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The Transformative Power of Green Chemistry: Advancing Sustainability and Natural Fiber Utilization

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Abstract

These days, one of the most studied subjects is green chemistry. The goal of extensive study on green chemistry is to maximize the intended product in an environmentally sustainable manner while minimizing or eliminating the formation of hazardous by products. Green chemistry is necessary to reduce the negative environmental effects of anthropogenic materials and the processes used to produce them. Research on effluence responsiveness is derived from scientific breakthroughs, as indicated by green chemistry. With the aid of the invaluable philosophy of green chemistry, scientists and chemists may greatly reduce the risk to the environment and human health. The application of safe, repeatable, environmentally friendly solvents and catalysts can help realize the goals of green chemistry. Green chemistry might involve everything from cutting waste to properly disposing of garbage. The best approach should be taken to dispose of any chemical wastes so as not to harm the environment or other living things.

Keywords: Environmental Sustainability, Green Chemistry, Natural Fiber

Introduction

The twelve guiding principles of "green chemistry" seek to minimize or eliminate hazardous materials from the synthesis, manufacture, and use of chemical products; as a result, the use of materials that pose a risk to the environment and human health should also be minimized or eliminated. In the early 1990s, the idea of "green chemistry" was first put forth. The renowned green chemistry journal of the Royal Society of Chemistry published its inaugural volume in 1999 and the Green Chemistry Institute was founded in 1997 [1, 2]. The deliberate aim of sustainability can be achieved by chemists with the aid of the twelve principles of green chemistry. Careful planning of chemical synthesis and molecular design to minimize negative effects is what defines "green chemistry." Synergies, not only trade-offs, can be achieved by thoughtful design [2]. They exclusively employ chemical procedures and materials, which have no adverse effects on the environment. Its foundation is the creation of initially created or recreated molecules, reactions, materials, and processes that are less hazardous to the environment and human health. Nearly every area of chemistry, including inorganic, organic, biochemistry, polymer, environmental, and toxicological, is involved in the processes of "green chemistry."

The objectives of environmental protection and economic benefit can be met by utilizing the various popular trends of the green program, such as catalysis, bio-catalysis, and the use of safety alternatives: renewable feedstock (biomass), reaction solution (such as water, ionic liquids, and supercritical liquids), reaction conditions (microwave irradiation), and new synthetic pathways (photocatalytic reaction). Examples of current trends in which green chemistry lessens the environmental impact of chemical processes and technology are shown in (Figure 1) .

The idea of "green chemistry" has affected industry, education, the environment, and the general public in addition to the research lab, which is why it has had such a significant impact. The

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study of "green chemistry" has demonstrated how chemists may create profitable, environmentally friendly, and next-generation goods and processes that also benefit human health. In addition, over the past 20 years, there has been an increase in government financing, teaching programs, green chemistry research center (CGRC) establishment, and scientific interest for green chemistry. Green engineering and chemistry courses are being offered by a number of universities [3].

Natural fiber

The fibers that are considered natural, like cotton, silk, and wool, are derived from plants, animals, and geological processes **shown in figure(2)** On the other hand, synthetic fibers are manufactured by humans using petrochemical resources like polyester, rayon, and acrylic.[4]

Natural resources, including plant fiber, are frequently used in companies as a substitute raw material for goods derived from fossil fuels [5].

Natural fibers are classified as lignocellulosic, meaning that cellulose, hemicellulose, and lignin constitute the majority of their composition (as shown in Fig. 3), with smaller amounts of extractives, pectins, waxes, and water-soluble substances also included, **Table 1** discusses cellulose and lignin, which are the main chemical components of fibers such as coir, bananas, pineapple leaves, sisal, palmyra, sunhemp, and so on. As a linear homopolymer of β-(d)-glucose, cellulose (Fig. 3A) is composed of highly crystalline segments that are successively bonded together to form microfibrils. It is a significant organic chemical that plants generate and serves as the fundamental structural component of plant fibers. Long chains of linked glucose units make up cellulose. Due to its amorphous, highly branching, low molecular weight, and abundance of acetyl and hydroxyl groups, hemicellulose (Fig. 3B) is partially soluble in water and hygroscopic. Plant fibers that are bound to cellulose fibrils, most likely by hydrogen bonds, include hemicellulose. Derived from the Latin word "wood," lignin (Fig. 3C) is a highly complicated, three-dimensional, amorphous polymeric structure with a high molecular weight that contains phenylpropane units, the precise structure of which is still unknown. Lignin gives plants their stiffness, which is necessary for crops or trees to flourish.[6-10]

cellulose is one of the most prevalent natural polymers in the world. It has the potential to be a source of environmentally beneficial and biocompatible products because it is renewable, biodegradable, and non-toxic. It comes from a variety of sources, including bacteria, cotton, grass, blast fibers, wood, and tunicates, with wood being the main source of cellulose. One of the various sources of cellulose is pineapple leaf.[9, 11-18]

Figure 1: Green Chemistry Principles that Anastas and Warner (Anastas and Warner, 1998) proposed.[19]

