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Progress in Green Extraction and Textile Applications of Plant Fibers from Agricultural Waste

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ABSTRACT
Agricultural residues such as pineapple leaves, banana pseudostems and peduncles, cereal straw, sugarcane bagasse, corn husks, and coconut shells contain cellulose that can be converted into textile materials. Their suitability depends on the fit between natural morphology, extraction damage, and downstream processing. This review follows three routes: long fiber bundles for direct spinning; short feedstocks converted to regenerated cellulose through pulping and dissolution spinning; and coarse, lignin-rich fibers for nonwovens or composites. Mechanical decortication, natural retting, alkaline degumming, enzyme and microbial treatments, physical-field assistance, and emerging solvent systems are compared. Particular attention is given to the effects of residual gum, fineness, length distribution, bending rigidity, and surface hairiness on opening, drafting, and yarn stability. Existing studies show that pineapple and banana bundle fibers require gentle separation followed by controlled degumming. Biological routes can reduce salt loads, although long treatment cycles, enzyme cost, and batch variation still hinder continuous production. Straw and bagasse are generally better suited to pulp-based regeneration or to nonwoven, acoustic, thermal, and reinforcement applications. Industrial feasibility should be judged from qualified fiber yield, process consistency, resource use, and product durability, supported by life-cycle and techno-economic data.

KEY WORDS: *Agricultural waste, plant fiber, green extraction, degumming, spinnability, textile application.*

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I. INTRODUCTION

Demand for textile raw materials continues to rise, while polyester still dominates global supply. The Materials Market Report 2025 records roughly 132 million tonnes of fiber production in 2024, with polyester accounting for about 59%; most of that polyester was still derived from fossil resources [1]. The European Union's strategy for sustainable and circular textiles, meanwhile, calls for products placed on the EU market by 2030 to be durable, repairable, recyclable, and increasingly made from circular feedstocks [2]. This combination of market growth and policy pressure has renewed interest in agricultural residues. Pineapple leaves, banana pseudostems, rice husks, and straw are no longer viewed only as fuel or disposal materials; they are also being explored as sources for natural fibers, regenerated cellulose, and nonwoven products. Fashion for Good has included the technical feasibility and scale-up barriers of these feedstocks in its industrial validation work [3].

Pineapple leaf and banana fibers were used in handwoven fabrics, ropes, and composite reinforcement long before the recent interest in sustainable materials. Earlier work has described the material features, textile uses, and development prospects of pineapple fiber [4]. Many reviews, however, still organize the subject by plant name and list composition and properties separately. They rarely follow the chain from feedstock form to extraction method, spinning system, and end product. Changes in cultivar, maturity, plant part, and storage conditions can alter cellulose crystallinity, microfibril angle, linear density, and strength. Extraction severity may widen these differences further [5-6]. Average tensile strength or cellulose content alone therefore gives an incomplete picture of textile suitability.

This paper classifies the feedstocks by the route through which they enter textile processing. Long bundles from leaves, pseudostems, and peduncles may be spun after separation, degumming, and softening. Short residues such as straw and bagasse are better purified into pulp and re-formed through viscose, Lyocell, or other dissolution-spinning processes. Feedstocks with short, lignin-rich, or highly variable fibers are more suitable for nonwoven webs, acoustic or thermal insulation, and composite reinforcement. The following sections examine length loss, residual-gum removal, and fineness control together with spinnability, environmental load, and scale-up conditions. Figure 1 summarizes the three processing routes.

