



Enhancing Value of Natural Waste by Converting It into Air-Filtration Media

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Abstract

This study investigates the properties and optimal conditions of air filter sheets and evaluates the air filtration efficiency of filter media produced from waste pineapple and bamboo leaves. The air filter sheets are fabricated from natural agricultural waste materials, specifically pineapple leaf fibres and bamboo fibres. Fabrication involved fibre quantities of 100, 200, and 300 grams combined with binder concentrations ranging from 5% to 20% by weight. The physical properties of the air filter sheets demonstrated favourable surface characteristics, including smooth texture, uniform colouration, and structurally intact fibres without evidence of tearing. Morphological analysis showed that the fibres were longitudinally aligned, densely packed, and mechanically robust. Comparative physical assessments indicated that pineapple leaf fibre exhibited lower water absorption and moisture retention than bamboo fibre, contributing to a higher dust removal efficiency of up to 70%, compared to 50% for bamboo-based filters. Despite these advantages, long-term use revealed challenges, including increased moisture accumulation and increased susceptibility to microbial growth. These findings suggest that pineapple leaf fibre is a promising biodegradable material for air filtration applications; however, further optimisation is necessary to enhance moisture resistance and incorporate antimicrobial functionality for sustained performance.

Keywords : air filter; natural waste materials; particulate matter; pineapple leaf; bamboo leaf

Introduction

Indoor air pollution is a significant environmental and public health issue, as modern lifestyles result in individuals spending over 90% of their time in enclosed environments such as homes, schools, offices, hospitals, and other public buildings [1]. Exposure to indoor air pollutants including fine particulate matter (PM_{2.5} and PM₁₀), carbon monoxide (CO), ozone (O₃), black carbon

(BC), sulfur dioxide (SO₂), and nitrogen oxides (NO_x) is strongly associated with various health problems [2]. These include respiratory and cardiovascular diseases, as well as Sick Building Syndrome (SBS) and Building-Related Illnesses (BRI), which present with symptoms such as headaches, fatigue, nausea, and allergic reactions [2, 3]. Indoor air contaminants originate from both external and internal sources. Pollutants may enter buildings through ventilation systems or arise internally

due to poor air circulation, accumulation of dust mites, chemical emissions from furnishings and paint, excessive humidity, and microbial growth on damp surfaces [2, 3]. The increasing prevalence and persistence of these pollutants underscores the urgent need for effective air filtration technologies to maintain indoor air quality and reduce adverse health effects.

Air filtration systems are widely employed to control indoor air pollution. Air filters function primarily through two mechanisms: mechanical filtration, which uses fibrous porous media to physically capture particles as air passes through, and chemical filtration, which relies on adsorption and chemisorption to remove gaseous pollutants, typically at the submicron scale ($<0.01\ \mu\text{m}$). The efficiency of chemical filtration depends on factors such as air velocity (residence time), temperature, and humidity [2]. High-efficiency filtration systems, including High-Efficiency Particulate Air (HEPA) and Ultra-Low Penetration Air (ULPA) filters, are recognized for removing up to 99.97% of airborne particles. However, these systems predominantly use synthetic polymer-based materials, leading to high production costs and environmental concerns regarding disposal. As a result, there is increasing interest in developing sustainable, biodegradable alternatives for air filter fabrication [4].

Agricultural residues represent a promising and renewable resource for air filtration applications. In Thailand, the cultivation of export-oriented crops generates substantial volumes of underutilized biomass. For example, approximately 2.7 million tons of pineapple leaf waste are produced annually [5]. The commercial bamboo industry similarly yields over 3.4 million tons of harvested biomass each year, with processing waste comprising up to 50-60% of the total, resulting in significant quantities of discarded leaf residue [6]. These materials are often burned in open fields, which contributes to external $\text{PM}_{2.5}$ pollution, yet they possess favorable structural properties for filtration. Pineapple leaf fiber offers high tensile strength and a rich cellulose network [7, 8], while bamboo leaves provide biogenic silica and structural flexibility [9, 10].

Lignocellulosic biomass, including pineapple and bamboo leaves, has attracted considerable attention due to its high cellulose content, biodegradability, and advantageous structural properties. Pineapple leaf fibers exhibit high tensile strength and cellulose content, while bamboo-derived fibers provide flexibility, porosity, and mechanical robustness, making them suitable for filtration applications. These materials present a promising approach for developing eco-friendly filtration media with reduced environmental impact.

