



Review

Harnessing Pineapple Leaf Fiber (PALF) for Sustainable Yarn Manufacturing: A Review of Plant-Based Fiber Technologies, Challenges and Future Prospects

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KEYWORDS

Pineapple Leaf Fiber (PALF); Sustainable Yarn; Natural Fiber; Spinning Technology; Circular Economy.

ABSTRACT

Ananas comosus-Pineapple leaf fiber (PALF) is an agricultural by-product that has been developed as a potential sustainable resource in yarn production and composite production as interest in environmental issues related to the traditional fibers grows. Due to its strength in cellulose level, low density, and competitive mechanical qualities, PALF possesses remarkable capabilities to replace synthetic and traditional natural fibers. Extensive information about its botanical structure, chemical composition, and physical-mechanical properties demonstrate that it can be used in a variety of textile and engineering solutions. The performance and quality of fibers and processing methods are highly dependent on the efficacy of different extraction and processing methods, such as mechanical, biological, and chemical methods. Nonetheless, limitations in the fiber elasticity, inconsistency and inability to match current spinning techniques require sophisticated processing measures, including cottonization and combinations with other fibers. Regarding the environmental dimension, PALF has also distinct benefits, such as reduced carbon emissions, low water usage, and full biodegradability, which justify its adherence to the principles of the circular economy. Industrial case studies and techno-economic assessments also show that its commercial viability is increasing, but constraints are still associated with standardization, scalability, durability and supply chain integration. As research and development continues and technology improves, PALF has a great potential of being an important resource in sustainable textile and composite industries.

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1. Introduction

The textile and composites sector of the world is experiencing a tremendous change due to the pressing need to be less reliant on synthetic and petroleum based materials and adopt renewable and biodegradable materials [1]. Natural plant-based fibers have been renewed as the attractive engineering materials which can be characterized by low density, competitive specific mechanical performances, carbon sequestration (potential) and end-of-life biodegradability which are not achievable by conventional glass or carbon fibers [2,3]. One of the most promising of these plant-based resources is pineapple leaf fiber (PALF), which is derived using the by-product leaves of *Ananas comosus*, a

tropical crop grown on a large scale in South and Southeast Asia, Latin America and West Africa [4,5].

PALF is a lignocellulosic fiber, which is categorized under the leaf or hard fiber group, together with sisal and agave. PALF is a highly flexible substance, often noted to contain roughly 70% to 80% cellulose and coupled with a density that is often lower than glass fibers, its tensile strength and flexural moduli are comparable to jute and flax, which are considered bast fibers. The unique combination of being highly flexible with low density and strong across multiple flexible axes, drives interest in PALF for compos-

ite materials [6–9]. Although with such an impressive mechanical profile, PALF was for many decades an untapped agricultural residue, with the bulk of the pineapple leaves burnt or left to decompose on the field after harvesting fruits, leading to greenhouse gas emissions and nutrient imbalances in the soil [10,11]. The increased appreciation of the potential of PALF as a technical textile fiber and composite reinforcement has spurred a frenzy of research, especially in the fields of yarn manufacture, surface functionalization, polymer matrix reinforcement and wearable textile systems [12,13].

PALF has unique opportunities, as well as non-trivial challenges, as a yarn manufacturing perspective. The natural stiffness of the fiber and the lack of elongation at break of such highly crystallized cellulosic systems requires precise optimization of the processes when exposed to traditional ring spinning, rotor spinning or air-jet spinning systems [14,15]. It has been reported to enhance processability and yarn uniformity when PALF is combined with softer carrier fibers, e.g. cotton, viscose or polyester, yet the PALF component retains the desired functional properties [16,17]. In more recent times, vortex spinning and friction spinning have been considered as avenues to access high stiffness of PALF in small, short-fiber yarn structures, creating new opportunities in technical and industrial applications of textiles.

In addition to mechanical reinforcement, PALF has also received a lot of attention due to its inherent multifunctionality. Its porous microstructure, polar surface chemistry due to hydroxyl-rich cellulose and hemicellulose networks and inherent lignin nature make it susceptible to numerous chemical modifications, such as mercerization, silane bonding, acetylation and enzymatic treatments, which can customize hydrophilicity, interfacial adhesion and even add antimicrobial or flame-retardant properties. These properties make PALF a candidate fiber in both traditional and new fields of application such as biodegradable packaging systems, geotextile, noise panels and smart textile substrates [18,19].

It is clear that PALF offers a number of sustainability related benefits when compared to other fibers, particularly other plant-based options. PALF's sustainability advantages begin with how it is harvested. Since it is harvested from leaves that result from fruit harvesting, it does not require/consume any additional land, irrigation, fertilizers, or pesticides (within the boundaries already set from the pineapple plant's original cultivation). This minimizes environmental impacts. Pineapple leaf fibers also show significant promise with less than half the water and carbon cost than that of cotton and less than one-tenth of that of flax with verified industrial lines running carbon costs of approximately $0.784 \text{ kg CO}_2 = 1 \text{ kg}$ of pineapple leaf fiber and 0.2 ton/ton of pineapple leaf fiber, which is over 90% less than the typical values for cotton. Additionally, pineapple leaf fiber's open burning/decomposition fiber management systems reduce the number of particulates and methane that would otherwise be generated. PALF's value stream also aids farming communities

financially. PALF based yarns also have the ability to support even more circular bioeconomy models that integrate agriculture with textiles, particularly in South/Southeast Asia, i.e. Bangladesh, where pineapple farming and textile production are significant [6,7,9,20,21].

Upon evaluating qualities conducive to yarn and fabric production, PALF demonstrates consistently high tensile strength and commendable dimensional stability at the fiber level, outperforming other lignocellulosic fibers. PALF exhibits rigidity and hardness that is equivalent to or superior to jute, justifying its application in composite and technical yarns. PALF fibers exhibit excellent moisture management, characterized by high sweat absorption, air and water permeability and thermal comfort, attributable to their permeable structures, rendering PALF suitable for garment applications. These advantages allow PALF fibers to be used in the production of textiles with the desired linen-like handle and other values in aesthetics and tactility for both fashion and functional textiles. PALF fibers, however, during processing, can cause issues due to their relatively coarse diameter when compared to cotton, stiffness and natural hydrophilicity which, if the fibers are not properly engineered, can adversely affect the yarn's evenness and hairiness by complicating processing on conventional spinning systems [6–9,20,22].

Utilizing PALF entails promising prospects, but it also poses some difficulties. Fibers vary when it comes to their extraction quality and coarseness, problems arise when their technologies have not been commercially developed and tested and their techno-economic evaluations are not conclusive. In addition, PALF fibers demonstrate inconsistent spinning performance and PALF is not well suited to be augmented by current textile machinery. Given these circumstances, PALF's industrial potential has not been fully realized and to achieve this, an extensive evaluation of PALF's extraction, processing, chemical modification, spinning and application potential must be extensively evaluated.

This review focuses on PALF and its structural properties, covering its innovative processing, extraction and modification, spinning, composite uses, biodegradability and cost and evaluating it as an environmentally viable sustainable textile fiber. It also involves PALF within the scope of fibrosis in order to facilitate advanced identifiable additional processing and fibrosis technologies, as well as to better understand PALF's comparative advantages, drawbacks and prospects in order to guide future industrial and academic research.

2. The Global Fiber Sustainability Crisis

The world fiber production has maintained its upward trend in rapid growth to a record level of about 132 million tons in 2024 compared to about 125 million tons in 2023 and 116 million tons in 2022 [23]. This proves that the world fiber output has increased over 2000, when the production was about 58 million tons, by more than two times, with the growth rate of production in the

textile industry increasing rapidly. Under the conditions of the existing trends of production, the overall fiber production is expected to increase to about 169 million tons by 2030, which is very worrying with respect to the environmental sustainability and availability of resources [24]. Polyester alone constituted close to 54 million metric tons of production, which has increased by more than four times since 1990 and is still rising at a compound annual rate of about 45 percent. Although economically explainable due to low cost and high uniformity of petroleum-based fibers, this synthetic superiority has a massive and ever-growing environmental cost throughout the whole fiber life cycle. The production and processing of fiber include the largest share of CO₂ emissions in the value chain of this sector.

