of PALF, from the pineapple leaf and raw fiber to the fiber cell wall, cellulose microfibrils, crystalline cellulose, and cellulose molecular structure, including the distribution of cellulose, hemicellulose, and pectin.

The morphology of PALF varies according to its location within the leaf and natural growth structure. Fibers extracted from different regions of the leaf can therefore differ in lumen size, cross-sectional geometry, and fineness. Raw PALF generally has a reported length of approximately 35–70 cm and a diameter ranging from 41 to 155 μm .²⁶

Modification of PALF

Modification of PALF is mainly performed to remove non-cellulosic constituents, alter surface characteristics, and improve fiber compatibility with polymer matrices. The principal approaches include alkali treatment, acid hydrolysis, bleaching, silane treatment, calcium hydroxide treatment, and combined treatments. These treatments modify the cellulose structure and the amount of hemicellulose, lignin, waxes, oils, and other amorphous constituents, resulting in changes in fiber morphology, crystallinity, moisture affinity, and composite performance, as shown in Table 2.

Table 2 An overview of PALF modification methods, treatment conditions, and their effects

Fiber loading	Matrix	Treatment and other composite conditions	Flexural strength (MPa)	Flexural modulus (GPa)	Tensile strength (MPa)	Tensile modulus (GPa)	Impact strength (J/m ²)	Ref.
25%	PE	Untreated	39.86	3.826	25.49	1.161	35.3	35
35%	PE	Untreated	50.97	4.08	27.53	1.4	41.25	35
45%	PE	Untreated	75.92	6.379	31.13	1.553	43.67	35)
25%	PE	Ca(OH) ₂ , 1 M, 1 h at room temperature	36.67	2.232	22.69	1.32	36.35	35
35%	PE	Ca(OH) ₂ , 1 M, 1 h at room temperature	27.59	1.449	22.05	1.19	39.27	35
45%	PE	Ca(OH) ₂ , 1 M, 1 h at room temperature	50.56	3.941	30.57	1.66	50.06	35
30%	PP	Untreated	-	-	66.28	-	-	36
30%	PP	Alkalization, 1% NaOH for 3 h at room temperature	-	-	81.53	-	-	36
30%	PP	Alkalization, 2% NaOH for 3 h at room temperature	-	-	90.56	-	-	36
30%	PP	Alkalization, 4% NaOH for 3 h at room temperature	-	-	90.85	-	-	36
30%	PP	Alkalization, 8% NaOH for 3 h at room temperature	-	-	116.17	-	-	36
30–40%	PP	Untreated	45.3	0.467	42.2	1.584	52.5	37
30–40%	PP	Alkalization, NaOH	45.6	0.49	45.06	1.584	55.9	37
30–40%	PP	Zinc chloride	50.1	0.536	45	1.509	59.08	37
30–40%	PP	Acetic anhydride	48	0.536	44.9	1.581	62.3	37
30–40%	PP	Maleic acid	51.6	0.59	51.5	1.574	64.1	37
45%	PP	Untreated	51	0.54	57	1.731	7.152	38
35%	PP	Alkalization, 7% NaOH for 1 h at room temperature	44	0.754	50	1.53	7.542	38
10%	PLA	Untreated	48.96	2.69	34.8	1.5	30.9	39
10%	PLA	Additive, 2% MAPE	49.61	2.752	30.2	1.636	31.2	39

Table 2 Continued...

10%	PLA	Additive, 4% MAPE	50.66	2.58	28.9	1.656	37.4	39
10%	PLA	Additive, 6% MAPE	51.27	3.375	27.3	1.506	31.5	39
50%	Epoxy	Alkalization, 0.5% NaOH	136	4.23	-	1.405	-	40
50%	LDPE	Untreated	78.42	5.705	26.44	0.533	33	41
50%	LDPE	Gamma radiation, 2.50 kGy	84	6.041	25.97	0.567	32.5	41
50%	LDPE	Gamma radiation, 5.00 kGy	92.64	6.622	27.05	0.511	36	41
50%	LDPE	Gamma radiation, 7.50 kGy	96.94	7.314	26.49	0.696	45	41
50%	LDPE	Gamma radiation, 10.00 kGy	87.03	6.306	25.55	0.913	40	41
30%	TRP	Untreated	-	-	15.37	0.86	-	42,43
30%	TRP	Alkalization, 5% NaOH for 1 h at room temperature	-	-	15.58	0.99	-	42,43
30%	TRP	Additive, 7% MAPP	-	-	22.7	1.13	-	42,43
30%	TRP	Additive, 3% MAPE	-	-	21.06	1.12	-	42,43
40%	TRP	Untreated	-	-	15.75	1.03	-	42,43
40%	TRP	Alkalization, 5% NaOH for 1 h at room temperature	-	-	16.44	1.07	-	42,43
40%	TRP	Additive, 7% MAPP	-	-	19.11	1.25	-	42,43
40%	TRP	Additive, 3% MAPE	-	-	17.4	1.17	-	42,43