Recent advances in air filtration research have focused on cellulose-based and biopolymer materials, particularly nanocellulose, due to their high surface area, tunable porosity, and renewable characteristics. Nanocellulose-based aerogels and membranes have demonstrated excellent filtration performance for both particulate matter and gaseous pollutants, with studies indicating their potential to compete with synthetic nanofiber filters [11, 12]. Regenerated and nanostructured cellulose filters have been fabricated to achieve high filtration efficiency through hierarchical pore structures and optimized fiber networks [13]. Recent studies on nanocellulose-reinforced air filters have demonstrated enhanced mechanical strength and antibacterial efficiency of up to 99.9%, suggesting potential for multifunctional filtration systems [14]. Additionally, microfibrillated cellulose-based composite filters incorporating antimicrobial agents have achieved filtration efficiencies exceeding 99.99% while providing antibacterial functionality [15].

Despite these advancements, several critical limitations persist. Many cellulose-based filters are highly hydrophilic, resulting in moisture absorption, structural instability, and reduced filtration efficiency under humid conditions. This issue is especially pronounced in tropical climates, where high relative humidity accelerates material degradation and compromises filter performance. Recent research has sought to address this challenge by developing composite biodegradable filters with improved humidity resistance and extended service life; however, issues related to long-term durability and consistent performance remain [16].

Although some advanced filtration materials incorporate antimicrobial functionality, most conventional and bio-based filters do not effectively inhibit microbial growth, which can result in secondary contamination risks. Recent studies have explored multifunctional designs that integrate antibacterial nanoparticles and functional coatings; however, these approaches often require complex fabrication processes or compromise biodegradability [14, 15].

Recent studies from 2023 to 2025 have shown that natural cellulose and biopolymer networks can achieve particulate capture efficiencies comparable to those of synthetic media [17, 18]. However, a significant research gap remains in their practical application: conventional biodegradable filters are highly hydrophilic. In high-humidity environments, this characteristic leads to structural degradation, increased pressure drops, and substantial losses in filtration efficiency [19]. Additionally, retained moisture and trapped organic matter can promote bacterial and fungal growth, posing secondary health risks [20]. Addressing these limitations requires the development of biodegradable filters that are moisture-resistant and possess additional functional properties.

The present study focuses on the development and optimization of advanced air filter media derived from waste pineapple and bamboo leaves. The specific objectives are to (1) investigate the physical and structural properties of these combined natural fibers, (2) determine the optimal conditions for producing air filter sheets, including the selection and concentration of binders to impart moisture resistance, and (3) evaluate the filtration performance of the fabricated media.

Methodology

Air Filter Sheet Production Method

The process for producing air filter sheets from pineapple or bamboo leaf fiber involves the following steps as shown in **Figure 1**: (1) Preparation of Raw Material: Discarded pineapple (PN) or bamboo (BN) leaves obtained from agricultural waste are cut into small, uniformly sized pieces as required. (2) Alkaline Treatment: The leaves are boiled in 2.5 liters of water mixed with sodium

hydroxide at a ratio of 1:10 for 3 hours. (3) Oxidizing Treatment: The boiling process is repeated with 35% hydrogen peroxide solution (H_2O_2) for 1 hours to further bleach and refine the fibers. (4) Washing: The liquid is filtered out, and the fibers are thoroughly rinsed with clean water to remove any residual chemicals. (5) Blending with Binder: The fibers are mixed with a starch-based adhesive in varying proportions of 5%, 10%, 15%, and 20% relative to the dry weight of the fiber at 100, 200, and 300 grams, respectively. These formulation parameters were systematically investigated to evaluate their effects on the permeability characteristics. (6) Sheet Formation: The fiber pulp is evenly spread onto a mesh screen with size 20*30 cm. to form a uniform layer. (7) Drying and Finishing: The formed sheet is allowed to dry at 60°C for 12 hours before being carefully removed from the mesh screen.

The sheet-forming process was rigorously standardised to achieve uniformity, consistent quality, and reproducible thickness in the air filter media. Rather than relying solely on post-fabrication thickness measurements, quality control was implemented by regulating the screening depth. For each sample, a fixed volume and concentration of the fiber-binder suspension were applied to the forming mold. This approach ensured a uniform basis weight and consistent distribution of the fibrous network across all sheets.