Table 1: Global Fiber Production [24]

Category	Volume (MT)	Share (%)
Total Fiber Production	~132	100%
Polyester	~78	~59%
Cotton	~25 (approx.)	~19%
Recycled Polyester	~9.3	~12%
Other fibers (plant based, MMCFs, animal)	Remaining	~22%

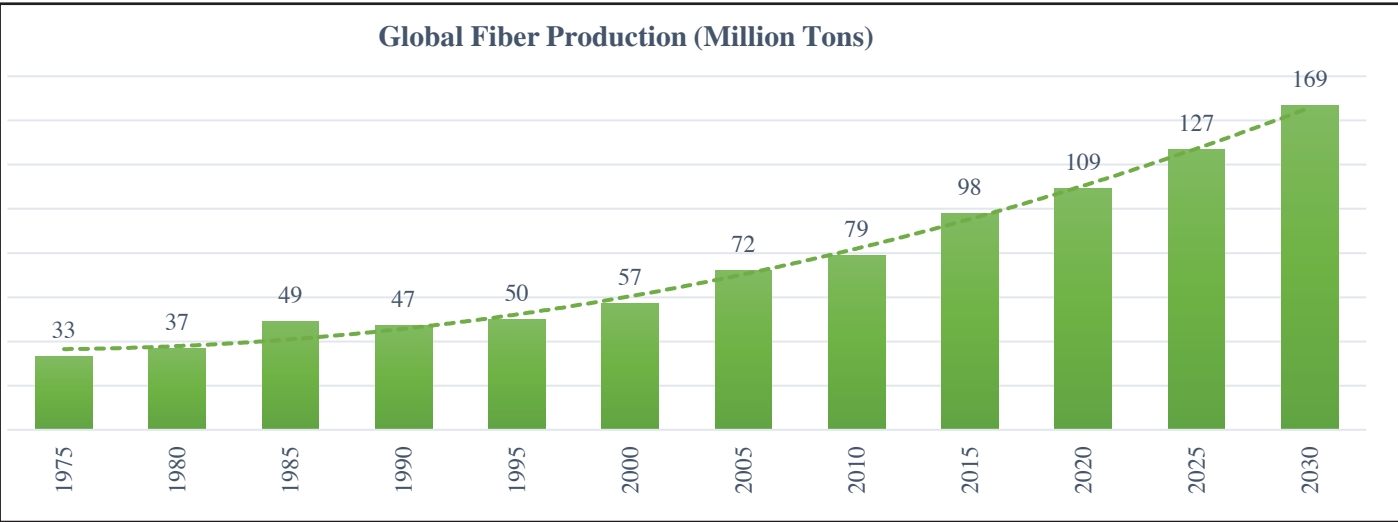


Figure 1: Global Fiber Production in Million Tons. Source: Textile Exchange based on data from CIRFS, FAO, ICAC, IVC, IWTO, Maia Research, and its own modelling

The disposal phase of these is also a burning issue. The amount of waste produced annually by the global textile industry is estimated to be 92 million metric tons in 2020, and it is expected to reach 148 million metric tons annually by 2030 [25]. Landfill or incineration is still the leading way of getting rid of textiles: in the European Union, as of today, 1% of textiles is recycled into new fiber products, and in most situations in the developing countries context, the percentage of textile waste that is mechanically recycled or composted is virtually zero [26,27]. Due to its natural property to resist biodegradation, i.e. polyester degrades on a 200-500 year timescale on ambient landfill conditions, synthetic fibers accumulate over time in both terrestrial and aquatic environment [28].

The problem of microplastic pollution is one of the most insidious aspects of the environmental effects of synthetic fiber. Research has reported that one domestic laundry cycle of a synthetic garment can emit between 100,000 and 700,000 microplastic fibres which are mostly unfiltered and enter freshwater and marine networks [29,30]. In contrast, PALF and other cellulosic natural fibers are biodegradable both aerobically and

anaerobically and do not release persistent microplastic contaminants during the washing process or ultimate disposal, which is a significant structural benefit over their synthetic equivalents in this respect [31,32].

The crisis is not limited to synthetic fibers but it also includes the traditional natural fiber systems. Cotton is the most extensively grown natural fiber crop on Earth, and each year its production is about 25-26 million metric tons, which is well-documented to have its sustainability issues of its own [33,34]. Traditionally cultivated cotton is cultivated on less than 3% of the world agricultural land, but takes up about 16 percent of all insecticide use and 7 percent of all herbicides use, exerting vast amounts of pressure on soil health, pollinator populations, and rural water supplies [35,36]. A bright historical example of the dangers of water-intensive natural fiber monocultures is the Aral Sea disaster, which was one of the most serious man-made ecological disasters of the twentieth century, which was predetermined in large part by the irrigation needs of the cotton industry of the Soviet era [37].

Jute, flax, hemp, and ramie are examples of bast fiber crops,

which have better environmental impacts compared to cotton, but have defined agronomic, geographic, or processing limitations that restrict their general applicability [38,39]. Jute is mainly grown in the Ganges-Brahmaputra delta area, which exposes the supply chain to vulnerability; flax and hemp need temperate climates and cannot be grown in large tropical producer countries; all the bast fibre systems use water retting processes that when not managed well release high biological oxygen demand effluents that can have disastrous effects on local aquatic environments [40,41]. The constraints highlight the necessity of diversifying a portfolio of plant-based fibers, which can provide sustainability advantages in a broader agronomic environment.

Leaf fibers such as sisal, henequen, abacá and PALF have been distinctly placed in this portfolio since they are not major crops, but are by-products of food or beverage crop farming [12,42]. The exploitation of PALF, as an example, does not require any further land clearing, no further irrigation, or further use of agrochemicals than the ones already allocated to pineapple fruit production, and its effective carbon and water footprint can be significantly less than that of dedicated fiber crops [43]. The annual pineapple fruit production is estimated to be 2830 million metric tons of fruit or 7283 million metric tons of leaf biomass, of which under 5 percent is nowadays valorized by extracting fibers [21,44].

The consumer and regulatory pressure is increasing the urgency of the transition to sustainable fibers. In 2024, the Ecodesign of Sustainable Products Regulation adopted by the European Union established a mandatory minimum recycling content in the textile products subjected to the EU market and a digital product passport requirement, which established structural incentives to adopt bio-based and recycled fiber systems [45]. In the same vein, the increasing preference of third party environmental certifications, such as the Global Organic Textile Standard (GOTS) or OEKO-TEX STeP and Cradle to Cradle, is also transforming procurement choices in large fashion brands around the world resulting in a demand push toward fibers with validated documented environmental attributes [46]. Having a source in agricultural by-products, high specific strength, low processing energy needs in comparison with synthetic products, and biodegradability, PALF is perfectly consistent with the material profiles required by these new regulatory and market structures [19]. Here is where the growing interest of the scientific and industrial community in PALF should be construed where environmental crisis, regulatory evolution, technological opportunity, and material constraint have converged.



Figure 2: (a) Pineapple Plant with Fruit (b) Extracted PALF (c) Raw PALF

3 Botanical and Structural Characteristics of Pineapple Leaf Fiber (PALF)

3.1 Botanical Origin and Morphology of Pineapple Plant

Pineapple is a monocotyledonous perennial herb of the family Bromeliaceae, which is grown mostly in belts of tropics and subtropics of South and Southeast Asia, Latin America, and West Africa to produce edible fruit. Each shoot of the pineapples generates 40-70 sword-shaped leaves which at maturity are 60-150 cm long and 4-6 cm wide [43]. The mass of these leaves is a significant agricultural residue stream: in each shoot, the biomass of leaves is about 2.3 kg, and at the field scale this is

7283 million metric tons of leaf biomass per year on a global scale, less than 5 percent of which is being currently monetized by extracting the fiber [43,47]. Economic and environmental rationality of extracting PALF out of this no-additional-land-clearing-no-additional-agrochemical stream is thus overwhelming.

PALF is a multicellular lignocellulosic fiber that is obtained at the anatomical level of the pineapple leaf mesophyll through vascular bundles. The scanning electron microscopic analysis shows that every leaf has two different groups of fibre bundles, which are bigger bundles of 100-460 μm diameter and placed towards the middle midrib and the smaller bundles of 30-80 μm diameter placed longitudinally below the epidermal skin layer [48]. Individual fibers (ultimate fibers) with diameters ranging

between 10 and 35 micrometers and average lengths between 3 and 9 mm are cemented together with an intercellular matrix made of pectin and lignin [21,49]. The cell wall structure of every elementary fiber is based on the classical multilayered lignocellulosic model: a thin primary wall covers a significantly thicker secondary one, and the latter can be divided into three concentric sublayers named S1, S2 and S3. The largest percentage of the wall thickness makes up the S2 sublayer, which includes the highest concentration of cellulose, and it determines the mechanical response of the fiber [50].

