Egypt. J. Chem. **Vol. 68**, No. 3 pp. 445 - 464 (2025)

Egyptian Journal of Chemistry

http://ejchem.journals.ekb.eg/

Natural Fibers Extraction Methods and Properties: A Review

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Abstract

Natural fibers generated from plants are gaining substantial interest as sustainable and renewable reinforcements for polymer composites because of their low density, high specific strength and modulus, biodegradability, and widespread availability. However, efficiently extracting these fibers from their various biomass sources remains a significant issue. This review provides a comprehensive review of various natural fiber extraction methods, evaluating their efficiency and environmental impact. Key techniques discussed biological retting processes (dew, water, and enzymatic retting), traditional mechanical methods, chemical extraction as well as modern approaches like ultrasonic, microwave, and steam explosion extractions. The review highlights the advantages and limitations of each method, with a focus on their potential for sustainable industrial applications. Key elements determining fiber quality include cellulose content, crystallinity, thermal stability, and mechanical characteristics.The primary focus of this review is on the efficiency and environmental impact of various natural fiber extraction methods. Comparing traditional and modern fiber extraction techniques aims to provide insights into the most sustainable practices for fiber extraction.

Keywords: Natural fibers, Extraction methods, Retting, Enzymes, Degumming

1. Introduction

Natural fibers have been a popular alternative to synthetic fiber reinforcements in plastics during the last two decades. Natural fibers are replacing synthetic fibers such as aramid and glass fibers in thermoplastics due to their low density, good thermal insulation and mechanical properties, reduced tool wear, unlimited availability, and low cost[1], [2]. However, their consumption has raised environmental concerns and global issues [3], [4]. Many research efforts have shown considerable advancements in laboratory-scale synthesis and modification of natural products. Despite the availability of fibers, there is still a need to fill the void caused by natural resource depletion. Natural fibers are gaining increased attention due to their sustainability and environmental benefits, which include biodegradability, reduced carbon footprint, and lower dependence on fossil fuel-based synthetic fibers. These fibers, derived from plant, animal, or mineral sources, offer an eco-friendly alternative that supports the global movement towards sustainable development[3], [5]. Fiber quality is influenced by crop location and climate, fiber age, plant type, transportation, storage, and inventory conditions [6]. Natural fiber reinforced polymers have comparable physical properties to glass fiber-reinforced composites. Natural fibers find applications across a variety of industries, including textiles, automotive, and construction. In the textile industry, they are valued for their comfort and biodegradability. In the automotive sector, they contribute to lighter and more fuel-efficient vehicles. In construction, they provide sustainable alternatives to conventional materials [7].Natural fibers are divided into three categories. These include plant, animal, and mineral fibers shown in (Figure 1). Plant fibers are important forms of natural fibers. Natural fibers are constructed up of layers of lignin, hemicellulose, and cellulose. The outermost layer of fiber normally consists of lignin, the inner layer of hemicellulose, and the innermost cellulose (Figure 2). Because cellulose is the most critical component of natural fiber, it has strong adhesive qualities with a structure that exists throughout the composite's manufacturing process (Table 1). Fibers with a high cellulose content often have more effective mechanical characteristics [8], [9], [10].

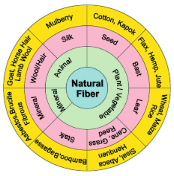

Figure 1 Classification of natural fibers according to their origin with several examples [11].

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Received date 10 June 2024; revised date 15 July 2024; accepted date 26 July 2024
DOI: 10.21608/EJCHEM.2024.296725.9842

Natural fibers are often taken from plant bark, stems, fruits, leaves, and roots. The chemical composition of natural fiber cellulose relies on its origin and age elements (roots, fruits, stems, bark, leaves) obtained from plants. Non-cellulose components in fibers include hemicellulose, lignin, and wax, covering the cellulose element. Fibers with a high cellulose content often have more effective mechanical characteristics[6], [10], [12], [13]. Cellulosic fibers occur naturally in two forms: in fiber form and embedded in a matrix within the plant.

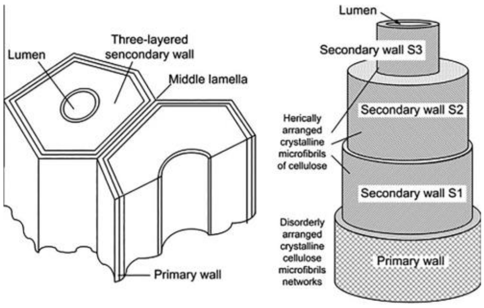

Figure 2 Plant fiber cell wall [12].

The first type of fibers is employed immediately and does not require Further extraction may merely need washing, drying, and cutting. The second sort of fibers require additional processing, including delignification and extraction. Processes might be chemical, biological, thermal, mechanical, or a mix thereof. The extraction procedure is regarded effective when cellulose fibrils are efficiently extracted from the hemicellulose and lignin matrix with little fiber damage and significant fiber length [14].

Table 1 Chemical composition of selected common natural fibers [12].

Natural Fiber Type	Cellulose	Hemicellulose	Pectin	Lignin	Wax	Ash	Moisture
Leaf Fibers (Extracted from Plant Leaf)							
Sisal	67-78	10-15	10	8-11	2	----	10
Pineapple Leaf Fiber	70-82	---	---	5-12	--	1.1	11.8
Banana	63-68	19	3-5	5-10	---	---	---
Abaca	56-63	15-17	---	7-10	3	---	---
Agave	68-80	15	---	5-17	0.26	---	8
Bast Fibers (Fiber Extracted from Surface of Plant Core)							
Hemp	70-75	17-23	0.9-3.0	3.7-5.7	0.2-0.8	2.6	6.5
Ramie	68-77	13-17	1.9	0.6-0.7	0.3	---	10
Jute	61-72	13-21	0.2	12-13	0.5	---	10
Flax	71-78.5	18-21	2.2	2	1.7	1.5	10
Kenaf	31-39	15-19	8.9	21.5	0.5	---	--
Seed Fibers (Fiber Obtained through Seeds)							
Cotton	82.7	5.7	6	0.75	0.6	---	7.85-8.5
Kapok	64	23	23	13	---	---	---
Stalk Fibers (Fibers Collected from Plant Stalk)							
Rice	28-48	23-28	---	14	20	---	---
Wheat	29-51	26-32	---	16-21	7	---	---
Oat	31-48	27-38	---	16-19	7.5	---	---

Grass/Reeds Fibers (Fibers Extracted from Grass)							
Bamboo	48-74	12-74	0.37	10.2-21.4	---	---	11.7
Bagasse	28.3-55	20-36.3	---	21.2-24	0.9	---	---
Corn	47	43.96	---	4.13	---	2.93	---

2. Extraction methods

The fiber extraction method involves removing fibers from plant elements such as stems, fruits, leaves, bark, and roots. Common extraction methods include mechanical extraction and retting. After extracting fibers using any of these methods, all extracted fibers are washed before drying. Fiber quality is impacted by moisture content, making proper drying crucial. Artificial drying produces higher-quality fibers than sun drying. To prevent beaching caused by direct sunshine, the fibers dried in the shade. Dry fibers are combed, graded, and put into bales. Mechanical extraction can be done manually or using a machine. Part of the plant fibers are separated using a decorticator machine, which has two grinding gears powered by either human or machine power. The gears will crush plant components to produce fiber. This is a costly and time-consuming procedure, and the quality of the fibers removed is determined by the laborer's expertise. Recently, these fibers have been removed using chemical, mechanical, and biological methods (Figure 3) [7], [12-13].