Characteristics and performances

1. Physical Characterization: Water Absorption Capacity and Moisture Content Analysis were evaluated in accordance with ASTM D3285 standard [21] and ASTM D6304 standard [22], respectively.

2. Morphological and Functional Analysis: Morphological characterisation of fibres was conducted using scanning electron microscopy (SEM). Regarding Filtration Performance Evaluation, the filtration efficiency of the developed filter media was evaluated using a laboratory-scale air filtration test system under controlled environmental conditions as illustrated in **Figure 2**. Aerosol particles were

generated and introduced into a continuous airflow stream passing through the test filter media. Talc-based baby powder was used as the particulate matter source, with a typical particle size range of 1-10 μm , representing total particulate matter (PM_{10}) [23]. This size range is widely recognized as relevant for studies of indoor air quality, aerosol exposure, and filtration performance, as such particles can penetrate the human respiratory system and are commonly encountered in indoor environments [23]

Airborne particle concentration was determined following the NIOSH Method 0500 (Particulates Not Otherwise Regulated, Total) [24]. This gravimetric method provides a reliable measurement of total suspended particulate concentration and is widely used in occupational and environmental exposure assessments [24].

Upstream (C_{in}) and downstream (C_{out}) particle concentrations were measured to evaluate filtration performance. Filtration efficiency ($\eta\%$) was calculated using the following equation:

$$\eta\% = \left(\frac{C_{in} - C_{out}}{C_{in}} \right) \times 100$$

where:

C_{in} = upstream particle concentration (mg/m^3),

C_{out} = downstream particle concentration (mg/m^3).

3. Application Testing: Operational performance tests involved replacing the commercial air filter in an air purifier fan with the fabricated air filtration media. The device was operated for 8 hours per day at 25-32°C over 5 days to assess the usability and effectiveness of the developed air filter sheets.