3.2 Chemical Composition

PALF is a lignocellulosic fiber consisting of a cellulose content of 70-82%, hemicellulose content of about 15-20%, and lignin content of 5-12% [21]. The comparatively high cellulose content, along with a low microfibrillar angle is the main cause of PALF competitive tensile strength among leaf fibers. Its ash level is about 1.1%. Crystallinity index of PALF is generally

71-76% similar to cotton and ramie, and it is indisputable that it has a well-organized cellulosic structure that allows good inter-fibril cohesion during spinning [8].

PALF has one of the highest cellulose contents of leaf fibers, similar to flax (60.85%), and better than sisal (53.78%), and coir (32.53%). Its lignin content (5.12%) is much less than jute (12.16%) and coir (31.46%) which is good since high lignin content is a constraint on the flexibility of fibers in the processing. The average hemicellulose level of PALF (15.20%) is linked to the hygroscopic propensity-a characteristic that has to be controlled during the production of the yarn. In comparison to cotton, which has cellulose in almost pure form (83.98%) although the cultivation of cotton involves intensive water and chemicals, PALF offers an attractive alternative with a competitive chemical profile and a significantly reduced environmental footprint. A comparative analysis of chemical composition of PALF and other commercially significant lignocellulosic fibers is provided in Table 2.

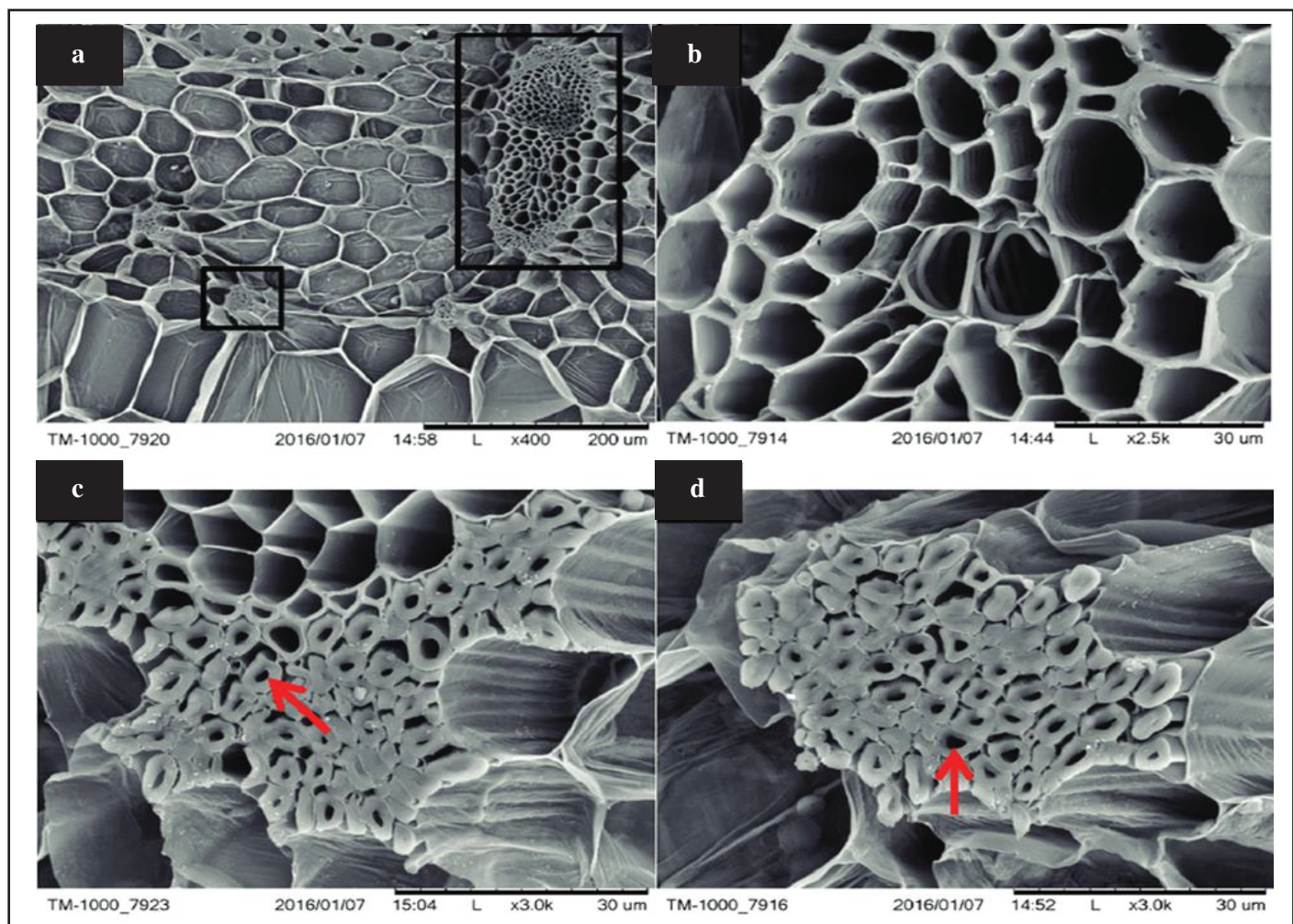


Figure 3: SEM micrographs display the transverse section of a pineapple leaf at low magnification in (a). The fibro vascular bundles, highlighted in the large rectangular region in (a), are viewed at higher magnification in (b) and (c), with mesophyll bundles shown in (d). Arrows point to the lumen within each cell. [49]

Table 2: Chemical Composition (%) of Selected Lignocellulosic Fibers [21,50–53]

Fiber	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Pectin (%)	Wax (%)	Ash (%)	Crystallinity (%)
PALF*	70 – 82	15 – 20	5 – 12	1 – 4	4 – 7	~1.1	71 – 76
Cotton	83 – 98	4 – 6	0.7 – 2	0 – 4	0.6	~1.2	70 – 80
Jute	58 – 73	12 – 24	12 – 16	0.2 – 2	0.5	~0.5	55 – 70
Flax	60 – 85	14 – 22	1 – 3	2 – 15	1 – 6	~1.5	65 – 75
Hemp	55 – 90	10 – 22	2.5 – 6	1 – 3	1 – 2	~1.5	65 – 78
Sisal	53 – 78	6 – 26	8 – 14	10 – 14	1 – 2	~1.0	60 – 70
Coir	32 – 53	0.3 – 20	31 – 46	3 – 4	0.6	~2.0	30 – 45
Ramie	62 – 76	5 – 17	1 – 9	0.3 – 2	0.3	~0.5	69 – 76
Kenaf	45 – 72	15 – 30	6 – 16	3 – 5	—	~2.0	50 – 65
Bamboo	36 – 65	11 – 30	2 – 32	—	1 – 4	~1.8	40 – 60

Table 3: Physical and Mechanical Properties of Selected Lignocellulosic Fibers [21,53]

Fiber	Density (g/cm ³)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Fiber Length (mm)	Microfibrillar Angle (°)
PALF*	0.8–1.6	170–1627	5.8–82	0.8–1.6	20–1500	8–14
Cotton	1.2–1.6	287–800	6–13	3–10	10–60	20–30
Jute	1.2–1.5	114–800	8–78	1.2–1.5	1500–3600	8–9
Flax	1.4–1.5	320–2000	10–103	1.2–3.6	5–900	5–10
Hemp	1.4–1.6	270–1110	14–70	0.8–4.0	5–55	2–6
Sisal	1.2–1.5	347–885	3–98	1.2–1.5	600–1000	10–22
Coir	1.2–1.3	131–343	3–17	15–30	50–350	30–49
Ramie	1.4–1.5	400–1000	24–128	1.2–4.0	40–250	7.5
Kenaf	1.2–2.7	223–930	14–60	1.6–6.9	1500–3600	—

3.3 Physical and Mechanical Properties

PALF has density of 0.8 to 1.6 g/cm³, tensile modulus of 5.8–82 GPa, and tensile strength of 170 to 1627 MPa depending on the fineness of the fibers, extraction mode and conditions of measurement [21,53]. The high variation of the reported values is due to the variability of natural fibers. PALF has a smaller fiber diameter, and a larger initial modulus and better tenacity than jute, but it is more variable. The low angle (8–14°) of PALF provides much greater load-transfer efficiency and axial rigidity than cotton (with a higher microfibrillar angle 20–30°) [8]. Table 3 provides a comparison of the major mechanical properties of PALF with other fibers that are often used in the yarn and composite applications.

4. Extraction & Processing Technologies.

The extraction and the degumming steps are the fundamental stages which determine the quality and commercial viability of the PALF-based yarns and composites. Fiber extraction should both maximize the fiber yield and length and minimize the damage to cellulose, and the three methods known -manual scraping, mechanical decortication and retting.

