



# Green Synthesis of High-Aspect-Ratio Nanofibers from Pineapple Leaf (*Ananas comosus*) Waste: A Sustainable Alternative to Synthetic Mineral Fibers.

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Received:20 January 2026; Revised: 08 February 2026; Accepted: 15 March 2026; Available online: 10 April 2026

**Abstract:** This review explores the transformative potential of Pineapple Leaf Fibers (PALF) as a sustainable, non-toxic alternative to hazardous synthetic mineral fibers like asbestos through the lens of green nanotechnology. As the global industry seeks to mitigate the carcinogenic risks of traditional fibers and manage the millions of tons of agricultural waste generated annually, PALF emerges as a high-performance candidate due to its exceptional cellulose content and mechanical strength. We examine a multi-stage green synthesis pathway that replaces harsh industrial chemicals with biological extraction, organic acid scouring, and high-pressure homogenization to produce nanofibers with high aspect ratios. These bio-based nanofibers effectively mimic the structural reinforcement and thermal stability of asbestos while ensuring biocompatibility and eliminating environmental persistence. The paper further evaluates the functionalization of PALF scaffolds with metallic nanoparticles via plant-mediated reduction for applications in green construction, lightweight automotive bio-composites, and heavy-metal water filtration. Despite challenges in industrial scaling and natural hydrophilicity, the integration of PALF into a circular economy framework offers a robust roadmap for phasing out toxic minerals in favor of biodegradable, high-value engineering materials.

**Index Terms:** Agricultural Waste Management, Cellulose Nanocrystals (CNCs), Green Synthesis, High Aspect Ratio, Nano fibrillation, Pineapple Leaf Fibers (PALF).

## 1 INTRODUCTION

The shift from hazardous mineral fibers to plant-based nanotechnology represents a pivotal moment in materials science[1]. To understand this transition, we must first look at the legacy of synthetic mineral fibers like asbestos. While these minerals were once prized for their incredible tensile strength and heat resistance, their microscopic structure stiff, needle-like fibers are biologically devastating. When inhaled, these fibers lodge deep within lung tissue, resisting the body's natural clearing mechanisms and eventually causing chronic inflammation or fatal diseases like mesothelioma. Simultaneously, the global agricultural sector generates millions of tons of pineapple leaf annually. Most of this biomass is burned or left to rot, which releases greenhouse gases and represents a massive loss of high-strength natural polymers[2].

The solution lies in the structural "blueprints" found within the pineapple leaf. Pineapple Leaf Fibers (PALF) are naturally rich in cellulose, a polymer that provides plants with their rigid structure. By applying green nanotechnology, we can break these raw fibers down into Cellulose Nanocrystals (CNCs) or nanofibers. These nano-scale building blocks possess a high "aspect ratio" meaning they are very long compared to their

width mimicking the physical reinforcement properties of asbestos. However, unlike mineral fibers, these cellulose-based nanomaterials are biocompatible and biodegradable. Because they are synthesized using "green" methods using water-based processes or natural plant extracts instead of harsh industrial acids, the resulting material is safe for both the manufacturer and the end consumer.

The core objective of this research is to bridge the gap between agricultural waste management and advanced materials engineering. This review explores the specific mechanical pathways required to peel away the protective layers of lignin and hemicellulose from the pineapple leaf to reveal the crystalline core of the fiber. Furthermore, we examine how these fibers can be "functionalized," or coated with other eco-friendly nanoparticles as shown in Fig. 1, to enhance their fire resistance and strength. By comparing the thermal and mechanical performance of these green-synthesized PALF derivatives against traditional asbestos, we can provide a roadmap for an industrial future where high-performance construction and automotive materials are harvested from the earth rather than mined from it[3][4][5][6].