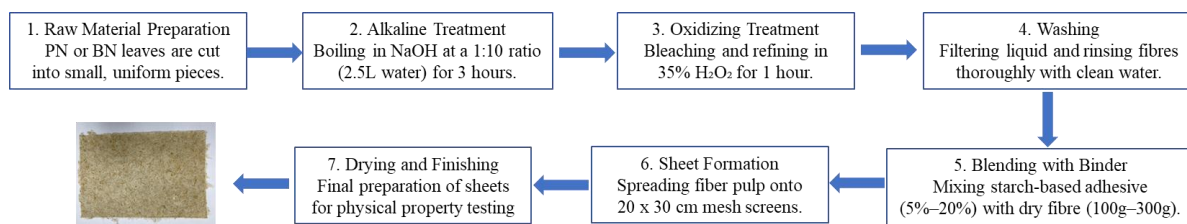


Figure 1 Schematic of the fabrication of air filter sheet process

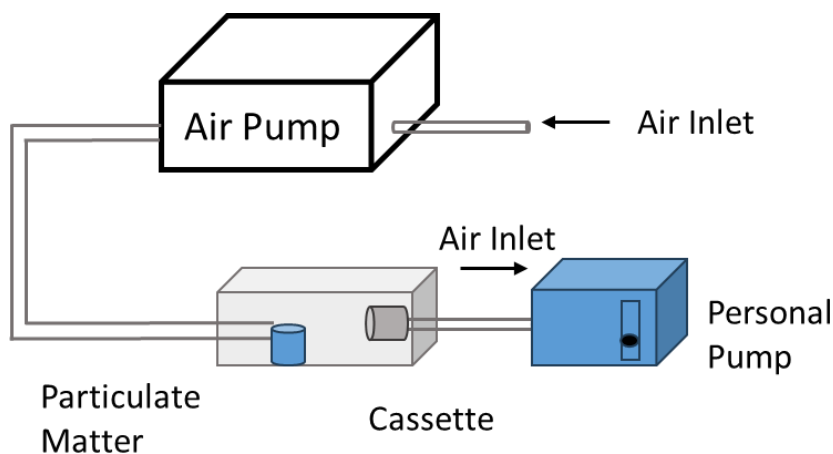


Figure 2 Schematic of Filtration Experimental

Results and Discussions

Morphological Characteristics of PN and BN Filter Media

The air filter sheet characteristic must demonstrate cohesive structure, resistance to tearing, and uniform thickness throughout. According to the specified criteria [25], the filter sheets should be free from perforations, tears, visible contaminants, or mold. Additionally, they must exhibit a clean and consistent surface, without smudging, peeling, flaking, or irregular coloration. As shown in Figure 3, the air filter sheets fabricated from pineapple and bamboo leaf fibers meet these quality standards. The surfaces were free of visible defects, including tears, contaminants, and discoloration. The sheets also demonstrated a smooth texture and consistent coloration, with no signs of surface irregularities. The results of this study demonstrate that natural fibers derived from agricultural waste, specifically those from pineapple and bamboo leaves, can be effectively utilized to produce air filter sheets that meet essential quality standards. The physical evaluation of the filter sheets revealed satisfactory performance across all samples, with particular attention to criteria such as surface cohesion, resistance to tearing, uniform thickness, and overall aesthetic integrity. These characteristics are critical for maintaining mechanical filtration efficiency and ensuring durability during use. Notably, the preparation method had a significant influence on the visual and structural properties of the filter sheets. This finding supports previous literature [2, 25, 26], which attributes such effects to the oxidative bleaching action of H_2O_2 on plant-based fibers. The bleaching not only improves the aesthetic quality of the material but may also enhance fiber porosity and cleanliness, which are favorable attributes in air filtration applications.

Furthermore, the physical appearance of the filter sheets remained consistent or improved with increasing fiber content. Samples prepared with 200 and 300 g of fiber exhibited consistently high overall quality, indicating that higher fiber loading did not adversely affect structural integrity. The evaluation was conducted according to community product standard criteria for air filter sheets [25], in which qualitative ratings such as “good” and “fair” are assigned based on visual and structural attributes,

including surface uniformity, fiber distribution, bonding integrity, and pattern consistency. A “good” rating generally reflects a uniform surface with well-distributed fibers, minimal defects, and satisfactory structural cohesion, whereas a “fair” rating indicates moderate uniformity with some irregularities in fiber arrangement, visible defects, or less consistent pattern formation.

These findings suggest that the manufacturing process is robust and scalable for producing thicker or denser filter media suitable for higher filtration demands. However, although the PN sample at 100 g was rated as “good” in overall appearance, it received only a “fair” rating in pattern quality. This discrepancy implies that lower fiber content may limit the formation of a well-defined and homogeneous fibrous network during sheet formation, resulting in uneven pore distribution. Such structural inconsistency could negatively affect filtration performance by creating preferential flow paths. Therefore, optimizing fiber concentration is critical not only for maintaining mechanical integrity but also for achieving uniform pattern formation and consistent pore structure, which are essential for effective filtration.

Air filter sheets fabricated using the PN method with 5% binder and varying fibre content exhibited continuous, elongated, and rounded fibres. These fibres were unfragmented and formed overlapping clusters, with binder distributed between them. When fibre content was held constant, and binder ratios varied, the fibres consistently formed overlapping clusters with a continuous and rounded structure, and the binder remained present between fibres [2]. The macroscopic appearance of bamboo leaf (BN) filter sheets remained highly uniform and consistent across all tested binder concentrations (5–20 wt%). This visual stability is attributed to the geometric and structural properties of the processed bamboo biomass. Milling and blending bamboo leaves into short, micro-fibre particles resulted in a highly homogeneous dispersion within the aqueous suspension. In contrast to long, flexible fibres that tend to entangle and form visible macroscopic clumps at higher binder concentrations, the short and relatively rigid bamboo fibres maintained an even distribution. As a result, the binder uniformly coated the pre-dispersed fibre matrix without causing large-scale

structural deformation. Although increasing the binder content significantly altered the internal micro-porosity and airflow resistance, the external macroscopic uniformity of the BN sheets was preserved.

Scanning electron microscopy (SEM) is frequently employed to examine fibre surface morphology, as shown in Figures 4-6. Figure 4 presents the morphology of air filter sheets fabricated with 300 grams of fibre at 500x magnification. Both fibre types exhibited continuous, elongated, and rounded structures

without signs of fragmentation, forming overlapping clusters with binder distributed throughout the fibre network [9, 27]. Notably, BN fibres appeared more densely packed than those produced by the PN method. Pineapple leaf fibers exhibited a long and slender morphology, as seen in **Figure 5**. The fiber morphology remained consistent regardless of the extraction method. At a magnification of 2,500× (**Figure 5**), the surface texture appeared distinctly rough and irregular. Densely packed fibrils were visible compared to those in **Figure 6**.