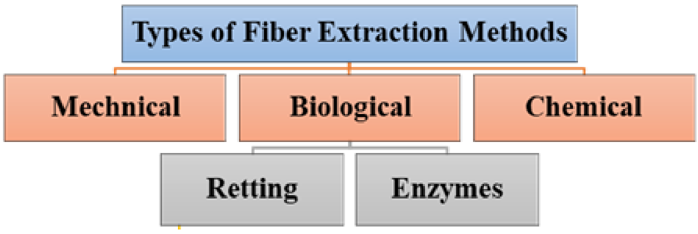

Figure 3 Types of Natural Fiber Extraction Methods [16].

2.1 Mechanical extraction

Mechanical extraction involves using mechanical processing equipment to remove fibers from bark and branches of plants. The fibers removed mechanically are usually not further separated chemically or biologically, though they may have undergone pre-treatments like retting or chemical/biological treatments. Shearing, pushing, and ripping forces are used to separate the fiber bundles from the woody shive/core material [17].

1) Decortication - Weakening the bonds between shives and fiber bundles.
2) Fiber cleaning - Further separating incompletely separated fiber-shive mixtures and removing dust.
3) Fiber opening - Breaking apart cleaned fiber bundles into finer fibers or single fibers [18].

While mechanical extraction reduces processing time compared to other methods, the results are often inconsistent. The fiber quality from mechanical extraction is suitable for only a few applications. Mechanical forces can cause fiber breakage, leading to poor separation efficiency and short fiber lengths, which makes fiber spinning challenging [19].

A mechanical decortication method is used to separate Sansevieria cylindrica fibers (SCFs) from the plant leaves. Isolated fibers have a relatively low density of 0.915 g/cm3 and high porosity of 37%, making them suitable for lightweight and insulation applications. Tensile testing indicates the fibers have strength of 658 MPa. Chemical analysis reveals the fibers contain 80% cellulose along with hemicellulose, lignin, and waxes [20].Another study reported on a novel process involving the use of plant ribbons instead of traditional water retting. A specialized fiber extraction machine equipped with a motorized rotor was used to separate fiber bundles from jute plant ribbons showed in Figure 4. An analysis of variance revealed that the cellulose, hemicellulose, and lignin content of the fibers were significantly influenced by the extraction method. Water-retted fibers exhibited higher cellulose and hemicellulose content compared to the mechanically extracted ribbon fibers. Conversely, water-retted fibers had lower lignin content compared to the ribbon fibers [21].

Figure 4 (a) Inner side view showing blade (b)fiber extractor machine [21].

The research reports on development of a power-operated machine called "Aashkol" to mechanize jute Fiber extraction from plant stems as ribbons shown in

Figure 5. Machine has primary and secondary extractors to decorticate Fiber bundles from broken sticks, avoiding the need for retting. Machine extraction plus improved retting gives 9% higher Fiber yield over traditional manual processes [22].

Figure 5 Jute fiber extraction by the developed Aashkol[22].

P. Badanayak utilized Banana pseudostems which are considered an abundant agricultural waste that can provide a sustainable source of natural bast Fiber. Mechanical extraction via decorticator's machine is faster and can enable large-scale production. The results show that Banana Fiber has high cellulose content ranging between 55-65% providing structural integrity. It also exhibits superior fiber length, fineness, strength, and length-to-width ratio that are comparable to jute and other bast Fibers [23].

An article focused on modifying jute fibers to achieve finer and softer characteristics while maintaining desirable properties like strength and length, researchers employed a combination of pretreatment and mechanical processing techniques (Table 2). Through optimal pretreatment and mechanical modifications, the refined jute Fibers achieved suitable linear density, length, and strength properties for use in high-quality textile end products. The modified Fibers exhibited increased fineness and softness while retaining their strength and length characteristics, making them suitable for textile applications [24].

Table 2 Detailed process routes used for mechanical modifications of jute fiber.

Process	Process route
Process I	Pretreated jute fiber – draft-cutting – speedily carding
Process II	Pretreated jute fiber – draft-cutting – slowly carding
Process III	Pretreated jute fiber – cutting – speedily carding
Process IV	Pretreated jute fiber – cutting – slowly carding

2.2 Biological Extraction

Biological extraction is conducted on fiber extraction as an environmentally friendly process to extract natural fibers from agricultural resources. Biological retting consists of two types: natural and artificial retting. Retting is a biological process that removes non-cellulosic components from fiber bundles by enzyme activity, resulting in unattached fibers. Except for chemical retting, all retting procedures require enzymes to remove fibers from bundles. Microorganisms, including fungus and bacteria, breakdown polysaccharides and split fiber bundles. The fiber extraction procedure has an important impact on ultimate fiber quality and yield. Microbial retting is a commonly used process for extracting high-quality cellulosic fibers from plants [7],[25].

2.2.1 Retting Extraction

Retting is a crucial process in plant fiber processing, Dew retting and water retting are commonly used, taking 14 to 28 days to degrade waxes, pectin, hemicellulose, and lignin. Alternative methods like mechanical extraction and chemical treatments are being explored to reduce processing time. The presence of bacteria and moisture during retting facilitates the separation of individual fibers [6], [17], [26], [27].

Dew retting process:

Dew retting, or field retting, is a popular and ancient technique for separating fibers in the retting process. It is sensitive to temperature and moisture, making it less widely used. After harvesting, plants are left for microbes to separate fibers (Figure 6). Over retting occurs when cellulose is degraded by fungus, affecting mechanical properties and causing challenges for further processing [12], [19], [25], [28].

Figure 6 Flax Dew Retting [29].