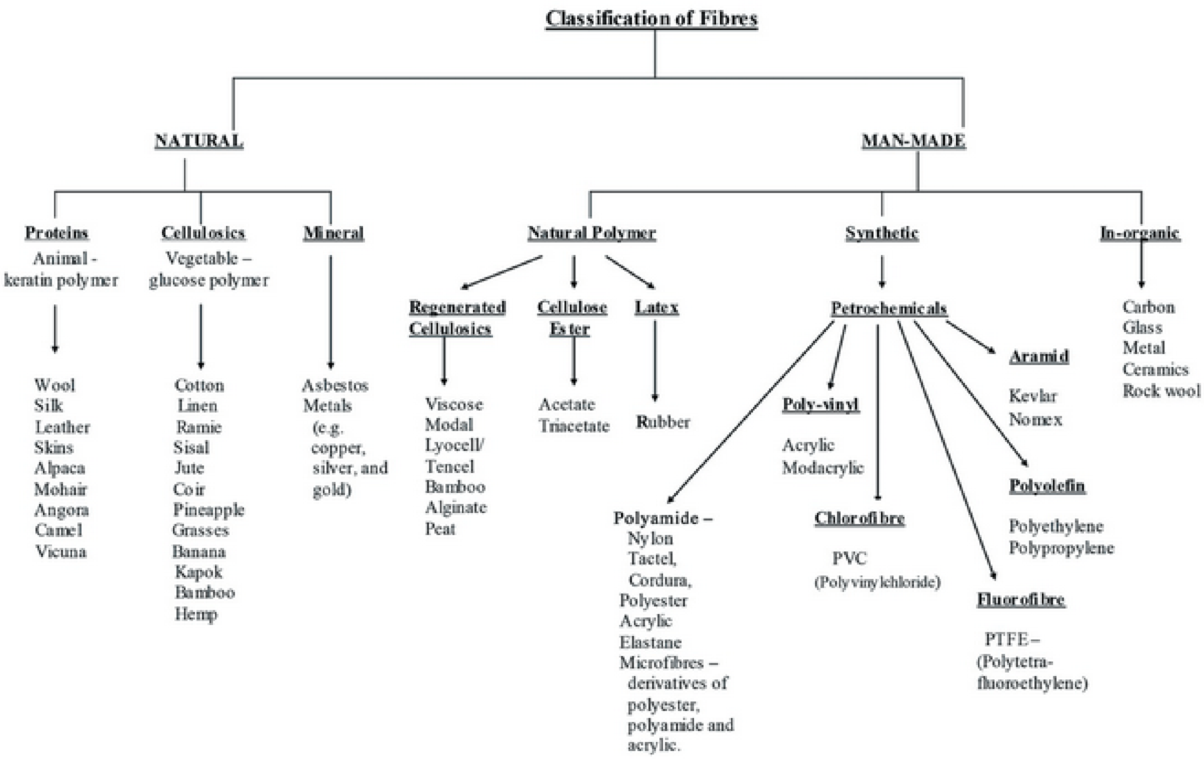


Figure 2: Classification of fibers

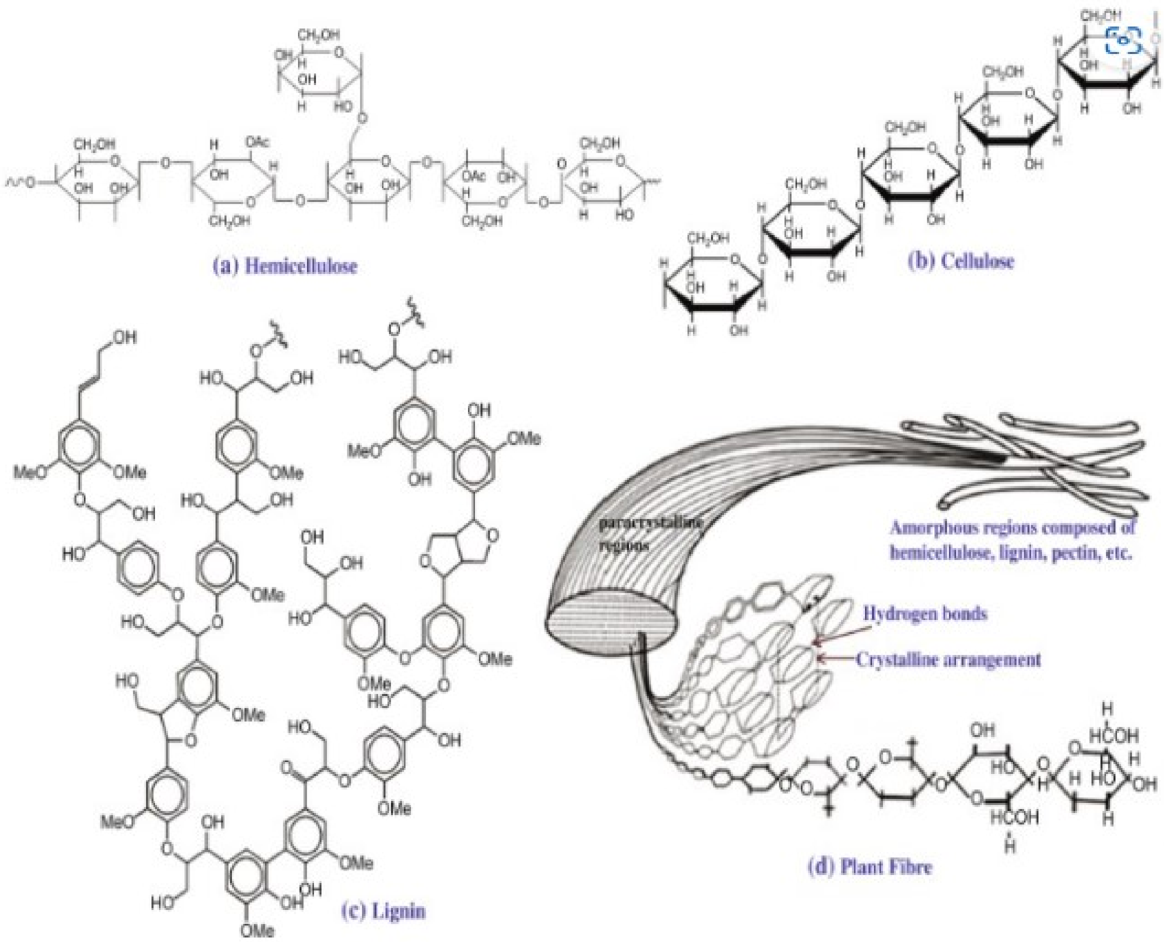


Figure 3: Visualization of structures of (A) hemicellulose, (B) cellulose, (C) lignin

Table 1 : Natural fibers' chemical structure[20]

Type of fibre	Cellulose	Lignin	Hemicellulose (%)	Pectin (%)	Ash (%)	Moisture content (%)	Waxes	Microfibrillar angle (deg)
Fibre flax	71	2.2	18.6–20.6	2.3	—	8–12	1.7	5–10
Seed flax	43–47	21–23	24–26	—	5	—	—	—
Kenaf	31–57	15–19	21.5–23	—	2–5	—	—	—
Jute	45–71.5	12–26	13.6–21	0.2	0.5–2	12.5–13.7	0.5	8.0
Hemp	57–77	3.7–13	14–22.4	0.9	0.8	6.2–12	0.8	2.62
Ramie	68.6–91	0.6–0.7	5–16.7	1.9	—	7.5–17	0.3	7.5
Kenaf	37–49	15–21	18–24	—	2–4	—	—	—
Jute	41–48	21–24	18–22	—	0.8	12.5–13.7	0.5	8
Abaca	56–63	7–9	15–17	—	3	5–10	—	—
Sisal	47–78	7–11	10–24	10	0.6–1	10–22	2	10–22
Henequen	77.6	13.1	4–8	—	—	—	—	—

Typically, synthetic fibers like aramid, carbon and glass are used to fabricate the composites along with synthetic polymer. However, there are two crucial issues, which are (i) relatively higher material cost and (ii) alarming issues with the environment, leading to the urge to find substitute materials, such as biocomposites.

The most important property of natural fibre is biodegradability and non-carcinogenic which bring it back into fashion, with the advantage of being cost-effective. Near about 30 million tonnes of natural fibres are produced every year and used as component of many manufacturing processes like clothing, packaging, paper making, automobiles, building materials, and sports equipment [21].

Natural fibres composites are eye-catching to industry because of its density and ecofriendly nature over traditional composites. The performance of natural fibre varies with part of the plant that is used for fibre extraction, age of plant, fibre extraction process, and many more factors. It can be extracted from the beast stem, leaf, and seeds from the plants in a bundle form; therefore it is also called fibre bundles; extraction method of fibres is similar in both bast stem and leaf, while seed fibres have many methods like cotton lint extracted from ginning process [22].

Pineapple Plant

The pineapple, a perennial herbaceous plant that grows to a height and breadth of 1-2 m in height and width, is a member of the Bromeliaceae family [23]. It is mostly grown in tropical and coastal areas, mostly for its fruits. It is grown on over 2250 000 acres of land in India and its production is steadily rising. A pineapple plant in the field is depicted in Figures 1(a) and 1(b); it has a short stem and is colored dark green. The initial leaf sprout appears beautiful; subsequently, it develops into a sword-shaped, three feet long and two to three inches wide leaf with many spirally arranged fibrous leaves that curve toward the cross section to keep the leaf firm [24].

The number of hexagonal pieces on the outer shell of each pineapple fruit is the same regardless of its size or shape. About 21.9 million tons of pineapples were produced in the world in 2011 pineapple plants consist of a rosette of 20–30 leaves that are generally 6 cm wide and up to 1 m long. About 96–100 tons of fresh leaves are generated per hectare[25]. Presently, Malaysia is among Asia's major producers, second only to Hawaii. Pineapple leaf fiber production is abundant for industrial use without the need for additional input, renewable annually, and easily accessible [26]. In Malaysia, pineapple is referred to as "Nanas." Basically, different types are used for different purposes; commercial purposes employ red and green pineapple, while edible purposes choose Sarawak and Morris pineapple. Pineapple fruits are packed with both main and minor components. [18, 27]

Table (2): Components that make up a pineapple plant.