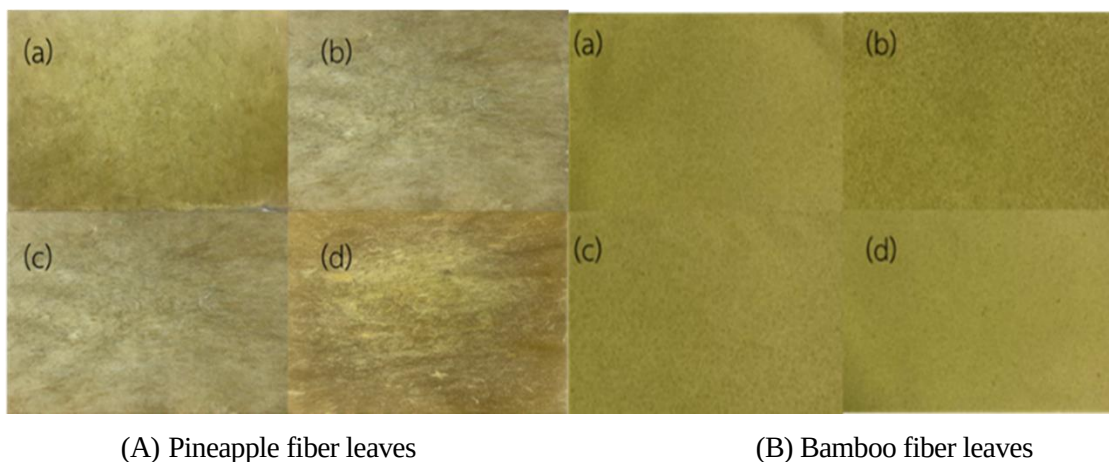


Figure 3 The surface characteristic of air filters fabricated from 300 g of (A) Pineapple and (B) Bamboo leaves at a function of binder concentration of (a) 5%, (b) 10%, (c) 15% and (d) 20%

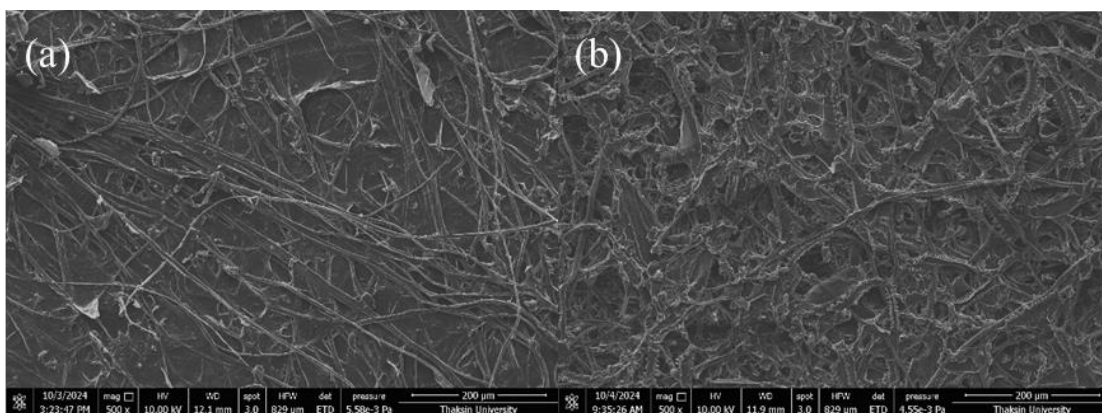


Figure 4 SEM image of the surface of air filter sheets fabricated from 300 g mixed with 20% binder at magnification of 500x of (a) Pineapple fiber and (b) Bamboo fiber