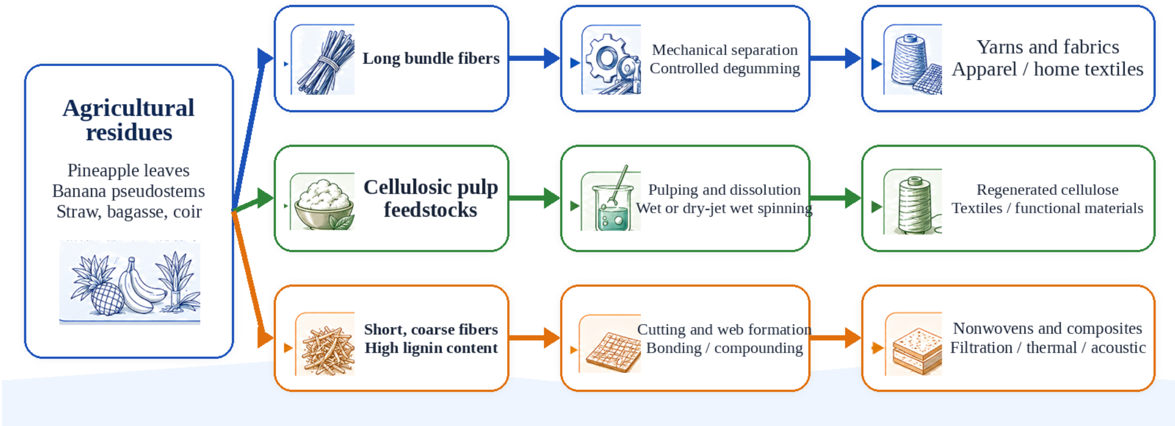

Figure 1 Three textile-processing routes for plant fibers derived from agricultural waste

II. FEEDSTOCK CHARACTERISTICS AND TEXTILE ROUTES

Pineapple leaves, banana pseudostems, and peduncles contain fiber bundles aligned along the plant axis. Mechanical scraping, decortication, or retting can retain bundle lengths of several centimetres, and sometimes much more. These feedstocks usually contain a substantial cellulose fraction and show useful axial strength without competing directly with food production. Their main processing problems are coarse bundles, residual pectin and hemicellulose, and high bending rigidity. When insufficiently opened fibers are fed into a cotton system, they tend to form clumps, draft unevenly, and increase end breaks. The choice between long-fiber spinning, controlled cutting and blending, wrapped yarns, and nonwoven formation should therefore be based on length, fineness, and cohesion rather than on the pursuit of the highest possible pure-fiber content.

Cereal straw, corn stalks, and sugarcane bagasse have a different structure. Their individual cells are short and remain embedded in tissues containing lignin, hemicellulose, and inorganic ash. After mechanical separation, the fibers are rarely long or uniform enough for conventional spinning. Conversion into high-purity cellulose pulp, followed by dissolution and regeneration into filaments or staple fibers, is usually more compatible with the feedstock. This route removes the natural length constraint but introduces stricter requirements for alpha-cellulose content, degree of polymerization, ash, metal ions, and reaction uniformity. Black-liquor treatment, bleaching intensity, and solvent recovery strongly influence both environmental performance and cost.

Coconut coir, oil-palm residues, coffee husks, and some straw fibers contain more lignin and are relatively stiff and moisture resistant. Stronger degumming does not necessarily provide the fineness and softness needed for next-to-skin clothing. In needle punching, wet-laid processing, thermal bonding, or resin composites, however, their pores, rough surfaces, and hollow structures can support sound absorption, filtration, thermal insulation, and reinforcement. Agricultural residues should therefore be assigned according to material fit: long and flexible fibers can enter yarn routes, whereas short, coarse fibers can retain the structural features that make them useful elsewhere. Table 1 summarizes representative feedstocks, preferred routes, and main limitations.

Feedstock	Main source	Fiber-form characteristics	Preferred textile route	Main technical limitation
Pineapple leaves	Leaves remaining after fruit harvest	Axially aligned long bundles; high strength; relatively coarse	Mechanical separation - degumming - blending; long-fiber spinning or nonwoven formation	Residual gum, stiffness, variation in fineness, and seasonal collection
Banana pseudostems/peduncles	Pseudostems and peduncles after harvest	Long bundles mixed with parenchyma; high moisture uptake	Biological retting or mechanical separation - softening - blending or cordage fabrics	High moisture, rapid decay, extraction damage, and batch variation
Cereal straw	Post-harvest stems	Short elementary fibers; high ash and silica	Pulping - dissolution spinning; wet-laid webs and filling materials	Silica removal, purification, pulp reactivity, and black-liquor treatment
Corn husks/stalks	Ear husks and stems	Sheets or short fibers; can yield cellulosic slurry	Cut-fiber blends, pulp regeneration, or nonwovens	Low bulk density, high storage/transport cost, and inconsistent properties
Sugarcane bagasse	Residue after sugar extraction	High fraction of short fibers; relatively concentrated supply	Pulp - regenerated cellulose; wet-laid nonwovens	Lignin removal, degree-of-polymerization control, and energy use