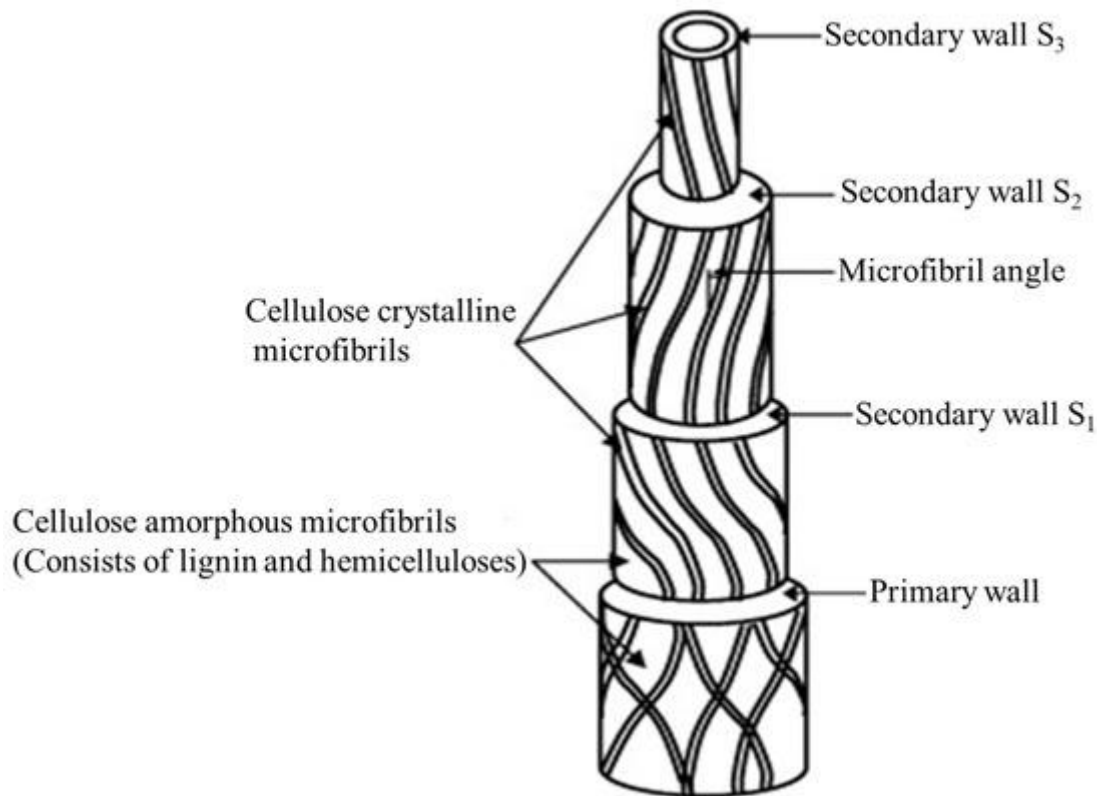


Fig. 1. Recent Developments of Pineapple Leaf Fiber (PALF) Utilization in the Polymer Composites [5]

## 2. EXTRACTION AND PRE-TREATMENT OF PALF

The transformation of raw pineapple leaves into high-performance nanofibers begins with mechanical extraction, a process designed to isolate the long, sturdy bundles of fiber from the fleshy green pulp. The most common method is decortication, where the leaves are fed through a series of rollers and scrapers as shown in Fig. 2. This physical shearing action strips away the outer waxy cuticle and the internal soft tissues, leaving behind "raw" Pineapple Leaf Fibers (PALF). While these fibers are incredibly strong at a macroscopic level, they are still coated in natural "glues" such as lignin, hemicellulose, and pectin. These binders must be removed to unlock the nano-scale potential of the plant, much like stripping the insulation off a cable to reach

the conductive wires inside[7][8].