4.1 Manual and Semi-Mechanical Extraction.

The steps used in traditional manual extraction are practiced in all pineapple areas of India, Thailand and the Philippines; the

extraction process involves pulling individual leaves over a serrated scraping instrument called locally as a ketam, to gradually strip off the fiber bundles within the parenchyma tissue and epidermal material [43]. Although this technique has proven to yield long, high-quality fibers with minimal mechanical damage, it is highly labor intensive -taking about 10 minutes per leaf and only giving 0.3 g of dry fiber per leaf- so it is not suitable to industrial scale fiber supply chains unless a large labor force is invested [54]. In Semi-mechanical extraction, decorticators are used, which operate by passing leaves through a series of crushing rollers, then brushing or combing stages to strip the leaves of adherent parenchyma. This type of extraction consumes 5–10 times less time than other methods, although fiber length loss is still reasonable [43]. Field deployment using portable decorticator designs have been envisaged, making the processing decentralized near the pineapple cultivation location, and lowering the cost of logistics, but any residual pulpy material on the fiber surfaces usually requires further degumming treatment [55].

4.2 Retting

In water retting, where leaf bundles are placed in tanks or ponds and allowed to remain between 7–28 days, the dissolution of the non-fibrous binding matrix, which releases individual fiber bundles, depends on the activity of the pectinolytic and hemicellulolytic microorganisms inherently present in the retting water



Figure 4: (a) Manual extraction and (b) Mechanical extraction of PALF [56].

[54]. The fineness of the fibers at an increased retting time at controlled temperatures of 25°C is a reflection of the enzyme and bacterial removal of gum, hemicellulose, lignin, and other non-cellulosic components by biological retting [57]. But prolonged retting longer than 21 days has been observed to produce a measurable degradation in tensile properties, which can be attributed to enzyme action on the cellulose constituent as such, and which causes effluents with high biological oxygen demand that must be treated before discharge [54]. Dew retting: subjecting leaves to wetting and drying turns in the field less controllable and more season-related yielding uneven fiber properties that cannot be used in technical textile applications.



Figure 5: Pineapple Leaf Fiber (Retted)

4.3 Biological and Enzymatic Degumming

Another potentially technically viable advancement in PALF processing is the use of microbial strains intentionally cultivated

to perform retting and degenerating in a single process. Peng et al. proved that the residual gum content of the processed fiber was only 3.50% when in-situ inoculated with *Bacillus subtilis* XW-18, which produces a complementary cocktail of pectinase, xylanase, and laccase, without any chemical pretreatment or post-process bleaching [58]. The resulting fiber had a dispersed fibrous structure and a commercially viable whiteness and removed the process effluent issues that were found in the traditional chemical degumming using sodium hydroxide. An all-enzyme based formulation of enzymatic degumming on the three key gum substrates: hemicellulose, lignin and pectin, is a comparably clean and damage-minimizing alternative compared to chemical treatment and is increasingly accepted as the right technology to produce cottonized PALF, which can be spun in short-staple systems [54].

4.4 Degumming and Surface Modification: Chemical

Traditional chemical degumming uses 2-10% NaOH at 80–100°C for 30–120 min. solubility to hydrolyze and solubilize the hemicellulose, pectin, and lignin substances that attach the elementary fibers into bundle structures. Mercerization (alkali treatment) is a crystalline transformation of the cellulose, which causes part of the cellulose I to be changed into cellulose II, and it also raises the surface roughness and hydroxyl group density of the treated fiber-effects that are useful in interfacial bonding with polymer matrices [21]. PALF has been tested as the surface to post-degumming by silane coupling agents, acetylation, benzoylation, and acrylic acid grafting and the successful addition of ester carbonyl groups by esterification and silane treatments. Such surface modifications lower the fiber hydrophilicity and increase fiber-matrix adhesion in composite systems and also lower processability in spinning because of a decreasing fiber-to-fiber and fiber-to-metal friction coefficient.

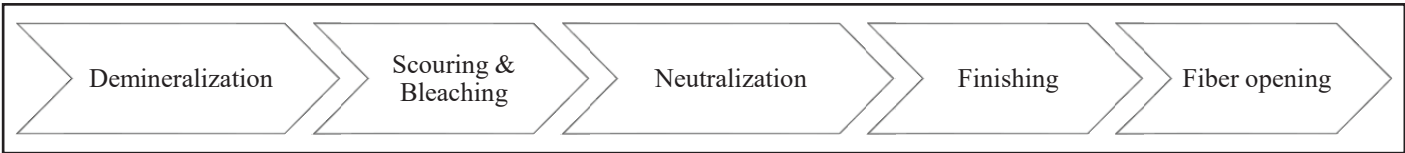


Figure 6: PALF degumming process

The hydrolysis of the hemicellulose, which is mainly made up of complex mixed polysaccharides, into simpler, water-soluble sugars by the process of degumming takes place. Meanwhile, saponifiable materials, e.g. gums and waxes are transformed into soluble soaps, whereas non-saponifiable oils are emulsified with the help of soaps and wetting agents, to be removed.

This is followed by the demineralization or swelling treatment which involves processing of the fibers with hot water, detergent and a sequestering agent. This will be effective in eliminating residual oils and waxes besides improving the contact between the fiber surface and water, which increases wettability. The fibers are later subjected to a scouring procedure that includes the chemical treatment at high temperature to remove lignin, pectin and other binding impurities on the fibers. The scouring process is repeated under the same conditions to make sure that a maximum amount of cleanliness and non-cellulosic material removal is achieved.

The scouring is followed by a hot washing phase to get the rest of the chemicals and impurities off to make the fiber surface purer. The fibers are then neutralized with a weak acid that serves to even the pH and cause a slight separation of the fibers and a distinct color change. Nevertheless, this stage also causes even greater stiffness, and the fibers are no longer the ones to be used in spinning. To eliminate this problem, finishing is done where a softening agent is added in an acidic medium. This last process gives back flexibility and softness to the fibers, greatly enhancing their hand feel and them making them more appropriate to the later processing and spinning of the textile.

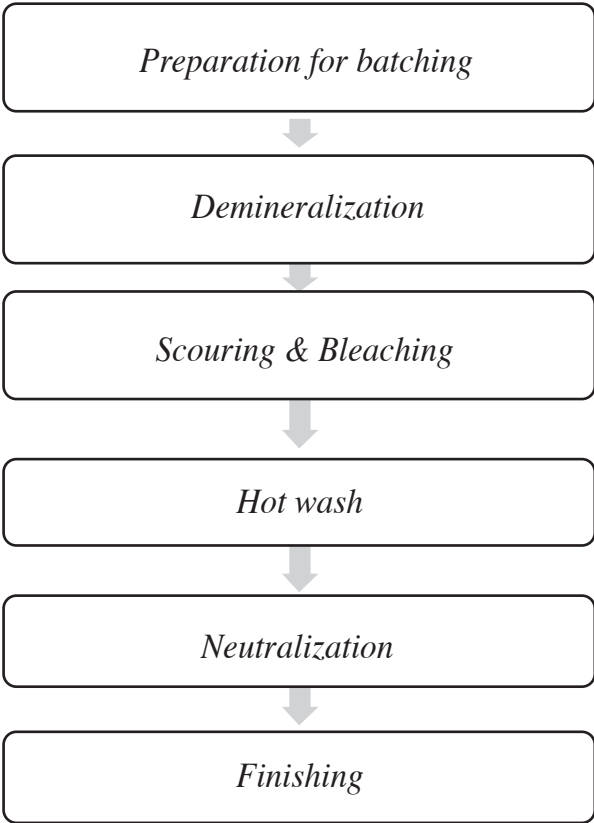


Figure 7: PALF chemical degumming (Process flow chart)