Coconut coir/oil-palm residues	Fruit shells and leaf sheaths	Coarse, stiff, lignin-rich, and moisture resistant	Needle-punched or thermally bonded nonwovens, thermal/acoustic materials, and composites	Poor apparel handle, costly refinement, and dark colour
Coffee and other fruit husks	Husks remaining after processing	Mixture of short fibers and particles; porous and irregular	Acoustic/thermal nonwovens, filling, and composites	Impurities, odour, particle size, and variable fiber fraction

Table 1 Resource characteristics and preferred textile routes of representative agricultural-residue fibers

III. GREEN EXTRACTION AND DEGUMMING TECHNOLOGIES

Mechanical separation performs the first stage of feedstock cleaning. Rollers, blades, or toothed drums remove leaf tissue, pith, and parenchyma. The operation is short and uses few chemicals, which makes it a practical starting point for continuous processing of pineapple leaves and banana pseudostems. Fiber-length retention is sensitive to machine settings: a narrow roller gap, unstable feeding direction, or unsuitable moisture content can cause transverse cuts and longitudinal splits. Reviews of plant-fiber separation note that mechanical methods raise throughput but do not fully remove pectin, hemicellulose, and waxes; degumming or surface cleaning is usually still required [7].

Water and dew retting rely on naturally occurring microorganisms to break down the gums surrounding fiber bundles. The equipment requirement is low. Hazarika et al. mechanically decorticated pineapple leaves, retted them in water for about 7 days, and produced yarn on jute-processing equipment [8]. Chaves et al. biologically retted Azorean pineapple leaves for 14 days at 25 degrees C. The resulting fibers had diameters of 34.9-168.3 micrometres, linear densities of 1.39-7.07 tex, and tensile strengths of 37-993 MPa [9]. These broad ranges show the combined influence of leaf position, feedstock age, and retting condition. Natural retting is suitable for primary treatment near the place of harvest, but weather, microbial communities, and water quality can affect each batch. Open-water retting also generates wastewater with a high organic load, so water recirculation and endpoint control are needed.

Alkaline treatment removes gums quickly and remains one of the most established routes for refining bundle fibers. Alkali saponifies waxes and dissolves pectin together with part of the hemicellulose. Moderate treatment roughens the surface and improves wetting, which can help later spinning or compounding. As concentration, temperature, or time increases, cellulose peeling reactions become more severe and reduce both degree of polymerization and strength. A single high-alkali step often removes several non-cellulosic components at once and leaves a narrow operating window. Production control should therefore consider fiber refinement, length retention, and functional-component retention together.

Liao et al. used stepwise degumming to adjust lignin and hemicellulose in pineapple leaf fibers. For the Queen cultivar, hemicellulose fell from 23.49% to 4.89%, fiber width decreased from 45-75 micrometres to 16.7 micrometres, and the refinement degree increased by 72.2%. Inhibition against three microorganisms remained above 90% [10]. The combination of narrower fibers and retained antibacterial activity suggests that apparel-grade degumming can work within a controlled residual-gum range; complete removal of every non-cellulosic component is unnecessary. Stepwise processing adds tanks and control points, but it also reduces strength loss caused by over-treatment and is better suited to high-value products that require both handle and function.