Traditional industrial cleaning involves harsh caustic soda (NaOH) which can be environmentally damaging, but green nanotechnology utilizes biological and organic alternatives to achieve the same goal. In this eco-friendly cleaning phase, organic acids derived from citrus or microbial enzymes (like cellulase and xylanase) are used to selectively digest the lignin and hemicellulose. This process is often referred to as "surface functionalization" or "scouring." By using these biocatalysts, the bonds holding the fiber bundles together are weakened without damaging the crystalline structure of the cellulose itself. This step is crucial because it ensures the final nanomaterial remains biodegradable and non-toxic, unlike the chemically treated synthetic fibers used in the past[8][9][10].

The final and most technically advanced stage is nano-fibrillation, where the cleaned macro-fibers are literally "shattered" into nanofibers. This is typically achieved through high-pressure homogenization or ultrasonication. In ultrasonication, high-frequency sound waves create microscopic vacuum bubbles in a liquid medium that implode with immense force a phenomenon known as cavitation. This force peels apart the individual microfibrils from the main fiber body. The result is a transition from a visible thread to a suspension of nanofibers that possess the needle-like morphology of asbestos but with the biological safety of a plant. These nanofibers exhibit an incredibly high surface area, allowing them to bond effectively with polymers to create the next generation of "green" reinforced composites.'

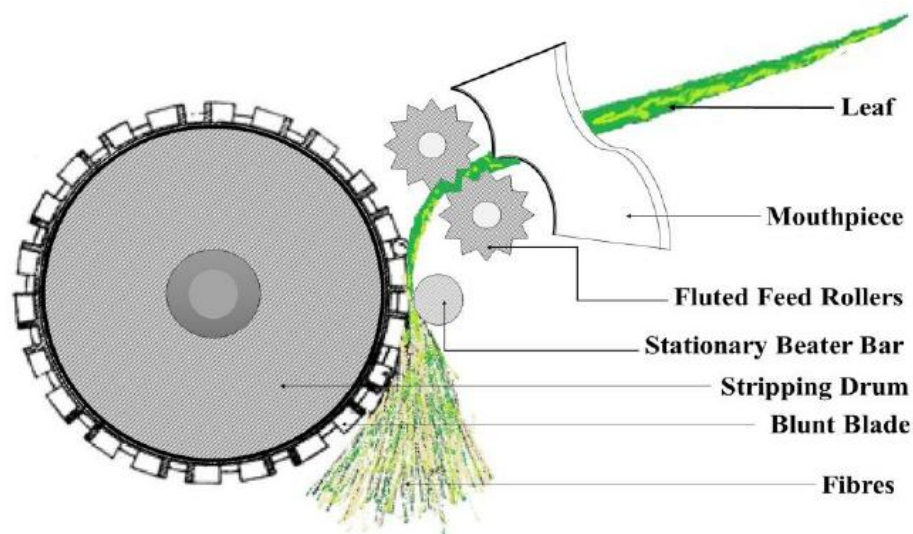


Fig. 2 . Pineapple Leaf

extraction machine mechanism

Fiber

### 3. GREEN SYNTHESIS MECHANISMS

The chemical "magic" of green synthesis occurs through a process called biological reduction, where the natural juices or extracts from pineapple peels and leaves replace hazardous laboratory chemicals. These plant extracts are packed with bioactive molecules like polyphenols, flavonoids, and organic acids. When these extracts are mixed with metal salts (such as silver nitrate or zinc acetate), the molecules act as "reducing agents," donating electrons to the metal ions to transform them into solid nanoparticles. Simultaneously, these same plant molecules act as "capping agents," coating the new nanoparticles to prevent them from clumping together. This entire reaction happens in water at room temperature, eliminating the need for toxic solvents or high-energy furnaces[11][12][13].

Once these nanoparticles are formed, the Pineapple Leaf Fiber (PALF) serves as a biological "scaffold" or skeleton for nanocomposite formation. Because the surface of the nanocellulose is covered in hydroxyl groups, it acts like a microscopic Velcro, allowing the newly synthesized silver (Ag) or zinc oxide (ZnO) nanoparticles to anchor firmly onto the fiber's surface. This creates a hybrid material where the PALF provides the structural "muscle" and the nanoparticles provide "functional" properties, such as the ability to kill bacteria or block ultraviolet (UV) radiation. By using the fiber as a template, we ensure that the inorganic nanomaterials are evenly distributed, preventing the structural weaknesses often found in poorly mixed synthetic composites[14].