Alkali treatment, commonly performed using NaOH, removes hemicellulose, lignin, waxes, and oils that restrict fiber interaction with polymer matrices. NaOH treatment also promotes fibrillation, reduces fiber diameter, and increases surface roughness by disrupting hydrogen bonding within the lignocellulosic structure. Under sufficiently strong conditions, the treatment can convert cellulose I into cellulose II through fiber swelling and rearrangement of the cellulose structure. These changes can improve fiber-matrix adhesion. For example, PALF treated with 2% NaOH for 1 h increased the tensile strength of PALF/PE composites by 4.73%,⁴⁴ while treatment with 5% NaOH for 1 h increased the flexural strength and modulus from 56.47 MPa and 4.24 GPa to 114.03 MPa and 5.70 GPa, respectively.⁴⁵

Acid hydrolysis preferentially removes amorphous regions and can be applied after chemical or bleaching treatments to further purify cellulose and produce finer cellulose structures. The effectiveness of acid hydrolysis depends on the removal of hemicellulose and other hydrolysable constituents during preceding treatments. Gnanasekaran et al.⁴⁶ reported that the alkali-bleaching-acid treatment sequence produced smoother and more uniform fibrils than the steam-bleaching-acid route, which retained a less uniform bundle-like structure.

Bleaching primarily removes lignin and residual non-cellulosic materials surrounding cellulose microfibrils. H₂O₂, NaClO, and NaClO₂ are commonly used oxidative bleaching agents, although their effects differ depending on treatment severity. Increasing the hypochlorite bleaching period from 1 to 4 h reduced the lignin content by 2.4%, increased the α -cellulose proportion, and produced cleaner and more separated fiber surfaces.⁴⁷ Bleaching can also promote defibrillation by removing lignin that binds fiber cells together, as reported for bleached PALF.²¹

Silane treatment is mainly applied to improve interfacial compatibility between hydrophilic PALF and hydrophobic polymer matrices. Hydrolysed silane molecules react with hydroxyl groups

on the PALF surface and form stable chemical linkages that reduce moisture affinity and improve fiber-matrix interaction. Suwanruji et al.⁴⁸ reported water retention of 80% for silane-treated PALF after 2 h of soaking compared with 86% for untreated PALF. After 24 h, the corresponding values were 85% and 92%, respectively. In another study, silane-treated PALF exhibited a tensile strength of 455.8 MPa, higher than NaOH-treated PALF (424.6 MPa) and Ca(OH)₂-treated PALF (303.4 MPa).⁴⁹

Calcium hydroxide treatment can modify PALF by removing amorphous constituents and surface impurities, although its effect may be weaker than NaOH or silane treatment. Treatment with 1 M Ca(OH)₂ removed characteristic bands associated with hemicellulose and lignin at 1737 and 1248 cm⁻¹ and increased XRD peak intensity, indicating increased crystallinity following the removal of amorphous components. However, Ca(OH)₂-treated PALF did not consistently provide substantial improvements in the tensile, flexural, or compressive properties of PALF/polyester composites.³⁵

Combined treatments enable the sequential removal of different PALF constituents. Alkali treatment is particularly effective in removing hemicellulose, followed by bleaching for lignin removal and acid hydrolysis for further cellulose purification. The alkali-bleaching-acid sequence produced more uniform fibrils and higher thermal stability than the corresponding steam-based treatment.⁴⁶ Similarly, treatment with NaOH followed by H₂O₂ bleaching increased the tensile strength of PALF/PE composites by 22.68% compared with untreated PALF/PE composites and produced a 38% increase in tensile modulus.⁵⁰

Fabrication of PALF Based Composites

PALF has been incorporated into a range of polymer matrices, including PP, LDPE, HDPE, PLA, polyester, and epoxy, as well as into functional aerogels and carbon-based materials. The fiber-

matrix interaction is influenced by the hydrophilic nature and surface characteristics of PALF, particularly the presence of waxy and other non-cellulosic surface constituents that can restrict adhesion with hydrophobic matrices.³ Fiber distribution during composite preparation is also important. Rahman et al.⁵¹ reported that four carding passages of the longest PALF removed 12 wt% of non-cellulosic materials and improved fiber distribution within PP composites, contributing to improved mechanical properties. PALF can therefore be processed into composite systems with different polymer matrices and material architectures.