After mechanical extraction, banana pseudostem fibers still carry pectin, hemicellulose, and lignin and often feel stiff. Badanayak et al. concluded that mechanical extraction is efficient, but surface modification is still needed to reduce bundle rigidity and moisture sensitivity [11]. Anafack et al. compared water retting, dew retting, and mechanical extraction of William banana peduncle fibers and found changes in linear density, crystallinity, and mechanical behaviour [12]. Extraction is therefore part of property development rather than a simple cleaning step.

Enzymatic and microbial treatments operate under milder conditions and usually damage the cellulose backbone less than severe alkaline treatment. They also produce lower inorganic salt loads in wastewater. Subash and Perumalsamy screened a biological treatment for banana pseudostem waste and demonstrated its use in textile-fiber preparation [13]; later work used the treated banana fibers in yarn manufacturing [14]. Manjusha et al. softened banana fibers with cellulase and pectinase from Aspergillus niger. The best overall properties were obtained after 2-4 h, while treatments lasting 24-48 h reduced both fiber diameter and strength [15]. Biological degumming therefore has a definable endpoint; longer treatment does not automatically improve spinning performance.

Scale-up of biological processing requires treatment time, enzyme use, and strength retention to be evaluated together. Low enzyme dosage and mild temperature help preserve length and strength but slow production. Higher dosage shortens the reaction yet increases enzyme cost and creates problems of deactivation and recovery. A more practical sequence is mechanical pre-opening, followed by a low-dose enzyme blend to remove the main gums, with short physical-field assistance when needed. Reducing sugars, dissolved gums, and image-based bundle separation can be used together to identify the endpoint and reduce batch variation caused by fixed treatment times.

Ultrasound, microwave heating, steam explosion, low-temperature plasma, and high-pressure homogenization are generally used as intensification steps. They improve mass transfer or weaken bonding within fiber bundles and can shorten enzyme or low-alkali treatment. Equipment investment and specific energy use must still be assessed. Excessive intensity turns opening into fiber cutting. For long bundles intended for direct spinning, settings should be limited to local loosening and length preservation. Pulp and nanocellulose routes depend less on natural fiber length and can tolerate stronger disintegration.

Deep eutectic solvents, ionic liquids, and recyclable organic acids can selectively remove lignin, and some systems can dissolve cellulose directly. These options create new routes for producing high-purity pulp and regenerated fibers from agricultural residues. Laboratory studies commonly report delignification or dissolution efficiency, whereas industrial assessment must also include solvent synthesis, recovery and purification, water sensitivity, equipment corrosion, and residue treatment. Most systems remain at laboratory or pilot scale. At present they are more realistic as supplementary routes for high-purity pulp and functional fibers than as replacements for mature alkaline processes.

The available technologies differ in their emphasis on length retention, gum removal, processing rate, and cost. Table 2 compares them within a common framework and indicates the feedstocks and production roles for which each is most suitable.

Technology	Main action	Effect on fiber quality	Environmental and cost features	Suitable feedstocks	Scale-up assessment
Mechanical decortication	Removes leaf tissue, pith, and woody matter	Length retention depends on machine gap; residual gum remains	Few chemicals and high throughput; moderate wear and energy use	Pineapple leaves and banana pseudostems	Best used as a continuous front-end operation
Water/dew retting	Microbial breakdown of pectin and gums	Limited damage but high batch variation	Low direct cost and long cycle; water retting has a high organic load	Leaf fibers, pseudostems, and bast-type materials	Suitable near the feedstock source with process control
Alkaline degumming	Dissolves pectin, hemicellulose, and part of the lignin	Strong refinement; over-treatment degrades cellulose	Mature and fast, but alkali, water, and saline effluent loads are high	Most lignocellulosic feedstocks	Commercially usable; should move toward lower alkali and water recycling
Enzyme blends	Selective hydrolysis of pectin and hemicellulose	Good strength retention and improved softness	Mild and low-pollution; enzyme cost and reaction time remain high	Banana, pineapple, and bast fibers	Promising for high-value fibers; enzyme recovery and continuous processing are needed
Microbial retting	Microbial communities produce several gum-degrading enzymes	Clean surface; result depends on the microbial community	Low chemical use; long cycle and hygiene control are required	Banana pseudostems and peduncles	Better suited to closed bioreactors
Physical-field assistance	Improves mass transfer and weakens bundle bonding	Shortens processing; excessive intensity cuts fibers	Higher equipment investment; specific energy must be assessed	Several feedstocks, coupled with chemical or enzyme treatment	Useful as an intensification step rather than a stand-alone process
Emerging green solvents	Selective delignification or cellulose dissolution	Can produce high-purity pulp or regenerated-fiber dope	Solvent recovery determines environmental and economic performance	Pulp feedstocks such as straw and bagasse	Currently more suitable for pilot-scale and high-value applications