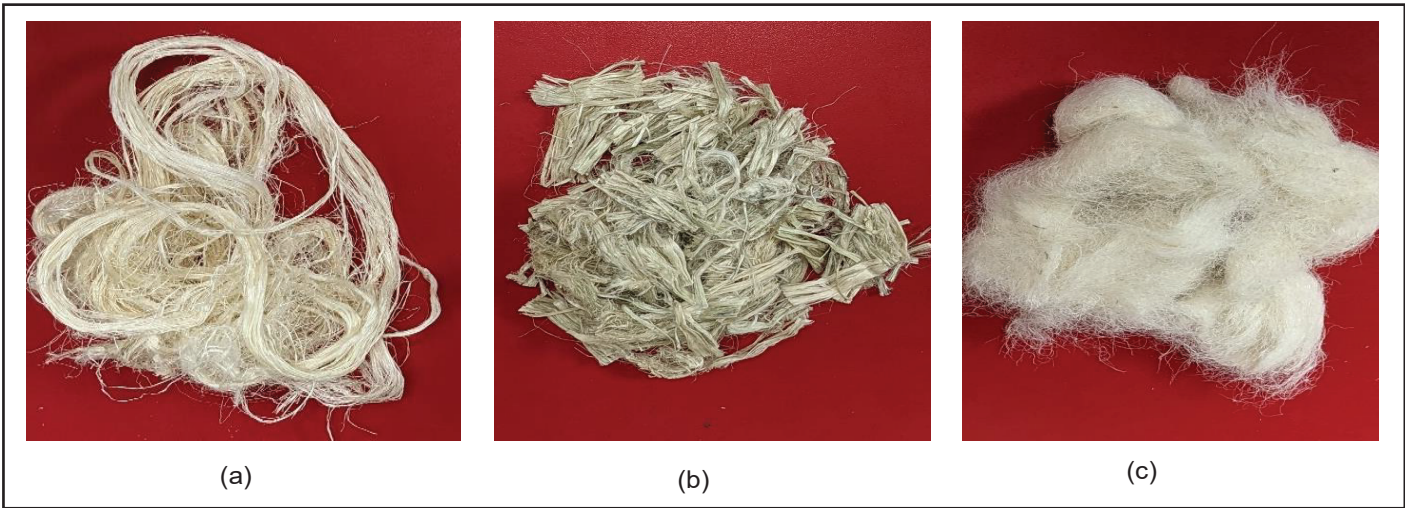


Figure 8: (a) Retted PALF Fiber (b) Cottonized PALF Fiber (c) Opened PALF Fiber

5. Cottonization and Spinning Adaptation

The greatest obstacle to the integration of PALF into the current short-staple spinning infrastructure is the structural incompatibility between raw PALF bundles and the machine configurations optimized to process cotton, with a staple length of 25–38 mm, a fineness of 12–22 μm and a characteristic crimp, which facilitates the adherence of fibers in the drafting and twisting stages. Normal bundle diameter is regularly more than 100–300 μm and bundle length is extremely variable, producing drafting anomalies, roller lapping, and high end-breakage rates upon typical ring-spinning frames [51]. The technological solution to this problem is the cottonization of PALF- a series of chemical, enzymatic, and mechanical treatment steps that are intended to disaggregate fiber bundles into spinnable ultimate fibers of dimensions and surface properties that are similar to those of cotton.

Cottonization, sequential decortication, enzyme or chemical decumulation to loosen the bundles, mechanical opening and carding adapted to the cotton blow-room and card environment, and a softening treatment, are used to reduce the natural rigidity of the highly crystalline cellulose structure, to loosen the bundles. It is explicitly similar to technologies of cottonization of flax and hemp fibers, where enzymatic degumming using multi-component enzyme systems has been shown to yield cottonized bast fibers that can be processed using typical short-staple ring-spinning equipment [59]. In the case of PALF, it has been demonstrated that cottonization when carried out successfully does not only lower the fiber linear density of the raw bundle (2–7 tex) to the ultimate fiber levels of around 0.5–1.5 tex, but also brings the fiber into the processable range of the available cotton spinning equipment [51].

One of the earliest systematic tests of PALF spinnability was made by Ismoilov et al. on a cotton short-staple ring-spinning system, working with cottonized PALF in 100% pure form and binary mixtures with cotton (50:50) and polyester (50:50) at the laboratory level through opening, carding, drawing, simplex, and ring-spinning. The 100 percent PALF yarn had good tensile characteristics and lower evenness than the control yarns of the same count made of cotton because variability in PALF ultimate fiber length and diameter is greater than that of cotton. Blended PALF/cotton yarns demonstrated better evenness as compared to 100% PALF and the cotton portion of the blends had a greater effect on drafting regularity due to having a uniform shorter carrier fiber, and the polyester blends had the highest tenacity values. The research determined that PALF has the essential spinnable qualities length, strength, fineness, cohesiveness, and elongation, required in the formation of the yarn, and that it is possible to correct the natural limitations of the unevenness of the raw natural fiber through blending strategies [51].

A complementary study by Jalil et al. examined spinnability of pure and blended PALF on apron-draft ring-spinning frames and

flyer-based jute spinning frames and obtained 100 percent PALF yarns at 121 tex and 138 tex, respectively and cotton-PALF blended yarns at 30 tex in 90:10 and 80:20 ratios. There was progressive reduction in unevenness (Um%) with an increase in the draw-frame passage number of cotton-PALF blended yarns and the finisher draw-frame recorded the lowest Um% of all the stages of the sliver preparation process, which validates that sufficient preparation of drafting is necessary to control the length and diameter heterogeneity of the fiber that is inherent in PALF. The woven fabrics made using these yarns had similar physico-mechanical characteristics of reference jute-cotton fabrics, and FTIR and XRD results showed that the spinning process had preserved the structural integrity of the cellulosic fiber component [8].

Recently, Zolkiflee et al. examined how the parameters of ring-spinning (twist speed of 800, 850, 900 tpm, total draft 8 and 10, and blending ratio 30%, 40% and 50% PALF in cotton) affected the PALF-cotton yarn properties based on the response surface approach [60]. The ratio of blending had the greatest influence on the yarn diameter and the higher the PALF content, the bigger the diameter because ultimate fiber diameter of PALF was larger compared to cotton. Increased twist speed and overall draft also lowered the diameter of the yarn and enhanced the quality of yarns, with the combination of 900 tpm and draft 10 giving the best and uniform yarns in all blending ratios. It was established that the mechanical properties of PALF-cotton blended yarns are non-linear with respect to processing parameters and fiber ratio and optimization of the ring-spinning arrangement is required to achieve the mechanical potential of PALF in blended yarn structures. Another avenue that has been investigated is open-end (rotor) spinning, where the fiber blending is completed before spinning; Rusman et al. showed that blow-room fiber blending before spinning gave statistically better tenacity and more uniform yarn count than draw-frame sliver blending, which is due to the higher degree of dispersion at the opening stage [61].

Although, PALF elementary fibers have a porous, hollow micro-structure and inherent antimicrobial properties that give them functional differentiation opportunities previously incapable of being performed by synthetic blends, a commercial incentive to invest in the process engineering necessary to overcome the current processability barriers.

6. Mechanical and Physical Property Comparison

To determine which areas of use the PALF has a significant performance benefit and to design PALF containing yarn and composite systems, a rigorous knowledge of the mechanical and physical properties of PALF compared to other competing natural and synthetic fibers are necessary and described below.

6.1 Tensile Properties

PALF has always been one of the best tensile strength and elastic modulus of natural leaf fibers. The claimed tensile strength of PALF bundles is between 413 to 1627 MPa and the values of Young modulus are between 34.5 to 82.5 GPa [50]. For comparison, sisal fiber tensile strength ranges from 468 to 700 MPa, jute from 393 to 800 MPa, hemp from 550 to 900 MPa, flax from 500 to 1500 MPa, and E-glass fiber typically 2000–3500 MPa [39,62]. On one strength scale, the tensile strength per density, PALF is competitive against E-glass fiber and far more competitive than most other natural leaf fibers, which is a result of its low density (1.44–1.56 g/cm³) coupled with its high cellulose crystallinity and low MFA [50,63]. The PALF density is significantly less than E-glass (2.5 g/cm³) and steel (7.8 g/cm³), and similar to other cellulosic fibers, is useful in lightweight structural and semi-structural designs where mass efficiency is a design factor.

It is always because its low microfibrillar angle is credited with the superior mechanical performance of PALF compared to other leaf fibers such as sisal, abacá and henequen. PALF has the lowest reported MFA of all natural fibers extracted in leaves of plants, of 8–14°, which directly translate into high modulus of elasticity and high resistance to axial deformation. Comparative studies of PALF with sisal in a similar composite matrix system under equivalent fiber volume fractions have shown 25–35% higher tensile modulus of PALF composite, which is similar to the difference in microfibrillar angle between the two fibers [62,64]. The highest tensile strength and stiffness of hybrid composite configurations when using PALF at 10 wt.% PALF loading and 20 wt.% glass fiber loading showed the highest tensile strength and stiffness at this intermediate loading, indicating that PALF can play a significant role in hybrid reinforcement strategies that can be cost effective, lightweight, and performance oriented [65].

6.2 Physical Characteristics and Changeability

The linear density (fineness) of PALF at the bundle level has been reported to be between 1.39–7.07 tex, with the finer side of the range being realized by optimized biological retting at 25°C [54]. At the bundle level, fiber length may be as long as 70.8 cm with hand-scraping extraction and offers an extremely high aspect ratio, which is beneficial to composite reinforcement efficiency and long-fiber spinning systems [54]. Ultimate fiber diameter range is 10–35 µm at the finer end, which accounts for the fact that cottonized PALF can theoretically be spun on short-staple machinery. The physical differences between fibers of the fiber positions in the same plant are pronounced: the fibers of the leaf tip are finer, but weaker fibers, whereas the fibers of the leaf base have the highest tensile strength and diameter [54]. This internal variability of this leaf necessitates the need to carefully homogenize the mechanically during cottonization and opening processes to reduce the occurrence of yarn evenness.