C	O	N	Ca	P	Fe	k	Mg	Cu	O/C ratio	Reference
73.13	24.17	2.70	0.00	—	—	—	—	0.00	0.33%	[46]
—	—	6.4–10	2.5–10	0.1–0.18	0.06–0.11	2.89	0.33	0.002–0.02	—	[47]

The percentage of elements in pineapple fruit is displayed in **Table(2)**. Bioactive chemicals are found in it, especially in proteolytic enzymes. Bromelain is abundant in pineapples, and various parts of the fruit contain additional cysteine proteases [28]. Commercial applications for bromelain include the food, cosmetic, and nutritional supplement industries [29].

History

The pineapple is a native plant of America that was discovered by Christopher Columbus and his companion on a West Indies island on November 4, 1493. Pineapple was widely cultivated in tropical and coastal areas of South America upon the discovery of the new continent. When De Oviedo, a Spanish government official, arrived in America in 1513, he brought with him some written records of pineapple types as well as some from the Indies. The fruit of the plant, which resembles a pine cone, gave rise to the name "pineapple." The fruit was originally known by the Tupi term anana, which means "excellent fruit" and is the basis of various language phrases like "ananas." An ancient symbol of welcome, the pineapple can frequently be seen in stamped decorations. Because of its ostensibly exotic qualities and scarcity, Americans began importing pineapple from the Caribbean in the 17th century, and it soon became associated with the wealthy in America. The fruit was brought to all tropical regions and major portions of the world, including the east and south coasts of Africa, Madagascar, south India, China, Java, the Philippines, and Malaysia, thanks in large part to the Portuguese .There are many different kinds of pineapple plants accessible now that are employed for industrial, medical, and gastronomic purposes. One enzyme that is taken from its leaves and helps with respiratory conditions is called bromelain. Pineapple juice and sand combined make an effective boat deck cleaning. Pineapple waste that has been dehydrated is fed to pigs, chickens, cattle, and other animals as bran [30]

Pineapple leaf fiber

Tonnes of pineapple leaf fibers are generated annually, yet only a very small percentage are utilized for feedstock and energy generation **as shown in figure (4)**. The industrial use of biocomposites has increased, which has opened up opportunities to reduce the waste of renewable resources. It encourages the agricultural business to enter non-food-based markets [31]. It is a medium-length, highly tensile-strength fiber that is white in color, silky, and smooth. Compared to other natural fibers, it has a softer surface and can absorb and hold onto color well [32]. Nonetheless, because of its high cellulose content, PALF has a high specific strength and stiffness and is hydrophilic by nature [33].

It has been shown that the microfibrillar angle of 14 in pineapple leaf fibers (PALF) leads to a reduced elongation. Traditionally, the outer layers of pineapple leaves are scraped off in order to hand harvest the fibers. In the past ten years, approximately 35 kg of fibers may be processed by decorticating machines in an eight-hour shift[34]. The process of extracting fibers from pineapple leaf fiber involves both mechanical and retting methods. About 2 to 3% of fibers are generated by fresh leaves.

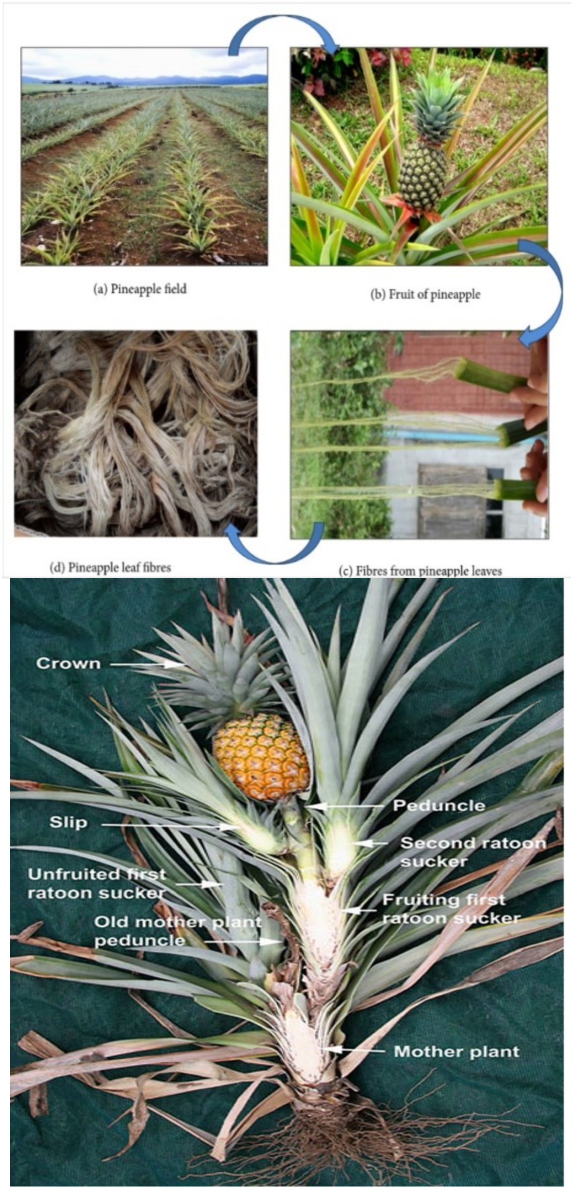


Figure (4): Production of pineapple leaf fiber involves the following steps: (a) pineapple plantation, (b) pineapple fruit, (c) pineapple leaf fiber extraction, and (d) Indonesian PALF.[35]

The fibrous cell of PALF is made up of groups of vascular bundles that are produced by mechanically removing the entire upper layer after harvesting. PALF is made up of numerous chemical components. Polysaccharides, lignin in significant amounts, and many mining chemicals such as fat, wax, pectin, uronic acid, anhydride, pentosan, color pigment, inorganic material, and so on are present in this multicellular lingo cellulosic fiber. A cluster of tiny, thin, multicellular fibers that resemble threads is called a fiber. Pectin helps to firmly bind these cells together [36]. The fiber organization in PALF is identical to that of cotton (82.7%) and comprises 70–82 percent cellulose [37].Pineapple leaf fiber has a good chemical composition and is the most suitable natural fiber resource in the collection. When used to make fine yarn, PALF has more mechanical strength than jute [29].The three-dimensional structure of the cellulose molecules model of PALF is parallel to the crystalline area of the fiber. The remaining molecular components are expected to associate in amorphous areas. Pineapple leaf fiber (PALF) is an essential natural fiber that is just as rigid, strong, and flexural and torsional as jute fibers. Industries can use PALF as an excellent substitute raw material in the possibility of reinforcing composite matrixes because of its unique features [38].