Table 2 Comparison of major extraction and degumming technologies

IV. SPINNABILITY CONTROL AND SPINNING-SYSTEM MATCHING

The yarn performance of long bundles is governed by several interacting variables; single-fiber tensile strength describes only one of them. Excess residual gum keeps bundles stuck together and hinders opening and drafting. Too little gum can cause excessive splitting, shorter fibers, and more hairiness. Coarse fibers with high bending rigidity make fewer effective contacts in the strand and provide less cohesion. Degumming should therefore be evaluated through residual-gum content, linear density, length distribution, bending rigidity, surface friction, and actual drafting and end-break behaviour.

Pineapple leaf fibers have sufficient intrinsic strength to permit some refinement, but leaf-position differences create wide distributions of linear density and strength [9]. Stepwise degumming can reduce bundle width toward the scale of coarse elementary fibers while retaining part of the antibacterial effect associated with lignin [10]. A similar approach can be applied to banana fibers: remove most parenchyma first, then use pectinase, hemicellulase, and low-concentration alkali in stages. The endpoint should be set from the target yarn count, handle, and length retention. Complete degumming is not a suitable universal criterion.

Bundles with adequate length but poor uniformity can be stretch-broken or cut to cotton- or wool-type lengths before blending. Jalil et al. used existing machinery to produce 121 tex and 138 tex yarns from 100% pineapple leaf fiber. They also spun 30 tex cotton/pineapple blends at 90/10 and 80/20 on cotton equipment and wove plain and twill fabrics [16]. The work shows that pineapple leaf fiber can enter conventional systems, although pure-fiber yarns remain coarse. Adding cotton lowers bundle rigidity and improves processing stability.

Blending with another natural fiber can also reduce the variability of banana fibers. Soraisham et al. processed Indian banana fiber with ramie, using the more stable length and spinnability of ramie to support the blended sliver [17]. For apparel, cotton, Lyocell, or viscose can improve softness and moisture uniformity. Small amounts of polyester or bio-based polyester may provide a structural framework when abrasion resistance and dimensional stability are important. Blend selection should be based on yarn strength, unevenness, hairiness, fabric handle, and environmental targets rather than on maximizing the agricultural-residue fraction.

Feedstock variation does not disappear during extraction. Cultivar, maturity, leaf position, and storage time can later appear as higher end-break rates and visible fabric variation. Industrial control can begin by separating feedstocks according to origin and maturity, followed by physical grading for length, linear density, and colour. Residual gum, moisture content, and strength can then guide the choice of spinning system. Machine vision can estimate bundle width and impurity content on the decortication line, while conductivity, a chemical-oxygen-demand proxy, and image-based separation may help identify the degumming endpoint. Figure 2 links feedstock assessment, extraction, property adjustment, spinning, and product validation and shows how quality is transferred from one stage to the next.