6.3 Compared to Traditional Textile Fibers

An actual performance comparison of PALF and fibers employed in traditional cotton-based yarn systems shows a discrete albeit complementing profile. The tensile strength of cotton (300–700 MPa) is less than what is reported by PALF on single-fiber basis, but the high rate of elongation at break (7–8%), fine and uniform single-fiber diameter (12–22 µm) and the natural crimp of cotton enable it to be far more amenable to short-staple spinning, as well as giving rise to more consistent, lower-hairiness yarns. Jute shares the same cellulose content with PALF (60–70%), is heavier than PALF, more varied in mechanical properties, and lower count produces a coarser yarn that can only be used in lower-count applications in bags, sacks, and technical fabrics [62]. Natural-feel Viscose/lyocell regenerated fibers that compete with PALF in the natural-feel yarn segment are easier to process and have tunable fiber properties, but are produced by a chemical pulping process that produces significant process chemicals and consumes significantly more energy per kilogram of fiber than mechanical PALF extraction [66].

PALF has been compared to jute, kenaf and sisal in polypropylene (PP) matrix systems in polymer composite applications. In direct comparative testing of jute-PP, kenaf-PP and PALF-PP composites at comparable 30–40 wt.% fiber weight fractions, PALF-PP composites were found to have tensile strengths and moduli competitive to or better than kenaf-PP composites, with the overall ranking of the mechanical properties of PALF-PP being PALF-PP ≥ kenaf- Polyester resin. Equal-weight PALF/sisal hybrid composites have shown ductile strength to 207 MPa, bending strength as high as 90.3 MPa and impact energy of 29 J/m² which is at par with the mechanical performance levels of glass fiber reinforced thermoplastic composites at the same fiber volume fractions [62]. The best reported tensile strength and modulus of PALF when hybridized with Kevlar fiber in unsaturated polyester was obtained as a result of the hybridization with PALF, which validates the performance of PALF in hybrid technical composite architectures [67].

7. Environmental Impact and Life Cycle Assessment (LCA) Comparison

The internationally accepted system of quantifying the environmental consequences of materials and products throughout their entire value chains, i.e. cradle (extraction of raw materials) to gate, to grave, in functional unit-normalized impact categories such as global warming potential (GWP), fossil resource depletion, water consumption, terrestrial ecotoxicity, and land use is life cycle assessment (LCA). There has been a significant increase in the use of LCA on natural fiber composites and textile fibers over the last ten years and offers a growing body of strong evidence to compare the environmental performance of PALF and other plant-based fibers with traditional synthetic equivalents.

7.1 Carbon Footprint and Global Warming Potential

The production of PALF has a structurally favorable carbon footprint relative to synthetic fibers due to two reasons which are well-established in fiber LCA literature. First, PALF is produced by using pineapple leaves as an agricultural by-product of fruit production, there is no extra cropland, irrigation, fertilizer, or pesticide use assigned to the fiber production system [44]. This by-product allocation implies that the environmental effects of PALF extraction are only confined to mechanical, retting, or enzymatic processing steps, and not the entire agricultural production cycle. Second, pineapple plants, similar to all other crops that undergo photosynthesis, capture atmospheric CO₂ as they grow, which partially cancels the greenhouse gas emissions of downstream processing [68]. A total carbon footprint analysis of cellulosic textile fibers comprising conventional and non-conventional natural fibers revealed that leaf fibers such as PALF belong to the unconventional fiber category with a mean GHG emission of about 1.03 tons CO₂-eq/ metric tons of fiber, as compared to conventional natural fibers such as cotton with 1.55 tons CO₂-eq. One kilogram of E-glass fiber produces a range of 1.7 to 2.2 kg CO₂-eq, which is significantly greater than the figure of PALF treated by mechanical or biological treatment [69].

7.2 Water Consumption

Application of water in PALF processing is mainly related to retting stage in case water retting is used and washing processes after chemical degumming. The relative standpoint of PALF is good compared to traditional cotton that needs about 1,559 liters of water per kilogram of fiber with a combination of rainfall and irrigation, which makes it one of the most thirsty agricultural fibers in production [70]. As PALF is produced in by-product leaves through the use of mostly mechanical processing or biological processing, the blue water footprint of PALF is a fraction of the cotton. Biological retting processes which rely on static bath instead of flowing water further limit the amount of water used and the replacement of water retting by enzymatic in-situ degumming processes such as the *Bacillus subtilis* XW-18 technique of Peng et al. do away with the water tank entirely [58]. The cradle-to-gate LCA analysis of natural and synthetic fiber production methods proved that natural cellulosic fibers such as a leaf fiber have much less impact on water consumption than the production of polyester which is not the process that requires the use of water but rather generates thermal and chemical pollution loads during the production of the polymer [70].

7.3 Land Use and Agrochemical Burden

Since PALF is a by-product fiber and not a specific fiber crop, the effective land use intensity is zero in the view that no more land area is cleared or dedicated to fiber production, the fiber substrate is produced at zero land cost on land already devoted to the

pineapple fruit crop [44]. This is in opposition to traditional cotton that requires dedicated cropland with high agrochemical intensity, and even with dedicated bast fiber crops like flax or hemp, that, despite having lower chemical intensity than cotton, still require dedicated land usage to fiber production [39]. Investigations of the land use and pesticide-related impact category of dedicated fiber crops, LCA analyses of natural fiber reinforced polymer composites always rank agricultural production as the largest contributor to this category of impact, an effect category where PALF scores significantly higher given the by-product nature of the product [68].

7.4 Comparison of End-of-Life Biodegradability and Biodegradation

One of the key environmental strengths of PALF compared to synthetic fibers is that it is biodegradable under aerobic and anaerobic environments. Unlike polyester, cellulosic natural fibers that include PALF are decomposed by soil microorganisms and their enzymes into water, carbon dioxide and biomass over a timescale of weeks to months under good composting or soil conditions, whereas polyester takes 20-200 years to be degraded to some extent under landfill conditions through partial photo-oxidation [27,68]. LCA end-of-life benefit of PALF over synthetic fibers is best articulated in the categories of biodegradation and eco-toxicity impacts: PALF and other cellulosic fibers do not produce persistent microplastic pollutants in use and disposal, whereas washing of synthetic textiles releases 100,000–700,000 microfibers per laundry cycle to freshwater PALF composites and textiles also have end-of-life recovery options not available to synthetic fibers, such as composting, anaerobic digestion to produce biogas, and soil amendment, returning carbon and mineral nutrients to biogenic cycles, making them a better option in a circular economy [68].

7.5 LCA Limitations and Knowledge Gaps

Although the overall environmental footprint of PALF is quite positive compared to synthetic fibers, LCA comparisons are prone to a variety of critical methodological limitations and knowledge gaps. The boundary of the system (cradle-to-gate and cradle-to-grave) has a strong influence on comparative rankings: PALF is undoubtedly favored over polyester at the gate (fiber production), whereas at any point in the use-phase where mechanical durability is a major concern, synthetic fiber products can have longer service lives to benefit their per-use environmental performance [70]. The geographic differences in the energy mix employed in PALF processing can have a substantial influence on the climatic impact of fiber production: mechanical processing in grid-electricity-intensive areas can have a higher GHG number than that of areas with renewable-driven power supply. The LCA database of PALF in particular is only sparse compared to cotton, flax or jute, and most LCA evaluations of pineapple fiber are based on process data of

similar leaf fibre systems instead of direct measure [68]. It is found that one of the research priorities in the field is to have a robust, regionally differentiated LCA inventory dataset of the extraction of PALF, including both manual and mechanical, as well as biological, degumming routes, so that it could be credibly compared to traditional fibers to support procurement decisions and regulatory environmental performance claims [69].

8. Techno-Economic Feasibility

To give a realistic assessment of how PALF can enter into the commercial production of yarns and composite products, one has to look beyond the mechanical performance and eco-friendly qualifications to look at the cost structure, scaling limitations, and economic value proposition that ultimately dictate the adoption in industry.