Ananas erectifolius

a plant similar to that of pineapple and commonly called as curaua, has been used to extract natural cellulose fibers . The plant is commonly found in the Amazon regions of Brazil and grows 1.5–1.7 m long and 4 cm wide leaves which are used to extract fibers. The density of the fibers was between 1.1 and 1.2 g/cm3, average diameter of the fibers was 60 μm, and moisture absorption varied from 9.2 to 12.1 %. The strength of the fibers varied from 2.7 to 6.9 g/den, modulus ranged from 115 to 308 g/den, and elongation varied from 3 to 5 %depending on the treatments used for the fibers. [18, 39, 40]

Application or Uses of Pina Fiber

Piña fibre, has a range of applications in the textile industry. It is white in colour, smooth, and glossy as silk, medium length fibre with high tensile strength. It has a softer surface than other natural f ibres and it absorbs and maintains a good colour. PALF has better mechanical strength than the jute when it is used in making of fine yarn .Here are some of the common applications of Piña fibre: **[31, 41]**

a) Clothing: Piña fibre is often used to create clothing, including dresses, shirts, skirts, and jackets. The lustrous and soft texture of the fibre makes it ideal for creating high-end fashion garments.

b) Accessories: Pineapple fibre is also used to create accessories such as bags, hats, and shoes. The durability of the fibre makes it a great choice for accessories that need to withstand daily wear and tear.

c) Home textiles: PALF is also used in the production of home textiles such as curtains, tablecloths, and upholstery fabrics. The shiny and lustrous appearance of the fibre makes it a popular choice for creating elegant and stylish home decor items.

d) Paper: Piña fibre is also used in the production of high-quality paper, which is commonly used in the printing of banknotes, certificates, and other important documents.

e) Industrial applications: Pineapple leaf fibre can also be used in industrial applications, such as reinforcement in composites or as a reinforcing agent in rubber products.

f) Automotive industry: It can be used in the automotive industry to create lightweight and durable parts for cars and trucks. The fibre can be combined with a resin matrix to create composite materials that are strong and lightweight.

g) Construction industry: Pineapple fibre can also be used in the construction industry to create composite materials for building structures. The fibre can be combined with a polymer matrix to create composite panels that are strong, lightweight, and durable.

h) Aerospace industry: PALF can be used in the aerospace industry to create lightweight and strong parts for aircraft and spacecraft. The fibre can be combined with a resin matrix to create composite materials that are strong and lightweight, which can help to reduce the weight of the aircraft or spacecraft.

Pineapple Leaf Fibre Extraction (PALF)

Despite having exceptional mechanical strength, pineapple natural fibers are still not being used to their full potential owing to ignorance. It can be applied to many different things, such as artificial fibers, thermal insulation, sound absorption, and more. The PALF can be extracted from pineapple leaves, stem , root **as shown in figure(5)** using a variety of techniques , the fiber-extraction methods have a major impact on yield and quality of fiber and it influences the structure, chemical composition and physical properties of fibers[30].

Figure (5): Fibers from (a) leaves, (b)stems, (c)roots[42]

Scrapping Method of Extraction:

The machine used to scrape the fiber from pineapple leaves is called a scraping machine [43]. Combining three rollers, the machine is made up of a) feed roller, b) leaf scratching roller, and c) serrated roller [44].The first roller in the machine is called the feed roller, and after that, the leaves pass through the second roller, which is known as the scratching roller. It removes the waxy layer off the leaf and scratches the upper layer. Finally, leaves reach the densely connected, serrated roller blade, which crushes the leaves and creates several openings for the retting bacteria to enter, During the last decade, decorticating machines have been developed that can process about 35 kg of fibers per 8 h shift[29].

The pineapple leaves were soaked in a water filled container for 72 hours. A rubber mallet was used to crush the waxy layer on the pineapple leaves. Then, a scraping tool was used to completely scratch the waxy layer, leaving the fibers exposed beneath the pineapple leaf. On completion of removal of the fiber from the leaves, a gentle combing process was performed to separate the fibers obtained into single fibers and to remove excessive substances. The fibers were dried in the hot air oven at 70C for 30min.

There are four manual methods of scrapping extractions methods are **described in table (3)** and the efficiency and the percentage of fiber of these different extraction methods **are explained in table (4).**

table (3): Method of Extraction[42]

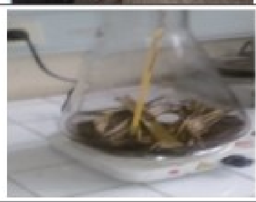
Extractions Processes	Description	
(1) Extraction by water retting (soaking in water) **Parameters** Ambient Temperature Distilled water	The plant sample is soaked in distilled water to promote the growth of microorganisms. These microorganisms feed on pectic matter which is responsible for the cohesion of the fibres in the plant.	
(2) Extraction by scraping + Washing with water **Parameters** Ambient Temperature	The sample is scraped with a serrated knife to mechanically extract the epidermis of the plant. The whole is then washed with luke warm water.	
(3) Extraction by beaten + retting in water **Parameters** Ambient Temperature	The sample is beaten with a wooden stick to cause partial de-cohesion of the fibres and to facilitate water penetration during the next stage of water retting.	
(4) Extraction sodium hydroxide (NaOH) **Parameters** 5% NaOH Distil water	The leaves are dried into the oven for 80 ℃ and then mixed with distill water and 5% NaOH.	

Table (4) :Percentage of fiber from different extracted method [42]

Extraction Process	Soaking solution	Duration	Temperature	% of fiber yield
Extraction by water retting (soaking in water)	Distill water	4 weeks in distill water	Ambient temperature	60 to 70%
Extraction by scraping + Washing with water	Distill water	Half hour	Ambient temperature	50 to 60%
Extraction by beaten + retting in water	Distill water	7 days	Ambient temperature	30 to 50%
Extraction with sodium hydroxide (NaOH)	Distill water + caustic soda	2 hours	100	20 to 50%

Retting the Leaves of Pineapples

Little bundles of scraped pineapple leaves are retted by submerging them in a water tank filled with urea (0.5%), diammonium phosphate (DAP) for quick retting reactions, or substrate: alcohol in a 1:20 ratio. Materials in the water tank are routinely examined with the finger to make sure the fibers have been released and are capable of extracting a wide range of chemical components, including pectin, lignin, fat, and wax, ash content, nitrogenous matter, and pentosans. Fibers are mechanically separated after the retting process by being washed in pond water. The extracted fibers are air dried in a hanging location. To extract PALF from freshly chopped pineapple leaf, a ball mill or disc mill can be utilized [45]. In addition to being straightforward, the procedures yield smaller fiber and a higher fiber yield than the traditional approaches. Wet ball milling is the slower of the two mechanical grinding techniques examined, but yields more elementary fiber for PALF [46].

Pineapple leaves were chopped to a length of 25 cm, immersed in 10% NaOH at 30°C for two hours, and then rinsed in water to extract finer fibers. Moreover, fibers were bleached for 90 minutes at 85–90 degrees Celsius with 0.4% sodium hypochlorite at pH 4. Furthermore, acetylation and acrylonitrile grafting were carried out. Tensile tests were conducted on fibers that had diameters ranging from 30 to 40 µm [47].

PALF Diameter

While the average diameter of PALF extracted using the conventional method was 90.7 µm, the average diameter of both treated and untreated PALF using extraction machine was 75.7 µm, the average diameter of PALF extracted from stems and roots **as shown in in table (5)** . More thin and fine fibers were produced by extraction machine[48].

Table (5) : Diameter of PALF extracted from stems and roots [42]

Fibers	Average length	Average diameter
Leaves	500 mm	40.3 µm
Stems	250 mm	42.3 µm
Roots	80 mm	51 µm

The composition of chemicals

According to criteria published by the Technical Association of Pulp and Paper Industry (TAPPI) [49]. the chemical composition and extractive materials, such as holocellulose, α-cellulose, lignin, and ash content of PALF, were examined from various fiber sources, ages, and climates. The process used to separate the fibers may have an impact on the cell wall's structure and chemical content [50].The PALF cell wall can be seen to have discrete primary (P), secondary, and tertiary layers when examined under transmission electron microscopy. Numerous chemical components, including α-cellulose, pentosans, lignin, fat and wax, pectin, nitrogenous matter, ash content, degree of polymerization, α-cellulose crystallinity, and antioxidants, are present in pineapple leaf fibers [34].