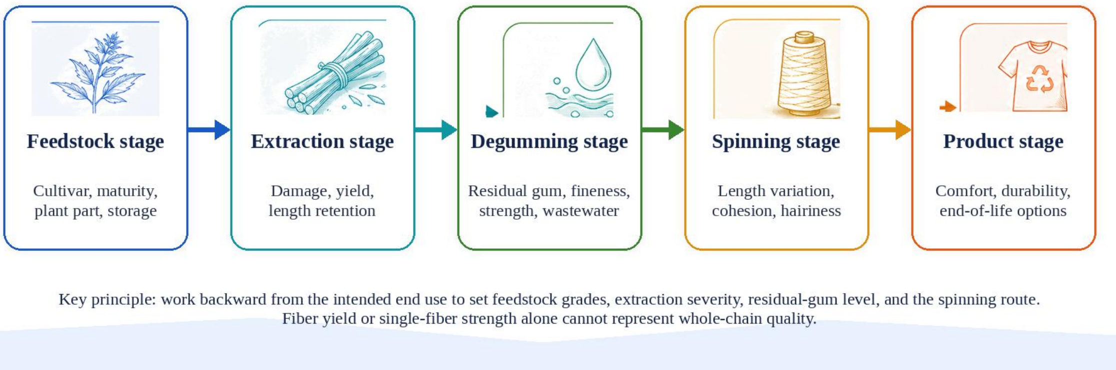

Figure2 Whole-chain quality control for agricultural-residue plant fibers

Results obtained under different extraction conditions should not be ranked by strength alone. Table 3 lists processing conditions, key properties, practical implications, and unresolved problems so that the textile relevance of each study can be compared more directly.

Feedstock/study	Process or product	Key result	Main implication	Unresolved issue
Pineapple leaf fiber [8]	Mechanical separation + about 7 d water retting; jute-system spinning	Fibers were processed into textile yarn	Natural retting can be combined with established long-fiber equipment	Cycle time and water-pollution control require improvement
Azorean pineapple leaf fiber [9]	Biological retting for 14 d at 25 degrees C	Diameter 34.9-168.3 micrometres; strength 37-993 MPa	Feedstock position and maturity must be graded	Very broad property distribution
Pineapple leaf fiber [10]	Stepwise selective degumming	Width reduced to 16.7 micrometres; refinement +72.2%; inhibition >90%	Refinement and retention of natural function can be balanced	More processing steps; industrial cost remains unverified
William banana peduncle [12]	Comparison of water retting, dew retting, and mechanical extraction	Extraction method changed structure and textile properties	Extraction should be selected for the intended end use	Climate and feedstock batch have a marked influence
Banana pseudostem fiber [15]	Cellulase/pectinase softening for 2-48 h	Best overall performance at 2-4 h; strength fell after long treatment	Enzyme treatment needs precise endpoint control	Enzyme cost and lack of continuous processing

Pineapple leaf yarn [16]	Pure-fiber and cotton-blend spinning	100% yarns at 121 and 138 tex; 90/10 and 80/20 cotton/PALF at 30 tex	Blending improves compatibility with conventional equipment	Pure-fiber yarn is coarse and handle needs improvement
Banana/ramie [17]	Blended processing	Ramie improved sliver stability	Combining compatible natural fibers is a workable route	Industrial blend ratios and durability need systematic validation

Table 3 Representative processing results and their implications for textile utilization

V. FABRICS AND END-USE PRODUCTS

Pineapple leaf and banana fibers have a natural lustre, moisture uptake, and useful axial strength. They can be used in summer shirts, decorative fabrics, footwear components, and luggage materials. Their use in clothing is limited mainly by prickliness, bending rigidity, weak crease recovery, and changes in hairiness after washing. Fabrics made entirely from these fibers retain a pronounced natural texture and regional character. For larger production runs, blends with cotton, Lyocell, viscose, or fine-denier polyester are usually easier to process and provide a better handle. Evaluation should extend beyond breaking strength to bending, shear, compression, surface friction, air permeability, moisture transport, and dimensional change after repeated washing.

Leather-like sheets are among the agricultural-residue products most readily recognized by consumers. They are usually multilayer structures made from a fiber web, binder, coating, and base fabric, and should not be described as a single plant-fiber material. Sustainability claims need to state the bio-based content, binder type, whether the coating can be separated, and the treatment route at end of life. A product name referring to pineapple leaves or banana plants cannot, by itself, establish the degradability of the whole composite.