Through dew retting explores the use of agricultural waste from hemp plants in Europe for natural fiber extraction. It demonstrates that this process can be efficient and sustainable, regardless of climate conditions. Experiments were conducted in various environments, including the Mediterranean and eastern France, and showed that the retting time did not affect the fiber's tensile or composite properties. The findings suggest that dew retting can yield suitable fibers for load-bearing composites [30].

Water retting process:
Water retting is a traditional method of soaking bast stems in water for a week or two, it has been used for centuries to improve the quality of fibers. This process involves exposing the stems to water, allowing moisture absorption, and causing the outer layer to crack (Figure 7). The treatment time depends on the type of water, temperature, and bacterial community. However, water retting has a significant environmental impact, polluting water, and energy. To address freshwater shortages and prevent watercourse pollution, it is suggested to explore alternative water sources, such as large tanks [24], [27], [31].

Figure 7 a) Jute water retting, (b)Jute Extraction and (c) Jute fiber drying [18]

A. K. Ghorai and A. K. Chakraborty explain an improved, sustainable technology for retting jute plants to extract high quality bast fibers. This new "micro-pond" method uses low volumes of water, recaptures residues, and integrates aquaculture and crops (Figure 8). The micro-pond retting method developed on farm lined pond with small water volume and microbial inoculum - reduces water need to 1/6th of traditional method. Microbial activators like molasses and fertilizers accelerate retting; gives quality golden fiber in 14-30 days [32].

Figure 8 A) retting in the roadside ditch, (B) ‘shyamla’ coloured fiber in traditional retting, (C) retting with native microbial inoculum and (D) golden coloured fibre [32].

Retting methods for jute fibers were improved to enhance fiber quality and manage waste. Conventional water retting has issues like water pollution and fiber damage. Ribbon retting with microbial formulations reduces time, water use, and costs, aligning with waste utilization goals [33].

A. Bezazi, et al., explores sustainable extraction methods for Agave Americana bast fibers, demonstrating that these fibers can be obtained without chemicals (Figure 9). The methods involve water immersion and burying leaves underground, resulting in strong fibers with higher mechanical properties. The study also suggests using agricultural residues containing cellulose/lignin-degrading fungi and bacteria for further extraction. Upcycling wastes for fiber production maximizes circularity and meets renewables demands [34].

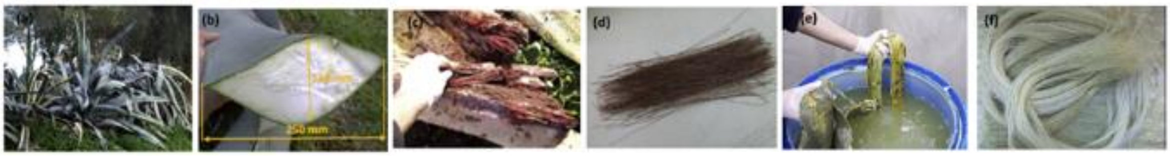

Figure 9(a) Example of Agave americana L. from the region around Guelma (Algeria), (b) its cross-section view,(c) Extraction from the ground of the plant buried after 90 days, (d) type of fiber obtained from this manufacturing process, (e) Agave leaves immersed in water for 10–13 days, (f) type of fiber obtained from the water immersion technique [34].

2.2.2 Enzyme Extraction Process

The increasing requirement for sustainable textile goods and clothing needs an upgrade in wet textile production, which involves replacing risky chemicals with more efficient procedures to save water and energy[35].

Retting, an old process, makes use of pectic enzymes produced by bacteria. These enzymes break down pectin, releasing bast fiber from the cortex (Figure 10). Because of advances in biotechnology, enzymes can now be economically produced, making enzymatic retting a popular alternative for long fiber production. Enzyme technology has various advantages over chemical catalysts, including faster processing, less waste, and more environmental sustainability [19], [36].

Enzymes are natural substances produced by bacteria, fungi, and humans that catalyze chemical synthesis and breakdown at mild circumstances (temperature, humidity, pH) conditions. Table 3 compiles the process parameters reported for the respective processes. Those parameters fall in the range ambient-60 ◦C, 65–85% RH, pH 3.5–10 with durations up to 40 days.

Enzymes provide high reaction selectivity and non-destructive polymer surface modifications. However, expensive expenditures, wastewater treatment systems, and a lack of industry support prevent their broad adoption. Pectinase and xylanase are acceptable enzymes for fiber extraction and degumming, notwithstanding their expense and industrial constraints [27], [37], [38].

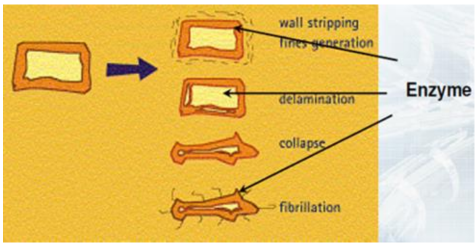

Figure 10 Actions of the enzyme on plant cell [38].

Table 3 Process conditions for biological action on bast fibers

Organism/Enzyme	Substrate	Temperature	Environment/ PH	Ref.
Aspergillus niger	flax	27 ◦C for 6.5 h 40 ◦C for 22 h	pH 5.0	[39]
Aspergillus nigerpgaserhizopuspgaseviscozyme l	flax	40 ◦C for 20 h	pH 5.0	[40]
Pectate lyase viscozyme l	Flax	50 ◦C for 1 h 40 ◦C for 24 h	pH 8.74 pH 5	[28]
Amycolata (pseudonocardia) pectate lyase	ramie	“Room temperature” for 15 h	pH 7	[41]
Bacillus sp. Pgase	Ramie and sunn hemp	50 ◦C for 12 h 60 ◦C for 11 h	pH 10.0	[42]
Bacillus sp alkalophilic bacteria	ramie	37 ◦C for 24–48 h	pH 10.0	[43]
Trameteshirsuta	flax	37 ◦C for 4 h	pH 4.5	[44]
Trametes versicolor	wheat	30 ◦C for 40 days		[45]
Ochrobactrumanthropistenotrophomnasmaltophilia	hemp	28 ◦C for 36–48 h		[46]
Clostridium felsineum bacillus subtilis.	hemp (Tiborszallasi)	35 ◦C for 3 days		[47]