The fibers derived from pineapple leaves contain comparatively larger percentages of lignin (10.4%), ash (4.7%), and cellulose (74%) , this percentage varies depending on the source of the fibers **as shown in table (6)** . Compared to other natural fibers such as oil palm frond, coir, and banana stem fibers, PALF has a higher cellulose content . The fruit's greater weight is supported by PALF's increased cellulose content . The performance of fibers is directly impacted by their chemical makeup [51].

The PALF also contains hemicellulose that functions as filler between lignin and cellulose that consists of sugars including glucose, mannose, xylose, arabinose and galactose. Despite acts as a filler, hemicellulose does not give significant contribution on the strength and stiffness of fibres or individual cells but only bound to the fibre through some ester bonding between lignin and cellulose . Lignin acts as a binder agent between the fibrils and individual fibre cells forming the cell wall of highly cross-linked molecular complex with amorphous structure. Lignin is a very important chemical composition of a plant since it provides protection against biological attacks, acts as water-holding capacity and strengthens the stem against gravity forces and wind. The arrangement of molecules in PALF is similar to cotton cellulosic fibres due to its high cellulose content [52]

Table (6) :PALF's chemical composition [30, 42].

Fibers	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Pectin (%)	Ash (%)
Pineapple leaf	72.14	4.86	13.55	1.6	1
Pineapple stem	53.09	20.91	15.16	3	0.95
Pineapple root	57.04	17.96	13.22	2.2	0.86

Mechanical and Physical Characteristics

Natural fibers that have been reinforced Bio composite and material science both heavily rely on composite. Because PALF is affordable and sustainable, it has been shown to be a good alternative to synthetic fibers. Without the need for extra processing, the unique strength of natural fibers helps to increase the polymer matrix's mechanical and physical strength. The low microfibrillar angle (14°) and high alpha-cellulose content of PALF are associated with its outstanding mechanical qualities. PALF has unique properties that make it suitable for application as a composite matrix reinforcement [38]. Any natural fiber's physicomechanical characteristics are determined by factors such as aspect ratio, orientation, fiber matrix adhesion, volume fraction of the fiber, and stress transmission efficiency at the interface [53]. Comparing PALF based polymer composites to other cellulose-based composite materials, the results demonstrate superior stiffness and strength [54].

FTIR Spectra

Functional groups found in natural fibers, including hydroxyl, vinyl, and carbonyl groups, ketone, and many more, can be observed using FTIR spectroscopy. It is useful in determining how the chemical composition of natural fibers varies both before and after chemical treatments Together with PALF, **as shown in table (7)** displays the typical FTIR spectra of several untreated natural fibers, including hemp, sisal, jute, kapok, kenaf, and oil palm fiber. Everybody shares the O-H group's feature, which is evident between 3338 and 3450 cm−1. The untreated fibers exhibit similar peaks at 2924.2 and 1741.1 cm−1, respectively, corresponding to C–H and C–O stretching [55].

Displays the FTIR spectra of holocellulose and -cellulose samples that are free of PALF extractive. For the -cellulose sample, the O-H groups are represented by the peak 3343 cm−1. The frequency of hydroxyl stretching was observed at 3,296 cm−1 in holocellulose samples and 3327 cm−1 in free-extractive samples. Another high frequency for the cellulose sample, located at 1725.25 cm−1, indicates the C–O bending frequency. Conversely, the peak frequencies of 1728 and 1733 cm−1 for holocellulose and free extractive, respectively, correspond to the carbonyl peak frequencies. The absorption of carbonyl stretching of ester and carboxyl groups, which is most prevalent in hemicelluloses from pineapple leaves, is responsible for the sharp band seen at 1733 cm−1[56].

PALF Treatments

PALF Interventions Three different types of treatments are used:

- heat treatment (boiling water at 100°C).
- alkaline treatment ($Na2CO3$).
- combination of alkaline and heat treatment.

After being submerged in 3% Na2CO3 for an hour, untreated PALF was labeled as alkali-treated PALF after being repeatedly cleaned with distilled water to remove any residual alkali. The PALF underwent an hour-long boil at 100°C as part of the heat treatment. The label on this sample reads "PALF, heat treated." After that, the sun is used to dry all of the treated PALF. Finally, if the PALF is receiving a combined treatment, it is first brought to a boil at 100°C, sun-dried, and then submerged in 3% Na2CO3 for an hour before being dried again.The label for this sample reads "coupled treated PALF."1

PALF's Obstacles as Reinforcement

Because PALF is hygroscopic, it has a reduced degree of compatibility with hydrophobic polymers. Low surface tension caused by a naturally occurring waxy material on the fiber layer's surface prevents a strong connection with the polymer matrix. Nonetheless, a number of techniques are offered in the literature to enhance the fiber surface in order to prepare it for effective interfacial fiber/matrix bonding. The physical degradation of the final product can be caused by humidity and water absorption in natural fiber-reinforced polymers. When producing composites, high moisture content in the fiber can result in swelling or dimensional defects that impact the final product's mechanical and physical properties. The stiffness of polymer chain segments acts as an impediment to the water molecule at low temperatures. A number of variables, including molecular structure, polarity, crystallinity, and the hardeners employed in composite construction, affect how moisture diffuses into polymers [57].

Table (7): Peaks in infrared transmittance (cm−1) of natural fibers without treatment

Bond/stretching	PALF (cm^{-1})	Hemp (cm^{-1})	Sisal (cm^{-1})	Jute (cm^{-1})	Kapok (cm^{-1})	Kenaf (cm^{-1})	Oil palm fibre (cm^{-1})
–OH	3349.9	3448	3447.2	3447.9	3419.7	3338	3450
C–H	2903.8	2920.5	2924.2	2918.8	2918.1	2899	2850
C=O	1737.4	—	1736.5	1737.2	1741.1	1736	1735
C=C	1608.3	1654	1653.9	1653.8	1596.1	—	1606
C–H	1374.2	1384.1	1384.1	1384.1	1383.6	—	—
C–H	—	—	1259.9	1255.6	1245.5	—	—

Effect of different treatments

Tensile tests were conducted on fibers that had diameters ranging from 30 to 40 µm. The features of the PALF both before and after different changes are displayed in **Table (8)**.

The tensile qualities of the fibers were drastically lost when they were treated with acetic acid; however, the tensile strength and elongation were increased through grafting. Fibers underwent morphological smoothing following the chemical and physical alterations. The crystallinity of the unmodified fibers was approximately 66%; however, grafting with acrylonitrile caused the crystallinity to drop to 41%.

Table (8): Tensile characteristics of fibers from chemically altered pineapple leaves[47]

	Tensile properties		
Type of chemical treatment	Strength [g/den]	Elongation [%]	Modulus [g/den]
Acetylated fibers	1.1	16.7	23.1
Scoured fibers	1.3	15.6	36.2
AN-grafted	1.6	12.8	53.1
20 % Acetic acid	0.3	7.6	22.3
10 % NaOH	1.2	13.4	31.5
Bleached fibers	1.3	14.5	35.4
Raw fibers	1.4	11.6	51.5

In order to remove fibers from the pineapple crown for possible usage as reinforcement for polypropylene, 1% alkali solution was applied [58].The percentages of crystallinity in the treated and untreated fibers were 42% and 38%, respectively .The fundamental cause of the more than three-fold variation in the fibers' strength and modulus is their varied cross-sectional areas. Larger cross sectional areas in fibers are typically associated with decreased modulus and strength because of the increased likelihood of faulty sections. Furthermore, the tensile qualities would have been influenced by the fiber composition, therefore comparing fibers with various compositions and unit areas might not be acceptable. A related investigation discovered that different degrees of alkali treatment caused the fibers' fineness to fluctuate between 20 and 15 denier, and tenacity ranged from 2.2 to 4.7 g/den.