Nonwoven processing allows short and coarse fibers to bypass the strict length and fineness uniformity required by conventional spinning. Gaminian et al. reviewed agricultural and forestry residues used in needle-punched, wet-laid, air-laid, and thermally bonded nonwovens and found that pretreatment, fiber length, and bonding method jointly control web uniformity and final strength [18]. Coffee-husk fibers and cotton-spinning waste contain many pores that lengthen sound-transmission paths. Periyasamy et al. used these materials in nonwovens and demonstrated their potential for acoustic and thermal insulation [19].

Agricultural covers, disposable horticultural substrates, and short-life geotextiles are also compatible with some natural short fibers. These products need to remain intact for a defined service period and then lose strength gradually; long-term durability is not always the primary aim. Lignin content, web bonding, and environmental humidity together determine the rate of failure. A structure that breaks down too early cannot perform its intended function, while a persistent binder may extend service life at the expense of the environmental benefit.

When natural fibers are too short or irregular for direct spinning, pulp regeneration offers a more suitable route. Plakantonaki et al. grouped cellulose-fiber production from agricultural waste into direct separation and purification of natural fibers, and pulping followed by manufacture of man-made cellulose fibers [20]. Frazier et al. noted that non-wood feedstocks differ from wood pulp in ash, silica, lignin composition, and degree-of-polymerization distribution. Pretreatment must therefore be designed around dissolving-pulp reactivity and dope filtration [21]. The ability to produce a stable pulp is more important here than the initial natural-fiber length.

Pulp can be converted into regenerated staple fibers, filaments, micro- and nanocellulose, functional membranes, and composite spinning feedstocks. The wider product range comes with a longer process chain. Low-cost or free residues do not automatically yield low-cost pulp. Collection radius, cleaning, drying, use of pulping by-products, and solvent recovery all affect the final cost. Agricultural-residue pulp can compete with wood pulp only when supply is concentrated, continuous processing is stable, and the recovery system is mature.

VI. ENVIRONMENTAL AND ECONOMIC FEASIBILITY

A waste origin describes the feedstock, not its environmental performance. Using agricultural residues for fiber production can reduce the land needed for dedicated fiber crops, but the former use of the residue must still be counted. If straw was previously returned to soil, used as feed, or converted to energy, its transfer to textiles may create replacement inputs elsewhere. Long transport distances and high moisture content can also offset part of the benefit through drying and transport energy. Chemical degumming, bleaching, dissolution spinning, and dyeing remain water- and emission-intensive stages.

Gonzalez et al. compared the life-cycle impacts of six natural and synthetic fibers and found pronounced differences among fiber types and processing stages in land occupation, water use, energy demand, and emissions [22]. Environmental reporting for agricultural-residue fibers should at least cover energy, water, chemicals, wastewater load, usable fiber yield, and by-product destinations from collection to the factory gate.

The functional unit should also reflect product life and the function replaced; mass-based data alone cannot represent value in use.

The purchase price of the residue is only one part of the cost. Field collection, baling, removal of impurities, short-term preservation, transport, mechanical separation, drying, degumming, wastewater treatment, grading, and rejects all enter the calculation. Banana pseudostems have a high moisture content, so centralized transport moves large quantities of water. A more efficient arrangement is primary separation and dewatering near the farm, followed by regional finishing. Pineapple leaves can be stored for a short period more easily, but leaf age, cultivar, and seasonal changes still require contracted supply and batch control.

Each product route has a different quality threshold and scale requirement. Apparel yarns demand the greatest fineness, cleanliness, and softness and may command higher prices, but they also carry the highest yield risk. Thermal, acoustic, and agricultural nonwovens accept a wider fineness range and can absorb early production. Pulp and regenerated-cellulose routes depend on scale economies and require a stable bulk supply together with a mature chemical-recovery system. Project calculations should work backward from the cost allowed by the target product to the economic collection radius, qualified-fiber yield, and unit processing cost. Regional theoretical residue volume is only a preliminary indicator.