The most significant breakthrough in this research is the concept of "Nano-Asbestos Mimicry." In materials science, the strength of a reinforcing fiber is determined by its aspect ratio of its length to its diameter. Asbestos was industrially successful because its fibers were incredibly long and thin, allowing them to weave into a tight, unbreakable matrix. PALF-derived nanofibers mimic this exact physical geometry, providing the same mechanical "interlocking" strength and thermal resistance. However, the critical difference lies in bio-persistence. While asbestos is a mineral that the human body cannot dissolve, PALF is made of cellulose. If a green nanofiber is inhaled, the body's enzymes and immune cells can eventually break down the organic polymer into simple sugars, removing the risk of the long-term scarring and inflammation that makes asbestos so deadly[14].

### 3.1 Step of Green Synthesis Mechanisms

#### Step 1: Pre-treatment and Extraction

The process begins with the collection of pineapple leaves, which are typically discarded after harvest. Through mechanical decortication, the tough, fibrous structural ribbons are separated from the soft leaf tissues. This raw fiber is then washed to remove surface contaminants like dust and pesticides, preparing the cellulose bundles for chemical refinement.

#### Step 2: Delignification (Green Scouring)

In this phase, the goal is to remove the "natural glue" lignin and hemicellulose that binds the cellulose fibers together. Instead of using harsh industrial alkalis, this is achieved using organic acids (like acetic or citric acid) or enzymatic cocktails. This step "unpacks" the fiber bundles, exposing the high-strength crystalline cellulose cores that provide the material's structural integrity.

#### Step 3: Synthesis of the Nanofiber Scaffold

The cleaned fibers undergo high-pressure homogenization or ultrasonication. The intense physical energy breaks the micro-scale fibers into nano-scale filaments. These resulting nanofibers possess a high aspect ratio, mimicking the needle-like geometry of asbestos. This creates a bio-based "scaffold" that is ready to be functionalized with other properties.

#### Step 4: Biological Reduction and Capping

To give the fibers advanced properties (like fire resistance or antimicrobial power), they are submerged in a solution containing metal salts and pineapple leaf/peel extract. The phytochemicals in the extract reduce the metal ions into solid nanoparticles that anchor directly onto the nanofiber surface. The extract also "caps" these particles, ensuring they remain stable and do not clump, completing the synthesis of the green nanocomposite.

## 4. COMPARATIVE ANALYSIS: PALF VS. ASBESTOS

Table 1 below presents a comparative overview of key properties between conventional asbestos fibers and

PALF-based nanofibers, including their origin, health impact, biodegradability, mechanical strength, and thermal performance.

Table 1. Comparative Analysis: PALF vs. Asbestos [15], [16], [17], [18], [19], [20]

Property	Asbestos (Mineral)	PALF Nanofibers (Green)
Origin	Mined Mineral	Agricultural Waste
Health Risk	Carcinogenic (Mesothelioma)	Biocompatible / Non-toxic
Biodegradability	Non-biodegradable	Fully Biodegradable
Tensile Strength	Extremely High	High (Comparable at Nanoscale)
Thermal Stability	Excellent	Good (Enhanced with green coatings)

## 5. INDUSTRIAL APPLICATIONS

The industrial application of Pineapple Leaf Fiber (PALF) nanofibers is most transformative within the construction sector, specifically as a direct replacement for hazardous asbestos in roofing and structural reinforcement. In modern "green concrete," these nanofibers act as a microscopic rebar system. Because of their high aspect ratio and crystalline strength, they interlock within the cement matrix to prevent micro-cracks from spreading under mechanical stress. When used in roofing sheets, PALF-derived composites provide the same fire resistance and durability as traditional asbestos sheets but without the risk of releasing carcinogenic dust during installation or weathering. This allows us to produce low-cost, high-performance building materials that are entirely safe for residential use[21][22].