18 filamentous fungi	(unspecified) plant fibers	30–37 ◦C for 3 days	pH 7.0	[48]
Field environment	hemp	ambient outdoors		[49]
0.05% viscozyme l plus 1.8% mayoquest 200	flax	40 ◦C for up to 24 h	pH 5.0	[50]
Various enzymes	flax	25–60 ◦C	pH 3.5–9	[51]
Pl-bri bacterial pectinolytic enzyme with lyase activity (e.c.4.2.2.2)	flax	42 ◦C up to 46 h	pH 8.5	[52]
Ser-3 and ser-4	flax	Sprayed in field		[53]
White rot fungi / extracellular oxidases enzymes	plant-based natural fiber	27 ◦C for 2 weeks		[54]
Viscozyme, ultrazyme or denilite, then cellusoft l/ ul	jute	40–60 .C for 72 h then 1–4 h	neutral or pH 8.0	[55]
Scourzyme l pectate lyase (ec 4.2.2.2),	hemp	55 ◦C up to 24 h	pH 8.5	[56]
White rot fungi (phanerochaetechrysosporium and ceriporiopsissubvermispora), cellulase enzyme, mixed enzymes (cellulase, xylanases, and pectinases)	jute	40 ◦C for 90 min	pH 5.0–5.5	[57]
Trametes hirsute laccase (ec 10.3.2)	flax (and coconut)	37 ◦C for 3 h	pH 4.5	[44]
Trameteshirsuta	flax	37 ◦C for 4 h	pH 4.5	[44]

Application of enzymes in degumming of fiber

Pectinases enzyme can be combined with other enzymes like amylase, lipase, cellulase, and hemicellulose, to be used in the textile industry to decompose sizing agents from cotton, reducing wastechemicals and improving environmental safety. Bio-scouring, a revolutionary procedure, uses enzymes to remove non-cellulosic contaminants from fibers like pectin, protein, and lipids. This eco-friendly and energy-saving method reduces fiber damage. Pectinase is also used in degumming plant fibers like ramie, jute, flax, and hemp to remove gum before textile manufacturing. This enzymatic degumming method is eco-friendly, cost-effective, and a great substitute for chemical degumming, which is polluting, poisonous, and nonbiodegradable [36], [37].

Cellulases are a kind of enzyme that hydrolyzes cellulose (catalyses cellulolysis), most commonly working on the -(1,4)-linkage [27]. Xylan is a polysaccharide that has -xylopyranose residues as spinal with glycosidic connections. Xylan-glucan-protein complexes connect xylan and pectic compounds. Enzymatic degumming of fibers can be achieved by combining xylanolytic and pectinolytic enzymes, with xylanase also playing a role. This method can replace traditional retting procedures and create new fiber liberation technologies. Xylanases arecrucial for degumming ramie fibers, and studies have shown that fibers treated with xylanase have higher linear density and lower costs compared to Laccase treatment [37].

Laccase enzymes are affordable, reaction-specific catalysts that degrade dense, sticky substances in fibers, resulting in cellulose-rich fibers. They are safe and environmentally friendly, capable of lignin breakdown, and have been shown to be effective in refining bamboo fibers, increasing lignin removal. Bamboo fibers can be refined with xylanase and laccase while maintaining strength [58], [59].

One of the studies investigated the dynamics of key enzymes (polygalacturonase, pectin lyase, and xylanase) released by a microbial retting consortium during the entire retting process. The retting process was divided into three stages: initial (1-2 days), middle (3-9 days), and final (10-14 days). The microbial retting consortium, consisting of three strains of Bacillus spp., efficiently produced pectinolytic enzymes (polygalacturonase and pectin lyase) and xylanase but did not produce cellulases, ensuring the structural integrity of the cellulosic fibers. The use of the microbial retting consortium accelerated the retting process, leading to faster biodegradation of pectin and xylan compared to conventional retting methods. This resulted in improved fiber recovery (10.9% higher), better fiber strength, fineness, luster, and reduced root content (undecomposed materials) [60].

Ramie fiber is an attractive alternative to cotton fiber due to its attractive luster, high tenacity, enhanced strength, and good microbial resistivity. K. Y. Abidin, et al., compared the effects of enzymatic degumming with and without bleaching (using a small amount of sodium chlorite) on ramie fiber quality. The results showed that the bleaching treatment (S6) resulted in higher fiber weight loss (9.52%), whiteness index (87.87%), tenacity (20.08 g/Tex), and fineness (1.05 denier) compared to the non-bleaching treatment. The combination of xylanase and pectinase enzymes effectively removed the gum from the decorticated ramie fiber, improving the fiber's physical properties. The bleaching process further enhanced the whiteness index and fiber brightness due to the delignification of the fiber surface. The authors conclude that enzymatic degumming using a combination of xylanase and pectinase enzymes can improve the quality of ramie fiber, making it a suitable alternative to cotton fiber [61].

H. Tibolla, et al., investigates isolating cellulose nanofibers (CNFs) from banana peels, an abundant agricultural waste, using chemical and enzymatic treatments (Figure 11). The aim is to find a use for this residue as a renewable and biodegradable source of reinforcing nanofibers for composites. Both acid hydrolysis (chemical treatment) and enzymatic treatment with xylanase effectively isolated CNFs from the banana peel bran. The resulting CNFs had diameters of 10.9 nm (chemical treatment) and 7.6 nm (enzymatic), confirming nanoscale cellulose fibers were obtained. The enzymatic method yielded longer fibers with higher aspect ratios, which should improve reinforcement. It also gave fibers with more negative surface charges, improving dispersion. However, it left some residual lignin and hemicellulose. The chemical treatment gave more highly crystalline CNFs, indicating better removal of amorphous components like lignin and hemicelluloses. But the harsher conditions shortened the fibers [62].

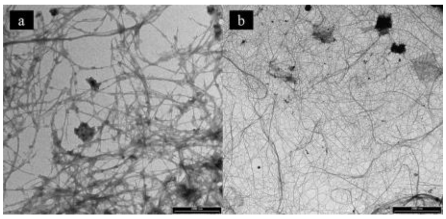

Figure 11 TEM images of the cellulose nanofibers obtained by (a) chemical treatment (CT) and (b) enzymatic treatment (ET) (1400x, scale bar = 2000 nm) [62].

Bio-degumming uses enzymes from microorganisms to remove non-cellulosic components from jute bast, extracting high quality fibers. A new strain Pectobacterium sp. DCE-01 is used after mechanical rolling pretreatment of jute. It simultaneously secretes pectinase, mannanase, and xylanase matching jute's biochemical composition. Degumming is achieved in 15 hours with low pollution and a high fiber strength of 5.12 cN d/tex. The process parameters like temperature, inoculum size etc. have been statistically optimized for 18.21% weight loss and 20.15% residual gum [63].