8.1 Raw Material Cost and Agricultural Economics

The most remarkable economic strength of PALF lies in the fact that the product is an agricultural by-product. Since pineapple leaves are a by-product of fruit farming which is already in progress, the economic cost that can be attributed to the production of fiber at the farm gate is the incremental cost of labor and equipment of leaf gathering and initial fiber harvesting—the land, irrigation costs, and agrochemical costs are all sunk costs of the fruit business [44]. Brazil estimates the cost of the raw material of PALF at about USD 15 per ton at field level (raw material) against the softwood fibers at about USD 250 per ton and cotton at USD 1,200–1800 per ton at an order of magnitude cost disadvantage to the conventional textile fibers [51]. In Asian manufacturing (especially the Philippines, Thailand and India, which contribute significant proportions of world pineapple production), the cost of labor in manual decortication further lowers effective fiber recovery costs and the community-based cooperative model of labor organization on leaf collection is a socially embedded supply chain model [71].

The main industrial target of PALF in the structural application is the natural fiber composite market that is estimated to be USD 7.1 billion in 2023 and be USD 14.0 billion in 2030, with a compound annual growth rate of about 10.1% [72]. In this larger market, non-wood natural fibers such as PALF compete in the automotive interior and packaging and technical textile markets, where low density ($1.44\text{--}1.56\text{g/cm}^3$), competitive specific mechanical properties, and proven sustainability credentials can provide a premium to brands and manufacturers working under environmental performance requirements [72,73].

8.2 Processing Cost Structure

The main cost motivators of PALF based yarn and composite manufacture reside in the processing chain and not the raw material stage and here again it is here which the techno-economic case of PALF is still most subject to the onward technological

advancement. The extraction of fibers by hand is labor intensive and spatially restricted and limits throughput and introduces quality variability; semi-mechanical decortication with portable decorticators is less labor intensive, but needs capital investment in equipment and minimum scale of processing to be economically viable [74]. Although chemical degumming works effectively to enhance the fineness of fibre and surface chemistry, process effluents have a high chemical oxygen demand and necessitate wastewater treatment facilities, which increase operating costs and regulatory compliance burden, which could be significantly lowered by biological and enzymatic degumming routes, should they deliver similar results at a commercial scale [55,58].

The cottonization process necessary to convert PALF into use in short-staple ring-spinning systems introduces an additional processing and the expense. A comparison with the cottonization of flax and hemp fibers, where commercial scale processes exist, indicates that well-optimized cottonization may be realized at a cost premium of USD 0.30–0.80 per kilogram of processed fiber over the raw extraction cost, and that cottonized PALF may be ex-factory in the competitive range of costs of viscose and modal fibers, and significantly less than specialty synthetic fibers. Nevertheless, the absence of a standard PALF cottonization procedure and commercial-scale lines of cottonization devoted to pineapple leaf fiber imply that present production is based on small-scale pilot production at higher unit expenses than large-scale counterparts [8,51].

8.3 Value Chain Economics and Price Positioning

The economic success of PALF-based products is determined by the segment of the market addressed and how well the combination of unique properties and characteristics of PALF, which include biodegradability, agricultural by-product source, natural luster, intrinsic antimicrobial activity and functional mechanical performance can be priced at a premium compared to commodity fibers [73,74]. PALF-based yarns and fabrics are capable of going 2–5 times high in price relative to commodity cotton equivalents in the high-end sustainable textile sector, which can be justified by demonstrable environmental credentialing and brand sustainability stories, provided that fiber consistency and processability can be shown at commercially viable scale [71]. The value proposition in the case of automotive composite use where the cost of natural fiber systems is generally only slightly more than glass fiber (5–15%), changes to the ability to comply with regulations as required by the EU End-of-Life Vehicles Directive requiring 85% recoveries and 80% recycling of vehicle parts and by rules to come requiring lightweighting of vehicles due to CO₂ fleet emissions.

One of the major techno-economic issues which limit the competitiveness of PALF in all market segments is the variability of high fiber properties of natural plant-based materials. Cultivar variability, variation in PALF tensile strength, fineness and length

due to positioning of leaves, seasonal climate variability, and extraction technique cause challenges in the quality level assurances that industrial clients demand, as well as requires a larger safety factor in composite design that further diminishes the weight efficiency benefit of the natural fiber system. The adoption of standardized harvesting procedures, retting or degumming environments, and electronic monitoring of quality of each fiber lot prior to spinning or composite treatment has been proclaimed as a requirement of PALF to meet the supply chain predictability that is required of automotive and technical textile original equipment manufacturers.

9. Industrial Case Studies

To translate the results of laboratory-level research into the commercial-level products, it is necessary to identify and examine industrial case studies where PALF-based or closely similar leaf-fiber-based technologies have succeeded, which can give empirical evidence regarding the conditions under which they can be successful, the remaining obstacles, and the scalability of the underlying value chains.

9.1 Piñatex® / Anam PALF® — Ananas Anam Ltd.

The PALF nonwoven leather-alternative material, under the Piñatex brand name, and the related Piñayarn staple textile fiber created by Ananas Anam Ltd., a certified B-Corporation based in the UK and founded in 2013 by Dr. Carmen Hijosa is the most commercially developed and widely mentioned industrial use of PALF [71]. Piñatex product platform is developed on PALF, which is extracted out of the pineapple plantation by-product leaves in the Philippines, semi-automatically decorticated using farming cooperatives; the extracted fiber fluff is combined with corn-based polylactic acid (PLA) to create Piñafelt, a nonwoven substrate, which then undergoes finishing in Spain and Italy to create the final leather-alternative product. The commercial supply chain serves as a pilot project of PALF valorization in a by-product and circular economy model: every linear meter of Piñatex avoids the emission of an estimated 12 kg CO₂ equivalent through waste diversion, and the extraction of the fiber does not produce net additional water, pesticide, or land use to fruit cultivation [71].

More than 1,000 brands worldwide have used Piñatex in their fashion, accessories, and upholstery designs, including Hugo Boss, H&M, and the Hilton Hotel Group, and has reached a commercial scale by taking a niche to mainstream market entry strategy based on sustainability certification (B-Corporation status since 2020, PETA vegan certification) and brand co-marketing [71]. Ananas Anam in 2021 has formalized a strategic alliance with Dole Sunshine Company in the Philippines to increase PALF leaf supply and more social impact within the farming communities, which may serve as an example of how agricultural conglomerates with large pineapple operations can be integrated as an upstream supply chain partner [71]. In 2020,

with a UK government PPE grant, the Piñayarn product demonstrated that PALF can be converted into a textile grade staple yarn that can be used in the production of fabrics, expanding the range of applications that can be addressed, beyond alternatives of nonwoven leather, into knit and woven textile systems [71]. Nonetheless, the acquisition of Ananas Anam in October 2025 highlights the longstanding issues of scaling sustainable material business ventures in price-competitive fashion markets, and shows that technical performance and environmental credentials are not enough without strong cost structures and diversified channels of demand.

9.2 Automotive Natural Fiber Composite Applications

The automotive industry is a highly documented industrial environment with the application of natural fiber composites that is directly applicable to the prospects of PALF, although automotive applications of PALF are at the prototype and pre-commercial phase. The incorporation of natural fiber reinforced polypropylene (NF-PP) composites in interior components of vehicles has been pioneered by German manufacturers, the Mercedes-Benz automobile maker having incorporated a multi-fiber blend of flax, hemp, sisal and wool in about 50 interior parts of the E-Class model [75]. In its collaboration with Bcomp (Switzerland), BMW has developed proven natural fiber composite components such as motorsport bodywork components (iFE.20 Formula E car, 2020 BMW M4 DTM) and road car exterior components (Volvo XC60 hybrid sill moldings, Polestar interior panels) with the natural fiber system showing equivalent stiffness and weight performance to carbon fiber panels at a lower cost and better end. These automotive case studies demonstrate that natural fiber composites can fulfill the functional needs of semi-structural interior and exterior parts at volume production quality levels— a standard that can be aimed to by developers of PALF composites, as a medium-term industrial goal, on the basis of the mechanical performance equivalence between sisal and kenaf reported in the academic literature [64,75].

The economic argument is well understood in regard to replacing natural fibers with automotive use. NF-PP composite interior panels weigh 15-20% less than similar glass fiber reinforced PP panel of the same stiffness and are 10-20% less cost per part at volume quantities [75]. Lightweighting is directly proportional to increased fuel economy: a 10 percent vehicle weight reduction yields about 6 to 8 percent fuel use reduction, which is valued in CO₂ units to the benefit of the increasingly strict EU fleet emissions standards [75]. In the case of PALF, high specific modulus, low density, and reported biocompatibility has placed it in the automotive application market in geographically close markets with pineapple cultivation infrastructure surrounding vehicle assembly, which lowers the logistics carbon expenses.