Names, composition labels, and test methods remain inconsistent in the market. Bundle fibers contain cellulose, hemicellulose, and lignin, while finished products may also contain cotton, viscose, polyester, binders, or coatings. Labels such as 'pineapple fiber fabric' or 'banana fiber fabric' do not reveal the true fiber content or the composite structure. Product information should specify feedstock origin, extraction method, fiber fraction, binder or coating composition, and the environmental conditions required for degradation.

Testing can be organized by material level. Fiber tests should include length, linear density, strength, residual gum, moisture content, and ash. Yarn tests should cover unevenness, hairiness, breaking force, and elongation. Fabric assessment should include handle, abrasion resistance, washing stability, and thermo-moisture comfort. Environmental evaluation requires a stated life-cycle boundary and clear degradation conditions. The feedstock story becomes useful for purchasing, quality control, and market communication only when it is supported by reproducible data. Table 4 combines supply, processing quality, product performance, environmental load, and economic results as linked levels for screening industrial routes.

Assessment level	Core indicators	Common error	Recommended criterion
Feedstock supply	Annual collectible amount, moisture, seasonality, collection radius, and competing uses	Using theoretical regional output as the available amount	Calculate monthly supply within an economic transport radius
Extraction and degumming	Qualified fiber yield, length retention, residual gum, wastewater load, and energy use	Reporting only extraction yield or single-fiber strength	Use the yield of qualified spinnable fiber as the main indicator
Spinning	Lap/sliver formation, end breaks, unevenness, hairiness, and yarn strength	Extrapolating industrial stability from a small laboratory yarn batch	Validate several continuous batches and report variation
Product performance	Handle, durability, comfort, function retention, and washing stability	Replacing standard tests with claims of natural antibacterial or moisture properties	Apply product-specific standards and repeated-washing tests
Environmental performance	Water, energy, chemicals, carbon emissions, by-products, and end-of-life route	Treating natural or waste-derived origin as proof of environmental benefit	Use an explicit functional unit and life-cycle system boundary
Economic performance	Cost per unit of qualified fiber, yield, selling price, and capacity utilization	Ignoring collection, wastewater treatment, and quality-loss costs	Perform separate sensitivity analyses for each product route

Table 4 Industrialization assessment indicators for agricultural-residue plant fibers

VII. CONCLUSIONS AND OUTLOOK

There is no single textile route for all agricultural residues. Pineapple leaves, banana pseudostems, and peduncles can retain long bundles and may enter yarn and fabric production after gentle separation, controlled degumming, and blending. Cereal straw and sugarcane bagasse contain naturally short fibers and are better converted into pulp before cellulose regeneration. Coconut coir, coffee husks, and other coarse, lignin-rich fibers can use their stiffness and pore structure in nonwovens, thermal and acoustic insulation, and reinforced composites. Technical and economic feasibility depends on the match between feedstock structure and product requirements.

Green extraction requires a measurable balance among length retention, residual gum, fineness, strength, treatment time, energy use, and wastewater load. Stepwise degumming, enzyme blends, closed microbial retting, and physical-field assistance all have value, but continuous equipment, affordable enzymes, endpoint monitoring, and water recirculation remain weak points during scale-up. Apparel fibers also need to be evaluated for bending rigidity, surface hairiness, yarn unevenness, and handle after washing. High single-fiber strength indicates potential; it does not replace spinning and fabric validation.

Further work should proceed along four connected lines: feedstock data, process design, validation scale, and environmental-economic evidence. Cultivar, maturity, plant part, and storage condition should be linked batch by batch with fiber length, fineness, residual gum, and strength to create practical grading rules. Treatment endpoints should be set from the target yarn count and product handle instead of using fixed severe conditions. Tonne-scale continuous runs and multi-batch spinning trials are needed to expose yield losses and quality variation that small laboratory samples cannot show. Life-cycle assessment, techno-economic analysis, verified bio-based content, and end-of-life options should enter product design from the start. These steps are necessary before agricultural-residue fibers can move from an appealing feedstock concept to a dependable textile supply.

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