J. Jayapriya and C. Vigneswaran investigates the effect of using white rot fungi (Phanerochaetechrysosporium and Ceriporiopsissubvermispora) and enzymes (cellulase, xylanases, pectinases) to bio-soften jute fibers from agricultural waste. Jute is a natural bast fiber that has high tensile strength and moisture absorption but is coarse and rigid due to lignin content. Bio-softening through fungi and enzymes aims to selectively remove lignin while retaining cellulose to improve fiber properties. Results showed fungi and enzymes effectively degraded lignin, decreasing fiber tenacity and flexural rigidity while increasing elongation percentage after 30 days treatment (Figure 12). This suggests improved spinnability for textiles. Scanning electron micrographs revealed increased separation of fiber bundles. Enzyme treatments also produced softer, smoother fibers dependent on concentration [57].

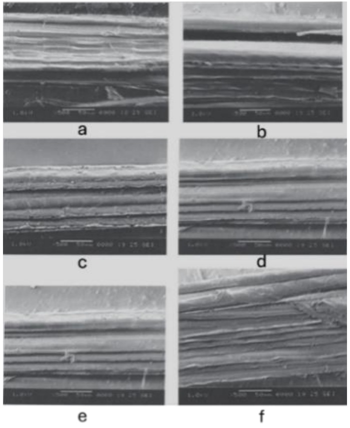

Figure 12 SEM images of (a) the raw jute fiber, (b) the jute fiber treated with fungus P. chrysosporium, (c) jute fiber treated with 2% cellulase, (d) jute fiber treated with 4% cellulase, (e) jute fiber treated with 2% mixed enzyme, and (f) jute fiber treated with 4% mixed enzyme [57].

X. Zhang et al investigates an efficient and environmentally friendly biochemical degumming method for hemp fibers using dilute solutions of alkali pectinase lyase and chemical additives. This addresses issues with traditional chemical degumming methods which use high temperatures, pressures, and cause pollution. It also improves on drawbacks of purely biological degumming which requires long reaction times and strict pH conditions. The optimized biochemical degumming solution was 1.5% alkali pectinase lyase with ≤0.4% alkali and ≤0.8% salt chemical auxiliaries. Optimal process conditions were a 1:10 bath ratio, 60°C temperature, and 60-minute reaction time. This resulted in a fiber composition of 3.69% lignin, 4.09% pectin, 13.34% hemicellulose, and 78.87% cellulose. The paper compares the biochemical method against traditional chemical and biological degumming. The biochemical method performed slightly less effectively than chemical but much better than biological. It produced a similar cellulose content (78.87% vs 80.66% for chemical) so can replace chemical degumming [64].

A. Dong, X. Fan, Q. Wang, Y. Yu, and A. Cavaco-Paulo found that treating jute fragments with 0.92 U/mL laccase at pH 4.5 and 60°C for 3 hours prior to membrane preparation increased tensile strength 30%, tear strength 21%, and burst strength 2% compared to untreated fragments. Additionally, laccase treatment increased the hydrophobicity of the membrane surface. The mechanical and hydrophobic properties were further enhanced by 13-15% and 10-26%, respectively, by using laccase in combination with natural mediators like guaiacol and alkali lignin or in multi-enzyme systems with xylanase or cellulase pre-treatments. FTIR and SEM analysis confirmed increased lignin content and cross-linking at the fiber surface after enzymatic treatment (Figure 13)[65].

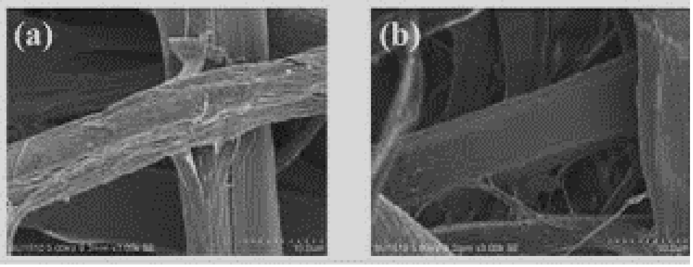

Figure 13 SEM images of jute fiber membranes after (a) control treatment (b) cellulase/lacasse combined treatment [65].

A patent describes a jute degumming process to produce a high-quality jute fiber that can be used for garment materials. The process includes four main steps:

1. Enzyme treatment using a combination of pectase and laccase enzymes to effectively remove impurities like pigments and xylogen from the raw jute fiber. This is done in two phases - first at pH 5-5.5 to optimize laccase activity and then at pH 7.5-8 to optimize pectase activity.
2. Reduction bleaching using a reducing bleaching agent and a decolorizer to further remove pigments and impurities from the jute fiber.
3. Mechanical stamping and rinsing of the jute fiber.
4. Oiling, dehydrating, and drying of the jute fiber to produce the final purified and softened jute fiber product.

The process achieves high removal rates of 89-91% for pigments and 76-79% for xylogen impurities using relatively eco-friendly enzyme-based degumming. This allows the jute fiber to meet quality requirements for use in garment materials either on its own or blended with other fibers like cotton [66].

Banana pseudostem is a major biomass waste generated after harvesting banana bunches, and it can be effectively utilized for bulk production of banana fiber, which has various applications in textile, handicrafts, composite boards, paper industry, and as a source of cellulose fiber. The study investigated the mechanical extraction of banana fibers from five different cultivars (Grand Naine, Red Banana, Poovan, Popoulu, and Karpuravalli) using a low-cost, user-friendly fiber extractor (Raspador machine). Among the cultivars, Karpuravalli and Red Banana exhibited higher fiber recovery and better mechanical properties, suggesting their suitability for applications like yarn, flexible materials, composites, and handicrafts. To improve the quality of extracted fibers, enzymatic degumming treatments were performed using pectinase, laccase, and their combinations to remove non-cellulosic components like pectin, hemicellulose, and lignin. Laccase enzyme treatment was found to be more efficient in improving the surface quality of banana fibers by removing the gummy substances, followed by the combination of pectinase and laccase (25:75 ratio). Enzymatic degumming resulted in the removal of non-cellulosic components, leading to an increase in moisture content and a decrease in ash content of the treated fibers [67].

2.3 Chemical Extraction

Chemical retting can also be used to remove plant fibers, which provides better control than dew and water retting. Unfortunately, chemical retting, while successful in fiber extraction, creates substantial environmental issues due to the greater amount of chemicals used. Alkali and specific reagents were used in the chemical extraction procedures. Alkali treatments cause fibrillation, which degrades the composite fiber bundle into smaller fibers. Sodium hydroxide (NaOH) is commonly used to minimize fiber roughness, although it also yields high-quality fiber. Chemical extraction can also be accomplished using reagents such as sulfuric acid, hydrogen peroxide, protease, and sodium citrate [16]. The fiber straws are immersed in an aqueous chemical solution medium such as sodium hydroxide, sulfuric acid, or potassium hydroxide during the chemical retting process. hydroxide and these solutions breakdown the fiber and eliminate undesirable non-cellulosic elements.