9.3 Bangladesh and India: Emerging Small-Scale Fiber Processing

In Bangladesh as well as India, where the pineapple plantations and natural fiber processing sectors are in close geographic proximity, small-scale PALF processing projects have already shown the viability of the agricultural supply chain of the fiber even without specific large-scale industrial infrastructure. Hand-extracted PALF has been woven into coarse-count yarns and woven fabrics on adjusted jute spinning and weaving equipment in Bangladesh, where the Dhaka, Sylhet and Chittagong divisions form some of the largest pineapple production areas, thereby providing a proof of concept of value-added production of PALF textiles using the existing natural fiber processing infrastructure [8]. Benchmarking of spinning performance of PALF against jute in Bangladesh context has established that physical and structural properties of PALF are similar to jute fiber and PALF performs better than jute in certain fineness and breaking tenacity properties, making the fiber viable as an option to be incorporated into the current jute industry supply chain [8]. The scalability issue in these situations is the standardization of the quality of fiber extraction, the creation of a proven decorticator technology that can run at the scale of a village cooperative, and the formation of buyer networks that can offer price discovery and offtake certainty to processed PALF.

10. End Uses of Pineapple Leaf Fiber (PALF)

Pineapple leaf fiber (PALF) has attracted a lot of attention as a sustainable and high performance natural fiber because of its high mechanical properties, cellulose content and the fact that it is eco-friendly. Previously considered an agricultural waste by-product, PALF is currently finding increased application in a variety of industrial applications, both in the textile industry and in high-technology compound-based composite materials, thus contributing to the principles of the circular economy and resource efficiency.

The first and one of the most established uses of PALF is in the textile industry where it is applied to creating fine fabrics like

Piña cloth. The lightweight structure, natural luster and great breathability are the features of this fabric. Its moderate length and high moisture absorbing power allow using the fiber in combinations with cotton, polyester, and silk to improve the performance of the yarns and comfort of the fabrics. Nevertheless, because of the quite coarse texture, chemical/enzymatic treatments are commonly used to enhance the softness and spinnability.

PALF is a potential reinforcement material in polymer composites with potential in the recent years. It has high tensile strength, low micro fibrillar angle and good aspect ratio which makes it to have good mechanical performance when embedded into thermoplastic and thermoset matrices like polypropylene and polyester. PALF reinforced composites are more and more applied to automotive parts such interior panels, door trims, and dashboards, and in lightweight construction materials. These bio-composites can be used as an alternative to synthetic fibers such as glass fiber to minimize environmental impact and total material cost.

Pulp and paper industry is another industry that uses PALF because of its high cellulose content and fiber length. It finds application in manufacture of quality paper, specialty paper products and biodegradable packaging materials. PALF based paper has excellent tensile strength, tear strength and durability which make it useful in both industrial and decorative.

PALF has also demonstrated a lot of potential in environmental and filtration applications. It has a porous nature with a hydroxyl-based surface which allows it to adsorb pollutants effectively such as heavy metals and organic pollutants of wastewater. Also, the oil spill absorption, air filtration, and acoustic insulation systems make use of PALF-based materials, especially at higher frequencies because of the porous structure. These characteristics render PALF a promising substance in environmental remediation technologies that are sustainable.

In addition to the traditional application, PALF is receiving interest in technical and industrial applications, such as in ropes, mats, carpets, geotextiles, automobiles and insulation boards.

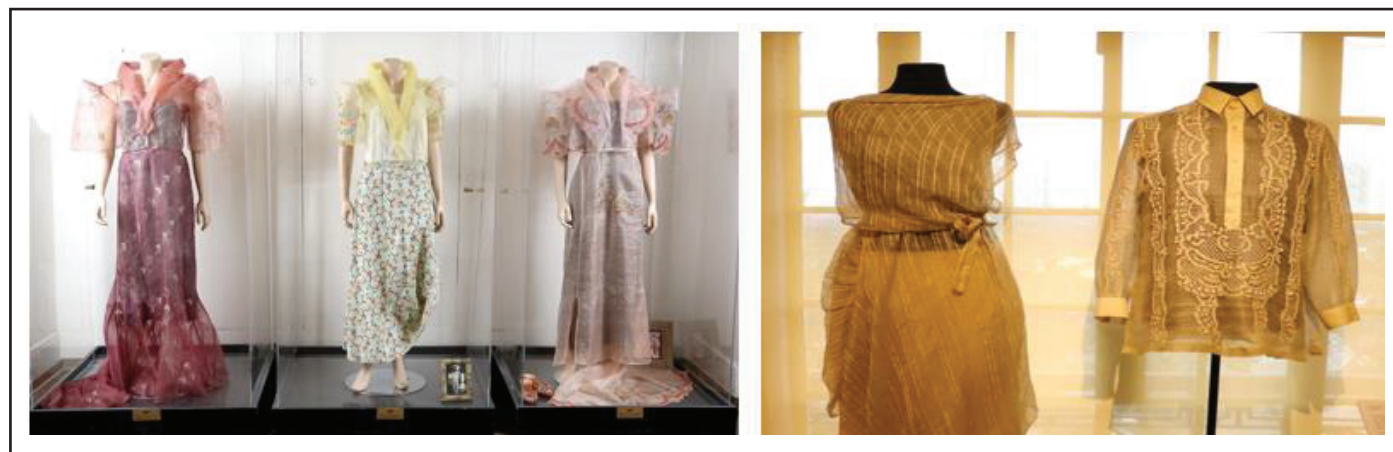


Figure 9: Various Traditional and Luxury Women Dresses

It is biodegradable and resilient to mechanical forces; thus, it can be used in civil engineering in erosion control and soil stabilization. Moreover, PALF is also under evaluation in high material applications, including nanocellulose-based extraction, biomedical scaffold, and packaging systems that are eco-friendly. The evolution of PALF-based nanofibers and biopolymers coincides with the new trends in sustainable materials science and green engineering.

environmental conditions since the hydrophilicity of the fiber causes absorption of moisture, dimensional instability and degradation when used in composite applications. The novel studies of PALF-derived nanocellulose emphasize its possibilities to be used in more sophisticated applications, such as the biodegradable nanocomposites, filtration membranes, and smart textiles, yet these domains are not thoroughly studied and demand the further technological development. Lastly, one can



Figure 10: Uses of PALF based Composite in Automobile Industry

11. Research Gaps and Future Roadmap

Nevertheless, even though the scientific community has been compiling a significant amount of research in the field of pineapple leaf fiber (PALF) over the last thirty years, the gaps in knowledge that are critical in advancing to a coherent, science-driven engineering framework to design PALF-based yarns and composite systems remain. Among the greatest weaknesses is that there are no standardized procedures of characterizing and grading of fibers, which results in the inconsistency of reported properties because of the differences in testing techniques and measurement regimens. Of equal significance is the lack of scalable and environmentally friendly cottonization process, since the existing methods are based on either chemical or biological treatment where the first can produce harmful effluents, or the second produces fiber quality inconsistency; enzymatic methods have potential, but need further optimization and industrialization. Moreover, systematic investigations that can be used to optimise spinning processes in various systems, including ring, rotor, air-jet, and vortex spinning, have not been carried out with PALF as its structural characteristics differ with traditional fibers. The other significant area of research gap is the long-term durability and performance of the PALF-based materials especially under different

barely find emphasis on the integration of PALF into a sustainable value chain, such as the optimization of supply chains, the economic viability, and the social implication as well as the circular economic models, which are necessary in transforming PALF as a research material into a commercially viable and environmentally sustainable resource.

12. Conclusion

Pineapple leaf fiber (PALF) is one of the most promising solutions to the development of the sustainability of the textile and composite industries because it is able to use agricultural waste and minimize the use of more resource-demanding conventional fibers. It has good mechanical characteristics, low density and cellulose content that allows its use in yarn production and in composite materials reinforcement. It is also biodegradable and has a low environmental footprint, which makes it especially well-suited to the inclusion in the systems of the circular economy. Although it has these benefits, there are a number of issues which do not allow it to be used in large scale industry, among them being the variability of fiber properties, the absence of standardized testing and grading systems, and the difficulties encountered in processing using existing spinning processes. The solution to these problems is to conduct a specific study on scalable and eco-friendly cotton-

ization methods, spin parameters optimization, and overall performance assessment in the real conditions. New trends in the development of PALF-based nanocellulose and higher-end functional materials expand its potential use even in high-value and technologically sophisticated applications. In addition, it is necessary to create effective value chains through economic modelling and policy programs to guarantee commercial scalability and industry acceptance. All in all, as processing, standardization and system integration are increasingly being planned strategically, PALF can make its way out of the niche material and into a mainstream sustainable resource, which will make a substantial contribution to the environmentally responsible material innovation and industrial development.

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