In the automotive industry, the drive toward "lightweighting" to improve fuel efficiency and reduce carbon emissions has made PALF nanofibers an ideal candidate for interior bio composites. Traditional car interiors often rely on glass fibers or heavy plastics, which are difficult to recycle. By incorporating PALF nanofibers into polymer matrices, manufacturers can create door panels, dashboards, and headliners that are significantly lighter yet possess the structural rigidity required for safety. These bio composites also offer superior acoustic insulation and vibration damping compared to synthetic mineral fibers. Furthermore, at the end of the vehicle's life cycle, these components are easier to process and do not leave behind the persistent environmental footprint of synthetic mineral-based materials[23].

Beyond structural uses, the environmental sector leverages the high surface area of functionalized PALF nanofibers for advanced water purification. Through green synthesis, these fibers can be coated with nanoparticles like iron oxide or silver, turning the fiber into a powerful "chemical magnet" for heavy metal filtration. As contaminated water passes through a PALF-based membrane, the functionalized surface captures toxic ions such as lead, arsenic, and mercury through a process called adsorption. This method is particularly revolutionary for developing nations where pineapple waste is abundant; it turns a local agricultural byproduct into a low-cost, biodegradable solution for providing clean drinking water, effectively solving two environmental problems waste management and water toxicity simultaneously[24], [25], [26].

## 6. CHALLENGES AND FUTURE PERSPECTIVES

While the transition to green nanotechnology offers a sustainable escape from the hazards of mineral fibers,

moving from successful laboratory prototypes to global industrial standards involves overcoming significant technical and systemic hurdles. The primary challenge is scaling up: while a lab can produce small, high-purity batches of nanocellulose through precision ultrasonication, doing so at an industrial volume of thousands of tons per year is incredibly energy-intensive. To make Pineapple Leaf Fiber (PALF) a viable competitor to mass-produced minerals, engineers are currently developing continuous-flow high-pressure homogenizers and industrial-scale enzymatic reactors. These systems aim to lower the "per-kilogram" energy cost while maintaining the uniform fiber length and width necessary to replicate the mechanical strength of asbestos[2], [4], [17], [21], [22].

A secondary technical hurdle is the natural hydrophilicity, or water-loving nature, of plant fibers. Unlike asbestos, which is naturally resistant to moisture, raw PALF contains high amounts of hydroxyl groups that readily absorb water. This can cause the fibers to swell, potentially weakening the structures they are meant to reinforce or leading to rot in high-humidity environments. To address this, the future of PALF research is focused on "green grafting." By using non-toxic surface treatments such as sialylation or acetylation researchers can create a microscopic waterproof "raincoat" around each nanofiber. This ensures that the green composite remains stable and durable even when used in outdoor construction or automotive parts exposed to the elements.

The final, and perhaps most critical, perspective involves the shift toward a circular economy policy. Global regulations are increasingly moving to phase out hazardous minerals entirely, creating a "policy vacuum" that PALF-based technology is uniquely positioned to fill. By treating agricultural waste as a high-value resource rather than a disposal problem, governments can incentivize a circular loop: farmers earn more by selling leaves, industries reduce their carbon footprint by using bio-based materials, and consumers are protected from carcinogenic exposure. The future of this field depends on harmonizing international standards for bio-nanomaterials, ensuring that these "green asbestos" alternatives are not only as strong as their predecessors but are officially certified for safety and performance in the global market.

## 7. CONCLUSION

PALF nanofibers offer a sustainable and biodegradable alternative to asbestos, combining high mechanical strength with environmental safety. Their green synthesis and high-aspect-ratio structure make them suitable for applications in construction, automotive, and water purification, supporting both circular economy principles and eco-friendly material innovation.

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