The extracted Fiber is of great quality, but the end product is expensive [12]. The effect of surface treatments on natural fibers is tabulated in **Error! Not a valid bookmark self-reference.**.

Table 4 Effects of chemical treatment on natural fibers

Natural fiber	Chemical Solution	Solution Concentration	Duration	Effect of chemical treatment	Ref.
Kenaf fiber	NaOH	2, 5, and 10 wt.%	1 h	Formation of glycoside bond and hemicellulose removal due to alkali treatment.	[70]
Sugarcane bagasse Fiber	Kmno4	5%	30 min	Thermal properties were enhanced both for fibers and resultant composites. Improvement in tensile properties was observed.	[71]
Areca fiber	NaOH	6%	1 h	The hydrophilic nature was reduced with increasing thermal stability.	[72]
Alfa fiber	NaOH	0.25–7 m	2.5 h	Non-cellulosic impurities were reduced, and MFI was increased.	[73]
Coconut fiber	KMNO4	0.25, 0.5, 0.75, And 1%	3 h	Fiber surface morphology was altered and increases surface roughness value.	[74]
Pineapple leaf Fiber	Stearic acid	10, 30, and 50 wt.%	—	The fiber dispersion was improved due to stearic acid treatment and stress transfer was reduced due to slippery interface.	[75]
Rice straw fiber	Acetic acid	2, 4, 6, 8, and 10% (v/v)	24, 36, and 48 h	The increase of treatment duration results in bio-methane yield reduction, which was due to cellulose lose.	[76]
Sisal fiber	Benzoyl Chloride	15% and 30%	30 min	The original smooth and clear surface of sisal fiber converted into rough surface. The crystallinity percentage and thermal stability were also enhanced.	[77]
Sugar palm fiber	NaOH	18%	30 min	The fiber color was changed to dark brown from black color, also the fiber diameter was reduced.	[78]
Jute	KMNO4	0.02, 0.03, 0.05, And 0.5%	1, 2, 3, 5 min	Physicomechanical properties were enhanced in treated fibers as compared to untreated one.	[79]
Agave, pine, and coir fibers	NaOH	2%	15 min	The uniform fiber distribution and morphology was observed without gaps and voids between matrix and fiber.	[80]

H. Suryanto, E. Marsyahyo, Y. S. Irawan, and R. Soenoko investigates the morphology, structure, and mechanical properties of natural cellulose fibers extracted from Mendong grass (Fimbristylisglobulosa) (Figure 14), an agricultural waste. Mendong fiber (MF) is composed of 72.14% cellulose, 20.2% hemicellulose, 3.44% lignin, and 4.2% extractives with low moisture content of 4.2-5.2% compared to other natural fibers. Alkali treatment of MF using 5% NaOH increases crystallinity from 70.7% to 74.1%, tensile strength from 452 MPa to 497 MPa, and modulus from 17.4 GPa to 20.9 GPa by removing non-cellulosic components. The diameter, density, and aspect ratio of MF is 33.4 µm, 0.892 g/cm3 and 101 respectively. XRD analysis confirms cellulose Iβ structure with a crystalline size of 14.3 nm. The mechanical and structural properties indicate MF canpotentially replace synthetic fibers as economical, renewable, and biodegradable reinforcement for polymer composites to mitigate climate change impacts [68].

Figure 14 (A) Mendong grass in agricultural land; (B) Dried mendong grass; (C) Fiber straw; (D) Extracted fiber [68].

A new natural cellulosic fiber extracted and characterized from the creepers of the Mikania micrantha plant using a 5% NaOH retting process. Mikania micrantha is an abundant, fast growing vine species found in Central/South America and Southeast Asia. The extracted fiber had high cellulose content (56.42%) indicating potential for strength and stiffness. Hemicellulose (21.42%) and lignin (15.78%) were also substantial. Physical characterization showed moisture regain of 9.17%, moisture content of 8.4%, density of XX, thermal stability up to 228°C.Mechanical testing gave tensile strength of 38.6 gm/tex and elongation of 1.8%. Crystallinity index was 72% comparable to established fibers like jute, hemp etc. FTIR and SEM analysis confirmed the fibrillar, lignocellulosic structure with functional groups of cellulose, hemicellulose, and lignin (Figure 15). Overall, the Mikania micrantha fiber shows promise as a novel, renewable and sustainable reinforcement for composites and other applications to mitigate climate change impacts [69].

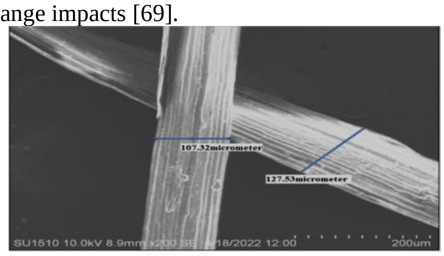

Figure 15 SEM image of Mikania micarntha fiber [69].

Long textile fibers are extracted from the midrib of date palm trees using an alkaline-mechanical treatment. Date palms are widely grown in Middle East/North Africa, generating large amounts of annual pruning waste containing lignocellulosic fibers. Fibers were extracted from the hollow, vascular bundles in the midrib through a combined NaOH treatment and mechanical processing. Alkaline treatment removed impurities, and increased cellulose content (up to 69%) and fibrillated fibers. More severe treatments gave better purification/fibrillation (Figure 16). Extracted fibers showed density up to 1.324 g/cm3, tensile strength 453 MPa, crystallinity index 58.4%, and thermal stability up to 226°C. The properties were comparable or better than some common natural fibers like jute, sisal etc. showing potential for textile applications [14].

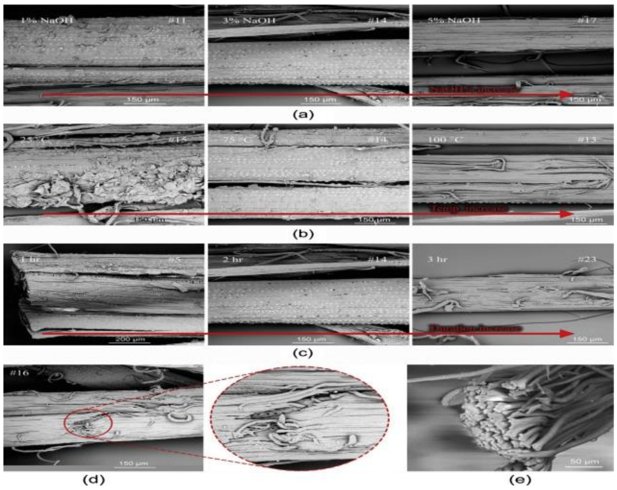

Figure 16 SEM micrographs of DPM fibers showing the effect of increasing (a) NaOH%, (b) treatment temperature, (c) treatment duration, (d) over treated showing fiber [14].