Table (9) :Differences in the tensile and diameter characteristics of pineapple leaf fibers generated through different physical and chemical processes[59].

Treatment	Diameter [µm]	Tensile strength [g/den]	Elongation [%]	Modulus [g/den]
Non-treated	241.9	1.5	7.8	27
Water soaked	235.3	1.5	8.4	22
Abrasive separated	121.7	2.3	6.6	40
Fine strands	72.7	3.9	8.7	63
Bleach 1 % (2 h)	246.9	1.7	9.1	22
Bleach 1 % (4 h)	157.4	1.8	6.3	39
Bleach 1 % (6 h)	171.2	1.8	5.7	47
Bleach 2 % (4 h)	177	1.7	4.1	60

After mechanical and chemical treatments, the diameter variations of the fibers were linked to the tensile qualities of the pineapple leaves. The strength of the finer fibers (72.7 µm) achieved through mechanical abrasion using grade 100 abrasive paper was 25% more than that of the non-treated fibers, **as shown in Table (9).** Likewise, bleaching using a hypochlorite solution resulted in smaller fiber diameters but also worse tensile characteristics. It was previously believed that the main cause of the increase in tensile strength following different treatments was an increase in fiber crystallinity [60].

Spinning System PALF

As of this moment, no unique system has been assigned to the PALF spinning system. In response to this worry, PALF is twisted into rope as opposed to yarns. PALF are the most often used fibers among those derived from different lignocellulosic agricultural by-products to create yarns, fabrics, and other textile products. Nonetheless, PALF can still be blended in binary or multiple ways utilizing the current fiber spinning technology to create yarns. Different spinning processes in India have been used to evaluate different blends of PALF mixed with other fibers [61].

Several spinning systems are utilized, including as the flax, cotton, semi-worsted, and jute systems, which need the application of specific processes. However, 100% PALF has been utilized in cotton manufacturing systems with a few machine adjustments, yielding PALF yarns with a good tenacity of 14.0 g/tex. While bleaching produced yarns with a 5% increase in fineness, the tensile strength of the resulting yarns decreased. After being combined with cotton, jute, and wool, PALF with a staple length of 20 cm, fineness of 1.5 tex, and tenacity of 26 g/tex was spun using different methods[62].

System of Jute Spinning

Jute and PALF fibers blended together produce high-quality fiber that is best used as a decorative element [61]. In terms of linear density, binary blending of PALF with jute yields incredibly fine yarn that appears unachievable when using Indian jute alone.

Semi-worsted Spinning System:

A semi-worsted spinning technology was used to spin yarns containing PALF and wool in varying blend proportions. Yarns made from a PALF: Wool blend proportion of 25:75 was perfect for making carpet face and home furnishings materials.

System of Flax Spinning

Compared to jute spinning system (dry), there is an improvement in weight irregularity that leads to better yarn diameter regularity of PALF spun using flax spinning system (wet). The comparison of PALF yarn spun using the flax and jute systems was **shown in table (10).**

Table (10) : Jute and flax spinning system of PALF [48]

Properties	PALF yarn	
	Jute System	Flax System
Linear density (tex)	85.10	82.14
Uster fineness (U%)	29.50	27.50
Average diameter (cm)	0.333	0.311
Breaking stress (gm/tex)	17.33	19.81
Breaking strain (%)	8.80	8.20
Packing coefficient	0.65	0.72

Cotton Spinning system :

Following chemical treatment, PALF's ability to be spun on a cotton spinning machine was enhanced. There are two ways to spin PALF using a cotton spinning machine: either 100% PALF with some system changes made to the machine, or binary blending, which blends PALF with cotton in varying proportions. Carding, drawing (draw frame), and spinning (spinning frame) are the three primary stages of PALF spinning on cotton machines [63].

Jantra

However, there is machinery in Indonesia that is used to spin short fiber, such as PALF, into skeins. Originally designed to spin silk, this machine was used to create yarn from silk waste and short fibers, which was then used on PALF [64]. This device, known as Jantra, **as shown in Figure (6).**

Yarns can spin out of PALF. The resulting PALF yarns are still coarse and do not have the same qualities as cotton yarns. Certain things need to be taken into account before spinning PALF. The PALF degumming procedure is one of them, Pectin, pentosan, and lignin, which make up roughly 30% of PALF, give it its steep texture [48]. Furthermore, PALF becomes brittle and coarser due to the residual resin. By employing acid, alkali, or axines in the degumming process, the coarse PALF can be made softer.

Subsequently, PALF must pass through the fiber cut and opener system to cut the fiber to the appropriate length. Only extremely soft and fine fiber will be chosen at the end. After that, the chosen fiber can be spun using a modified cotton spinning technique. Carding, drawing, and ring spinning are steps in the spinning process. In addition, more research is required to determine how fiber characteristics and linear density affect the hairiness of PALF yarn in the spinning system. Yarn hairiness is influenced by a number of factors.

Figure (6): Junta[48]

For a thorough assessment of yarn hairiness, the following hairiness characteristics should be considered:

(a) Total number of hairs per unit yarn length.

(b) Total length of hairs per unit.

(c) Length and number of hairs longer than or equal to 3mm per unit length. Prior to conducting a thorough assessment of yarn hairiness, it is necessary to examine several fiber qualities.

These include trash count, fiber length, micronaire, strength, elongation, short fiber index, and uniformity ratio.

A fiber contamination tester (FCT), advanced fiber information system (AFIS), or high volume instruments (HVI) equipment can be used to test each of these parameters.[62]

The enormous number of pineapple plantations in Malaysia, more than 147,000 hectares of land are utilized for pineapple plantations, which create 65 tons of residue per hectare. an alternative to reduce waste, fibers from pineapple leaves were extracted and dyed to improve the aesthetic value and market ability of pineapple leaf fiber by adding dyeing substrates using a low energy consumption dyeing approach. The plant is called “pineapple” because of its fruit which look like pine cone. The native Tupi word for the fruit was anana, meaning “excellent fruit;” this is the source for words like ananas, commonin many languages. [65].