Beyond conventional polymer composites, PALF has been fabricated into highly porous aerogels through fiber homogenization or microfibrillation, gel formation, solvent exchange, and subsequent freeze- or supercritical drying. PALF-based aerogels prepared using PVA-based systems achieved porosity above 98%, densities of 0.013–0.033 g/cm³, thermal conductivity of 0.030–0.034 W/mK, and a noise reduction coefficient of 0.52.⁵² Functional modification of these aerogels further expanded their application potential. Lim et al.⁵³ incorporated DETA and CMC into PALF-based aerogels and reported an ethylene gas and nickel ion adsorption capacity of 0.835 mol/kg. Similarly, combining PALF with cotton waste fibers produced hydrophobic aerogel composites with an oil adsorption capacity of nearly 16 times their own weight and a higher Young's modulus than PVA-based PALF aerogels.

PALF has also been used as a precursor for carbon-based materials because of its cellulose-rich structure. Direct pyrolysis converts PALF into carbonaceous materials, while subsequent nitrogen doping and chemical activation using KOH or H₃PO₄ can further modify their porous structure and surface properties. These processing routes have produced PALF-derived carbon materials in nanosheet, nanofiber, and interconnected porous forms, supporting their potential use in electrochemical energy storage and related technological applications.

Environmental footprint of PALF based composites

The environmental footprint of PALF-based materials is strongly influenced by fiber extraction and processing. A carbon footprint assessment covering pineapple leaf harvesting through the production of ready-to-ship PALF non-woven textiles reported emissions of 4.43 kg CO₂ equivalent per m², compared with 0.176 kg CO₂ equivalent per m² for PP non-woven textile.⁵⁴ This higher production-stage footprint was associated with the relatively less mature and smaller-scale PALF production process and the use of sodium hydroxide during conventional alkaline degumming. However, improved extraction and degumming technologies may reduce these emissions, as enzymatic degumming of PALF has been reported to prevent up to 6 kg CO₂ emissions per kilogram of Piñayarn® (Anam). Recycling waste generated during PALF processing may also reduce material losses and support circular use of agricultural residues. At the end-of-life stage, PALF can naturally decompose within approximately 21 days, whereas PP may persist for 20–30 years.⁹ Thus, although PALF currently has a higher production-stage carbon footprint than PP in the reported assessment, improvements in processing efficiency, lower-impact degumming, and waste recycling, together with its rapid biodegradation, can reduce its overall environmental burden.

Several research gaps remain in assessing the environmental and economic feasibility of PALF-based composites. Existing environmental comparisons may differ in system boundaries, functional units, and processing assumptions, limiting direct comparisons between materials. Further life-cycle assessments should consider fiber extraction, chemical treatment, energy and water consumption, transportation, composite manufacturing, and end-of-

life management under clearly defined conditions. In addition, techno-economic analyses and pilot-scale studies are needed to determine whether improvements in extraction efficiency, chemical use, and waste utilization can support cost-effective industrial production. Standardized assessment methods would enable more reliable comparisons and help identify the most sustainable applications of PALF-based materials.

Conclusion

PALF has demonstrated considerable potential as a lignocellulosic material for composite and other value-added applications because of its high cellulose content, favorable mechanical characteristics, and availability as an agricultural residue. However, the presence of hemicellulose, lignin, waxes, and other non-cellulosic constituents, together with its hydrophilic nature, can limit its compatibility with polymer matrices. The reviewed studies indicate that alkali, bleaching, silane, calcium hydroxide, acid hydrolysis, and combined treatments can modify the chemical composition, surface characteristics, morphology, and crystallinity of PALF, resulting in improved fiber-matrix interaction, moisture resistance, and composite performance under appropriate treatment conditions. PALF has been successfully fabricated with matrices such as PP, PE, PLA, polyester, and epoxy, while its conversion into aerogels and carbon-based materials has further expanded its application potential. Although conventional PALF extraction and chemical processing can contribute to production-stage environmental impacts, improved extraction efficiency, enzymatic processing, waste utilization, and the rapid biodegradability of PALF can support the development of materials with lower environmental burdens. Future research should focus on standardized and scalable processing methods, environmentally less intensive fiber modification, and systematic optimization of PALF dispersion and interfacial performance in different matrices. Further comprehensive life-cycle and end-of-life assessments are also needed to establish the environmental advantages of PALF-based materials across their complete life cycle.

Acknowledgments

The authors would like to thank the researchers and authors whose published work contributed to the development of this review. The authors also acknowledge the support and resources that facilitated the preparation of this manuscript.

Data Availability Statement

No new data were generated or analyzed in this study.

Author Contributions

All authors contributed equally to the conceptualization, literature review, analysis, writing, revision, and final approval of the manuscript.

Funding

None.

Conflicts of interest

The authors declare that they have no known conflicts of interest.

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