Sodium hydroxide treatment was optimized on jute fabric to improve its compatibility as reinforcement in an unsaturated polyester resin matrix for developing bio-composites. Jute fiber on its own lacks' compatibility with hydrophobic resins. Sodium hydroxide treatment is commonly used to modify natural fibers, but often requires high concentrations (>3%) and long treatment times. The study utilized an L9 Taguchi orthogonal array to test the effects of 1% sodium hydroxide concentration at different material-to-liquor ratios (1:5, 1:10, 1:15), temperatures (30, 40, 50°C) and times (30, 60, 90 mins). The optimized treatment was found to be 1:10 ratio at 50°C for 60 minutes. This improved the flexural strength, flexural modulus and interlaminar shear strength of the resulting jute/polyester bio-composites by 23%, 33%, 59% and 207% respectively compared to untreated jute fiber composites. The treatment partially removes hemicellulose and lignin components, increases fiber crystallinity, and improves fiber cohesion. This in turn enhances interfacial bonding between the jute reinforcement and resin matrix by increasing surface roughness and contact points. SEM analysis confirmed improved fiber-matrix interaction [81].

Alkaline and enzymatic degumming methods are compared for hemp fibers, which is essential to remove lignin and separate fibers for textile applications. Optimizing the process aims to reduce fiber strength loss. Alkaline degumming using NaOH, MgSO4, H2O2, etc. was found to be most effective. Optimized conditions were 75°C temperature and 50-minute heating time. This gave 15.23% weight loss, 21.5μm fiber diameter and 57.2 gf/tex fiber strength. Enzymatic degumming is eco-friendly but gives poorer fiber separation and higher diameter fibers. Strength and weight loss were also inferior. Optimized 1.45ml enzyme concentration gave 20.13% weight loss, 29μm diameter and 50.34 gf/tex strength [82].

A degumming method to isolate lignocellulosic fibers from jute bast on an alkali-free, organic solvent-based. The goals were to develop an eco-friendly alternative to traditional alkaline degumming (TAL) that requires high alkali concentrations and generates hazardous wastewater. The proposed method uses the organic solvent 1-2 propylene glycol (PG) plus an additive called green oxygen (GO-OS) containing anthraquinone and sodium sulfite (Figure 17). It works by degrading and dissolving away non-cellulosic components like lignin, hemicellulose, and pectin under high temperature, while protecting the cellulose fibers. Optimized conditions were 180°C, 120 min reaction time, and 0.9% GO-OS additive content. The resulting jute fibers met quality standards for residual gum content (<18%) and tenacity (>2 cN/dtex), with better tenacity (7.1 cN/dtex), yield (65.7%) and elongation than TAL fibers. The GO-OS reaction time was much shorter than TAL (120 vs 300 min). Analyses showed significant removal of non-cellulosic, increase in cellulose content from 59.5% to 67.5%, and increased cellulose crystallinity. The milder GO-OS method gave higher fiber yield and quality than TAL. An advantage is avoiding hazardous chemicals. The organic solvent could potentially be recycled [83].

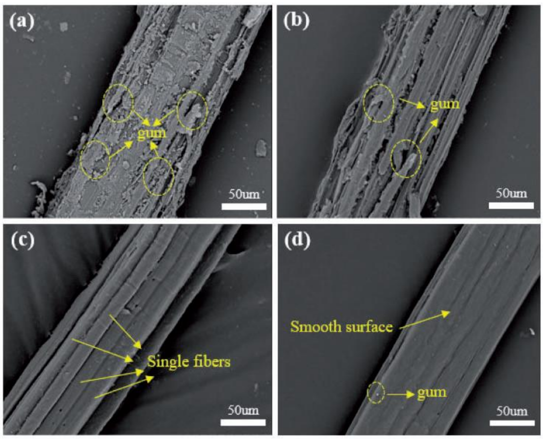

Figure 17 Surface morphology images of jute fibers with different treatments: (a) scanning electron microscopy images of a raw jute bast fibers, (b) jute fibers pretreated by distilled water boiling, (c) jute fibers degummed by the optimized green oxygen system, (d) jute fibers treated by the traditional alkaline degumming method [83].

W. Wang and Z. Cai examines the effect of different degumming process parameters on properties of jute fiber related to spinnability, including gum decomposition, fineness, breaking strength, and breaking extension. The parameters studied include concentration of sodium hydroxide, treatment time, temperature, concentration of additives like sodium silicate and penetrating/degumming agents, and fiber-to-liquor ratio. The results showed sodium hydroxide concentration, sodium silicate concentration and treatment time to be the most important factors affecting degumming. Optimized conditions selected based on an L9 orthogonal experiment were: 12g/L NaOH, 3g/L sodium silicate, 2g/L penetrating agent, 2g/L degumming agent, 105 min treatment time at 100°C with 1:20 fiber-to-liquor ratio. Analysis of the chemical composition showed effective removal of non-cellulosic components like hemicellulose, lignin, and pectin after degumming. Under optimized conditions, 61.9% gum decomposition and 2.02 tex fineness were obtained, indicating enhanced potential use of the jute fiber as a textile material[84].

The effects of two chemical treatments - mercerization using sodium hydroxide (NaOH) and acetylation using acetic anhydride - on four natural fibers: hemp, sisal, jute, and kapok were investigated. The aim was to modify the fiber surface and structure to improve adhesion with polymer matrices for composite applications. Differential scanning calorimetry of mercerized fibers (DSC) shows alkali treatment lowers thermal stability of fibers by increasing amorphous cellulose, while acetylation provides some improvement. XRD indicates alkali treatment increases crystallite order rather than intrinsic crystallinity. FTIR confirms grafting of acetyl groups, reducing hydrophilicity. SEM shows increased surface roughness after alkali treatment. The results demonstrate both mercerization and acetylation can effectively modify natural fibers to create better bonding with hydrophobic polymer resins [85].

L. Bacci, et al., present a comprehensive study on the extraction and characterization of fibers from nettle (Urtica dioica L.) stalks using various methods, including chemical, water retting, microbiological, and enzymatic treatments:

- Mechanical decortication of nettle stalks stored for one year resulted in a good degree of separation between fibers and shives, likely due to natural retting processes occurring during storage. This step could be routinely applied before retting to reduce the volume of biomass and save water, energy, and enzymes required for further processing.
- Microbiological retting using a combination of anaerobic and aerobic bacteria produced fibers with a higher quality than water retting, characterized by finer diameters (around 28-29 µm) and higher tenacity (64 cN/tex).
- Enzymatic retting, particularly using Pectinex Ultra SP-L with EDTA (chelating agent), improved fiber fineness (33 µm) and cellulose content (80.8%) without compromising tenacity (58.9 cN/tex) compared to water-retted fibers.
- Spray enzyme retting, though successful for flax, resulted in coarser fibers with lower tenacity for nettle, highlighting the need for further optimization of this method [83].