Effect of acid treatment

- The effect of citric acid treatment on the quality of fresh-cut pineapple was evaluated during storage at 10 and 2°C. The fresh-cut pineapple was mechanically sliced into small portions (5 cm) and immersed in solutions containing 0 (control), 1.0, 1.5 and 2.0% citric acid. Samples stored at 10°C were evaluated every 2 days whereas those samples stored at 2°C were evaluated every 4 days. No significant difference was observed in the change in colour of the fresh-cut pineapple stored at 10°C for 6 days and at 2°C for 14 days. Loss in fresh weight was somewhat more rapid at 10 than at 2°C and increased over time in all treatments stored at the two temperatures. Variation in firmness was small throughout the storage period at both temperatures and there was no consistent change over time. Microbial growth over time did not change for samples stored at 2°C, but increased steadily in those stored at 10°C. Fresh-cut pineapple treated with 1.5% citric acid was more accepted by the panelists, possibly due to the combined effect of the pH and TSS value as indicated in the taste preference[66].
- PALF that has been pretreated Prior to chemical treatment, processed PALF were cut to a length of 3–4 mm and treated with 4 weight percent of mild sulfuric acid (H2SO4) at 80°C for two hours. After washing it with water to get rid of the acid, it was dried for fifteen hours in an oven. 2.2 Hydrolysis of Acid PALF treatment The PALF was then given another treatment utilizing sodium hydroxide (NaOH) at 80°C for two hours, followed by a further 15 hours of oven drying and washing [67]. After 45 minutes of immersion in 64wt% H2SO4 at 45°C, the hydrolysis process of the pretreated PALF was stopped by diluting it ten times with water. To separate the acid from the treated fiber, the mixture was centrifuged for ten minutes at 7000 rpm. After being cleaned with water to a pH of neutral, it was dried for 15 hours at 60°C in an oven [68]. PALF treated with acid hydrolysis and PALF pretreated. The pale brown color of the pretreated PALF indicates that moderate acid and mild alkali treatments have altered the fiber's surface structure. White PALF after acid hydrolysis treatment indicate that they are cellulosic. Following the pretreatment procedure, the fiber's remaining hemicellulose and lignin were further removed by acid hydrolysis treatment.

Effect of alkaline treatment: [69]

- In NaOH, the PALF fibers were submerged at different treatment concentrations of 4%, 6%, and 8% (w/v), The PALF fibers were chopped to a length of approximately 400 mm, submerged in the NaOH solution, and then rinsed with distilled water. Alkalinity was measured by submerging pH paper in the solution. Washing the fibers continued until pH 7 was reached. Oven drying was the final stage of the alkaline treatment at 60°C.
- The fiber diameter generally varies over the spectrum of various NaOH concentrations and treatment periods. The mean diameter of untreated PALF fiber is 0.070 ± 0.024 mm, The alkaline treatment enhanced the single strand fiber's diameter. This is because, in contrast to untreated fiber, the treatment caused the fibers to cluster together and made it more difficult to separate them into a single fiber strand.
- Treatment concentrations higher than 6% NaOH resulted in a decrease in fiber diameter. The study found that a 6% NaOH concentration and a 3-hour immersion period is the ideal alkaline treatment for PALF, producing a tensile strength of 164.55 MPa. On the other hand, the best NaOH concentration for interfacial shear strength is 6% with a 1-hour soaking time, which results in an IFSS of 42.67 MPa. The

mechanical characteristics of PALF decline by 18%, to 134.75 MPa, when the concentration rises to 8%. This can be the result of excessive delignification on the fiber surface, which accelerated the degrading process.

- While the TGA data demonstrate that the alkali treatment improves the thermal stability of the fiber by an increase of 14.32 °C for the burning temperature, the SEM micrographs demonstrate that the treatment increases the surface roughness of the fiber.

Composite Based on PALF

Researchers and industry are concentrating on studying natural fibers as a potential replacement for glass fibers. The use of natural fibers in the upcoming decades is being accelerated by the quickening pace of environmental study. In order to create composites with increased mechanical strength, PALF has recently been used in polymer matrix technology successfully [70]**.**The final output of each PALF reflects its exceptional mechanical qualities. The use of thermoset , thermoplastic , biodegradable polymers , and natural rubber to reinforce PALF has been the subject of numerous studies[71] .

PALF Reinforced Composite with Epoxy Basis:

Excellent qualities of epoxy resin include strength, adhesion, minimal shrinkage, resistance to corrosion, and many more. It is a pricey resin, but its chemical and mechanical qualities are excellent. Research has been done on natural fibers with epoxy reinforcement, such as jute, flax, sisal, and bamboo fibers . There hasn't been any work done on PALF yet. Adhesion with numerous polymer matrices is a significant issue for PALF. Due to its hydrophilic nature, PALF does not mix well with hydrophobic polymers. The low surface tension caused by the waxy component on the surface of PALF significantly impacts the bonding with the polymer matrix. The PALF surface is altered to enhance bonding in order to resolve this problem. Reagents used in the surface modification procedure cause fibers to become hydrophobic, and suitable polymers and resin matrix are grafted onto the fiber's surface. Several studies have been conducted to enhance the adherence of PALFs to the matrix, including cyanoethylation, alkalization, dewaxing, and acrylonitrile monomer grafting [72].These techniques have shown to be a very successful modification to improve PALFs' polymer matrix adhesion properties. Alkali-treated benzoylated PALF is utilized to improve its tensile and adhesive characteristics. The fibers' surface becomes rough due to the alkalization process, which also improves mechanical grip. A rough surface increases the epoxy matrix's affinity and strengthens the interfacial adhesion created by DGEBA resin depositing on the fiber surface. Furthermore, when alkalization and DGEBA solution are combined, PALF-epoxy composites would show good results in interfacial bonding. The flexural, tensile, and impact properties of epoxy composite will be improved by these types of surface modification [70].

PALF-Based Polyethylene-Reinforced Composites

High performance composites are demonstrated by a polyethylene-reinforced pineapple leaf fiber. Pineapple leaf fiber (PALF) has superior mechanical and physical qualities when compared to other natural fibers; however its hydrophilic nature has drawbacks. To increase the water resistance, a chemical treatment using alkali, isocyanate, saline, and permanganate was used. Reducing the hygroscopicity of fibers is made possible by peroxide modification [73].

PALF-Based Polypropylene Reinforced Composites:

Pineapple leaf fibers (PALF) are rejected as an affordable and abundant alternative to the expensive, nonrenewable synthetic fibers. PALF's high specific strength improves the polymer matrix's mechanical characteristics. PALF is lignocellulosic, multicellular, and possesses excellent mechanical qualities. Stress is inversely related to fiber content in the investigation of the stress behavior of PALF reinforced polyethylene composite. The mechanical characteristics of composites reinforced with polypropylene and pineapple leaf fibers are presented. The volume fraction of composites affects their tensile and flexural properties. Excellently useful composites with superior strength were demonstrated in the recent investigation. In place of pure resin, PALF is employed as a reinforcing agent in a polyropylene matrix to enhance the mechanical qualities. The volume fraction is directly correlated with both flexural modulus and flexural stress. However, because of issues with dispersion and fiber-to-fibre repulsion, value is negligible. The primary goals of research are to enhance the interfacial relationship and mechanical characteristics of PALF-PP composites[53].

PALF Composite Based on Polycarbonate

Insects and pests can cause deterioration of PALF and matrix due to inadequate interaction, which can lead to moisture intake . Therefore, altering the fiber's surface is a crucial and required step in lowering the fiber's polarity. Numerous techniques exist, including saline coupling agents such c-aminopropyl trimethoxy silane (Z-6011) and c methacrylate propyl trimethoxy saline (Z-6030) , grafting with maleic anhydride copolymer , and alkaline treatment . Thermoplastic resin that is amorphous is called polycarbonate (PC). It offers many essential and significant qualities, including strong impact strength, dimensional stability, high heat and flame resistance, and clarity. Despite this, there are some restrictions on how the PALF can be used. It softens and becomes easier to remove from mold at low temperatures [74].

PALF Reinforced Polyester Based

The leaves of the pineapple plant are used to make PALF. The main constituents of PALF are lignin (5–12%), ash (1.1), and cellulose (70–80%). According to a recent study, polyester matrices can be reinforced with various surface-modified pineapple leaf fibers. Flexural, tensile, and impact strengths increased significantly when PALF fiber loading was up to 30% by weight with polyester. The composite material's toughness meets or exceeds that of engineering materials. Chemical surface modification can improve the mechanical strength of PALF/polyester composites intended for commercial use, as well as the strength of individual fibers [75].