The potential of utilizing water hyacinth, an abundant aquatic weed, as an alternative source of natural fibers was studied by S. Chonsakorn. Water hyacinth stems were obtained from a local river in Thailand, and various extraction methods were employed to obtain the fibers, including mechanical, chemical (using sodium hydroxide), combined mechanical and chemical, boiling, natural alkali (from banana stem ash), and retting (drying and acid treatment). The results revealed that water hyacinth consists of 72.17% cell walls, 52.63% lignocelluloses, 2.25% lignin, 54% hemicelluloses, and 50.38% cellulose. The mechanically extracted fibers were 30-50 cm in length and approximately 50 µm in diameter. Regarding tensile properties, the boiling extraction method yielded the highest tensile strength of 115.26 gf/den, followed by chemical extraction (112.76 gf/den) and mechanical extraction (109.14 gf/den) showed in Table 5. Scanning electron microscopy (SEM) analysis showed that the fibers produced by the combined mechanical and chemical extraction method had an even surface texture and exhibited the highest number of split fibers. This combined approach, along with the mechanical extraction method, was found to be superior for improving the quality of natural fibers from water hyacinth [84].

Table 5 Tensile strength comparison of water hyacinth fiber using different extraction methods.

Extraction methods	Tensile strength (grams-force per denier)	Standard deviation	Coefficient of Variation	Elongation (%)	Standard Deviation	Coefficient of Variation
Mechanical extraction	108.62	70.99	121.11	7.72	5.98	77.48
Chemical extraction	112.76	72.51	64.30	3.07	1.28	41.88
Mechanical and Chemical extraction	109.14	66.19	60.65	6.33	6.39	100.96
Natural alkali extraction	110.14	72.12	58.63	5.89	5.30	89.28
Retting extraction	109.54	68.20	59.32	6.65	6.10	94.49
Boiled extraction	115.26	58.51	50.76	2.51	0.96	38.38

Table 6 Major advantages and disadvantages of various Extraction techniques.

Methods			Advantages	Disadvantages	Ref.
Physical Extraction	**Decortication**	Manual operation	Easy operation.	Inefficient	[88]
		Blade crushers	Enable short length of fiber bundles and shives.	The outcome (fiber bundles) is impure with much core.	[89]
		Hammer mills	Have high extraction productivity and are more protective to fiber bundles compared with blade crushers.	Has high energy consumption and low production efficiency.	[90]
		Roll crushers	Enable long fiber length with low energy consumption.	The method is only applicable for retted stalks.	[91]

Semi-Physical Methods		Ball mills	Can avoid fiber wrapping.	Severe fiber loss in the process.	[92]
		Planetary decorticators	Have high production efficiency.	The quality of final fibers is yet to be improved.	[93]
		Modified machines	More effective in field decortication.	The design of a modified machine takes time.	[94]
		Scutchers	High-feeding quantity up to 500 kg.	Not applicable for un-retted samples.	[95]
	Fiber cleaning	Step cleaners	Has higher separation efficiency comparing with scutching.	Has high energy consumption.	[96]
		Comb shakers	Moderate processing could ensure long fiber length.	Low processing speed.	[97]
	Fiber opening	Opening cylinders	High-feeding quantity.	May form fiber wrapping if fine fibers from between gears are not cleared frequently.	[96]
		Carding machines	Fibers can be fully opened.	Much easier to form fiber wrapping compared with opening cylinders.	[98]
	Steam explosion		Increase the hydrolyzation of hemicellulose and lignin content and reduce the entire chemical oxygen demand.	Dangerous process to undertake.	[99]
	Microwave energy assistance		Gums exposed to large microwave energy.	May have potential harm to workers due to microwave radiation.	[100]
	Cryogenic treatment		Form micro-cracking of the gums.	Can be expensive and is hard to scale.	[101]
	Ultrasonic treatments		Provide access for reagents to penetrate the fiber matrix with low chemical dosage.	Has a limitation of treatment quantity.	[102]
	Supercritical carbon dioxide treatments		Can swell the fibers and allow chemicals to digest gums.	Energy consumption for CO2 compressing; high cost for the qualified working vessels.	[103]
Chemical Treatment	**Alkali treatment**		More effective than physical treatments.	May produce inhibitors.	[104]
	Oxidation		Less time required than alkali degumming.	The strong oxidizing ability may lead to partial degradation of cellulose fibers	[105]
	Organic solvents treatment		Have advocated potential for gum recovery.	Hard to handle/extract the residual organic solvents.	[106]
Biological Treatment	**Natural retting**		Meets the requirements of environmental and economic consideration	These methods are constrained by weather-dependence and land-possession.	[107]
	Enzyme retting		Has high efficiency and low pollution.	Enzymes are difficult and expensive to produce in volume.	[108]
	Cultivated-microorganism retting		Screened strains are highly effective in degradation of the non-cellulose materials.	Difficult to cultivate and recombine technologies.	[109]

3. Conclusion

The extraction of natural fibers from plant sources is an important step in using these renewable and sustainable materials in a variety of applications such as polymer composites, textiles, and paper goods. This review has thoroughly investigated the utilized fiber extraction technologies, focusing on their principles, benefits, limitation, and environmental concerns. Mechanical extraction methods, while relatively rapid, can produce irregular fiber quality and shorter fiber lengths, which restricting their uses. Biological retting methods, such as dew, water, and enzymatic retting, are more ecologically benign, but they require more time and are affected by external conditions like temperature and bacteria activity. Chemical extraction methods, including alkali, oxidation, and organic solvent treatments, effectively remove non-cellulosic components while also improving fiber characteristics. However, these approaches raise issues regarding the harm they may cause to the environment and the importance of effective waste management. Modern methods of fiber extraction, such as ultrasonic and microwave extraction, offer significant improvements in efficiency and environmental sustainability compared to traditional techniques. These methods not only reduce processing time and energy consumption but also minimize the use of harmful chemicals. Future research should focus on optimizing these techniques and exploring their scalability for industrial applications. The required fiber quality, end-use applications, environmental concerns, and economic viability influence the extraction technique. Enzymatic therapies have received a lot of interest because of their eco-friendliness, specificity, and promise to reduce chemical use and waste formation. Moving forward, developing efficient, environmentally friendly, and cost-effective natural fiber extraction procedures will remain a major task.

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