Dyeing of PALF

Dyeing with synthetic dyes

Both the traditional EX(Conventional exhaustion dyeing technique) dyeing method and the IR (Infrared dyeing) dyeing method were used to complete the dyeing process. Reactive dye was then utilized to dye the fiber from the pineapple leaf. Reactive dyeing is usually used for the coloration of cellulose fiber because it reacts with fiber molecules to form a chemical com pound that permanently attaches to the fiber. The pineapple leaf, which acts as cellulose-based fiber material, was dyed by using reactive dyes for applicability enhancement. **Figure (7)** displays the dyeing profile for this investigation.

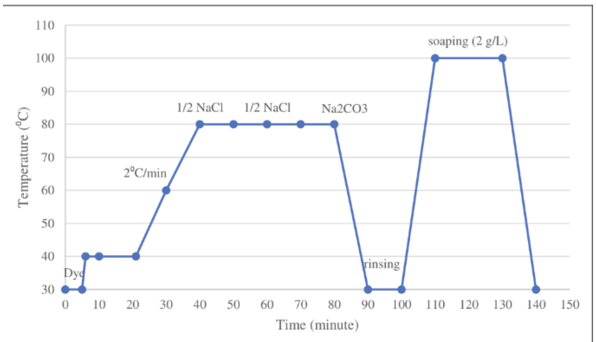


Figure (7): Dying curve of pineapple fiber

Infrared dyeing

For the dyeing procedure, four specimens weighing roughly five grams each of pineapple leaf fibers were chosen. The liquor ratio for dyeing process is 1:20. Three main colors were added to the roughly 5g of oven-dried pineapple leaf fibers in four different quantities (0.25%, 1%, 2%, and 4%). Soda ash at 20g/L and sodium chloride at 60g/L were used to dye reactive red 11, reactive blue 5, and reactive yellow 86 dye types. For 60 minutes, the dyeing temperature was maintained at 70C. The pineapple leaf fiber dyeing method was carried out using a lab IR dyeing machine. After the pineapple leaf fiber was dyed using the IR dyeing method, the samples were washed under running tap water and then heated to 100C for 20 minutes while soaping with 5g/L of regular soap. The samples were then oven dried and evaluated for color characteristics.

Dyeing with natural dyes

Use the natural coral jasmine dye on pineapple fabric and Acacia nilotica (babul bark) as a bio-mordant. The dyed fabric was assessed using standard techniques for its durability against many launderings, anti-microbial activity, antioxidant qualities, and ultraviolet protection. It was also evaluated for wash, dry, and wet rubbing fastness.

The colorimetric examination, K/S Vs. wavelength spectra of dyed samples, FTIR study, and UV–Visible spectroscopic investigation of mordant and dye extracts have all been used to analyze the fastness, color strength, and functional aspects of dyed pineapple fabric.

The color yield (K/S) increased when babul bark and coral jasmine concentrations rose, according to the data. The wash and rubbing fastness qualities were obtained to be good to exceptional. The fabric sample that had the greatest dye and mordant concentration—5% owf babul bark and 20% owf coral jasmine—showed outstanding UV protection, antibacterial activity up to 98.23%, and antioxidant activity up to 99.37%. Even after 20 LCs, no appreciable reduction in functionality is seen. And thus, research was done on pineapple's unique and sustainable functional coloring.[76]

Conventional exhaustion dyeing technique:

A 1:20 dyeing liquor ratio was employed. Reactive dye red 11, reactive dye blue 5, and reactive dye yellow 86 were applied in four different doses (0.25%, 1.0%, 2.0%, and 4.0%) to roughly 5g of pineapple leaf fibers. Specifically, EX dyeing at a temperature of 70C for 60 minutes was studied in a manner akin to IR dyeing. The fiber samples were submerged in a dye solution comprising sodium carbonate (20g/L) and sodium chloride (60g/L), which served as dyeing auxiliaries for the duration of the operation, prior to dyeing. The dying procedure was carried out using an EX dyeing machine. After the EX dyeing process was finished, the samples were hot-soaped for 20 minutes at 100C using 5g/L normal soap and then rinsed under running tap water. Following soaping, the samples will be oven-dried for 30 minutes at 60 degrees Celsius, and their color strength will be evaluated.

Comparing the IR dyeing method to the traditional EX dyeing, it was found that the former produces a little more dazzling and strong color result. The dye concentration rose, resulting in the development of darker color tones. Furthermore, deeper and richer hues were obtained through the application of infrared dyeing. Because of the high rate at which the dye fixes to the textile substrate, IR dyeing processes yield better results[77].

Conclusion

In tropical areas, pineapple leaf fiber is quite prevalent and easy to separate from the leaves. The use of pineapple leaf fiber in composite materials offers a new, sustainable, and recyclable source of resources. The primary problem with PALF, however, is that it is hydroscopic, which presents a significant obstacle to the use of fiber as a reinforcing material in polymer composites. In order to achieve good interfacial adhesion of PALF with polymers in the manufacturing of polymer composites, surface modification of PALF is necessary. When creating composite goods for various uses, PALF can completely or partially replace synthetic fibers. One of the natural fibers with the highest cellulose content, around 80%, is pineapple. PALF has a density that is comparable to other natural fibers, a very high Young's modulus, and the highest tensile strength of all the related natural fibers. These qualities make it appropriate for use as furniture, automobile parts, and building and construction materials.

It makes financial and ecological sense to boost research and development efforts to improve PALF productions and utilization as pineapple plantations and their industrial significance grow. To improve the PALF's qualities, particularly its wet strength, developmental effort must be done to mechanize the extraction and treatment of the PALF. Recent advancements in PALF technology indicate that it has the potential to become a significant substitute for natural fibers. However, industry concerns have been raised over the availability of sufficient supplies. One way to enhance the current procedure is to assess the machinery in order to advance technology.

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Conflict of Interest

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القوة التحويلية للكيمياء الخضراء: تعزيز الاستدامة واستخدام الألياف الطبيعية

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المستخلص

في هذه الأيام، إحدى أكثر المواضيع التي تتم دراستها هي الكيمياء الخضراء. الهدف من الدراسة المكثفة حول الكيمياء الخضراء هو تعظيم المنتج المقصود بطريقة مستدامة بيئيًا مع تقليل أو القضاء على تكوين المنتجات الخطرة. الكيمياء الخضراء ضرورية للحد من الآثار البيئية السلبية للمواد البشرية والعمليات المستخدمة لإنتاجها. إن الأبحاث حول استجابة التدفقات السائلة مستمدّة من الإنجازات العلمية، كما تشير الكيمياء الخضراء. بمساعدة فلسفة الكيمياء الخضراء التي لا تقدر بثمن، يمكن للعلماء والكيميائيين تقليل المخاطر على البيئة وصحة الإنسان بشكل كبير. إن استخدام المذيبات والمحفزات الآمنة والقابلة للتكرار والصديقة للبيئة يمكن أن يساعد في تحقيق أهداف الكيمياء الخضراء. قد تتضمن الكيمياء الخضراء كل شيء بدءًا من تقليل النفايات وحتى التخلص من القمامة بشكل صحيح. وينبغي اتباع النهج الأمثل للتخلص من أي نفايات كيميائية حتى لا تضر البيئة أو الكائنات الحية الأخرى.

الكلمات **المفتاحية**: الاستدامة البيئية، الكيمياء الخضراء، الألياف الطبيعية