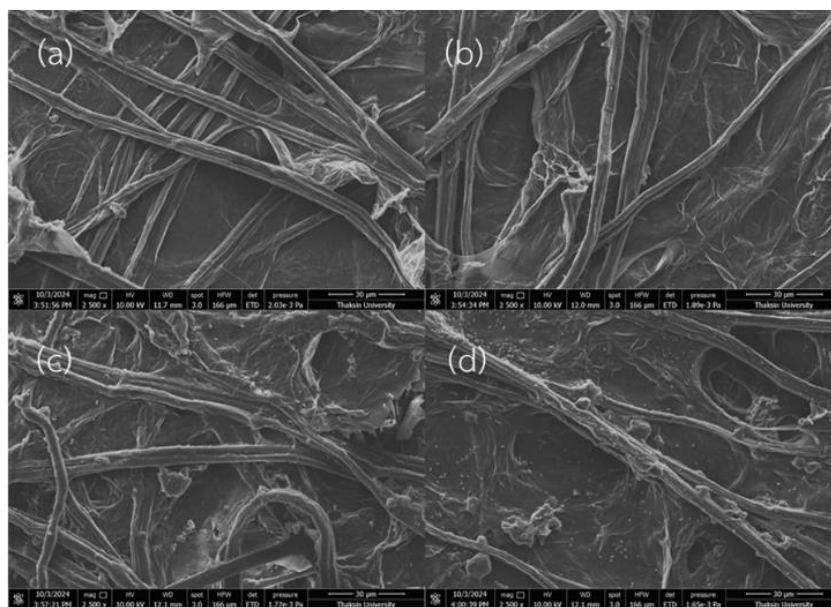


Figure 5 SEM image at magnification of 2,500x of the surface of Pineapple air filter sheets fabricated from 300 g at a function of binder concentration of (a) 5%, (b) 10%, (c) 15% and (d) 20%

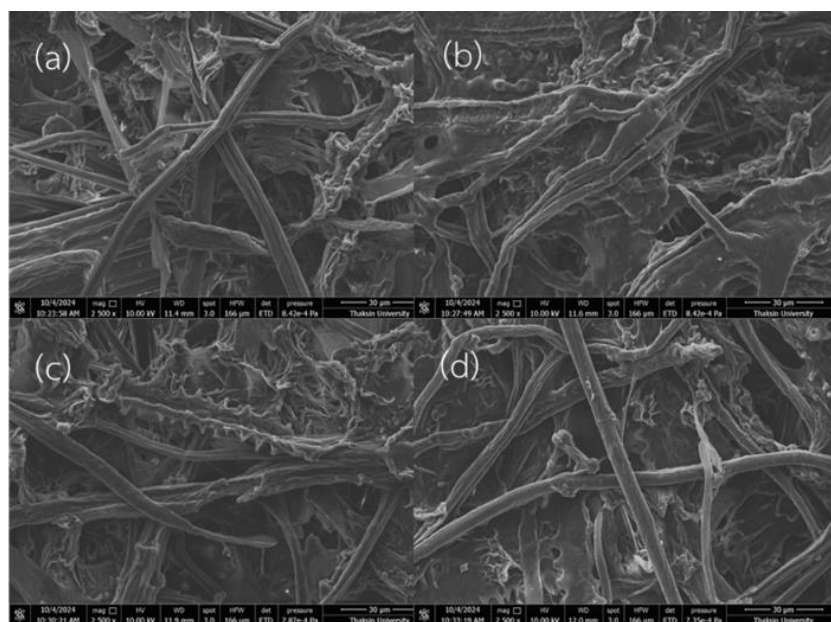


Figure 6 SEM image at magnification of 2,500x of the surface of Bamboo air filter sheets fabricated from 300 g at a function of binder concentration of (a) 5%, (b) 10%, (c) 15% and (d) 20%

Scanning electron microscopy (SEM) observations of pineapple leaf (PN) and bamboo leaf (BN) waste fibres indicate that binder concentration (5-20 wt%) controls the development of fibre network architecture, which in turn determines bulk properties and filtration performance. At a low binder content of 5%, the loosely arranged fibrous network with large inter-

fibre voids results in high porosity and airflow permeability. However, limited fibre contact at this level reduces mechanical integrity and increases moisture uptake through open, hydrophilic pathways [28]. Increasing the binder concentration to 10-15% promotes the formation of bridging structures and thin film-like coatings, which enhance inter-fibre adhesion and create

a more integrated network. This modification reduces pore size while maintaining sufficient connectivity for airflow. The resulting intermediate structure achieves an optimal balance between permeability and particle capture, as rough fibre surfaces, particularly the more fibrillated PN fibres, improve mechanical interception, diffusion, and adhesion mechanisms. At 20% binder, excessive coating and pore filling produce a dense, compact matrix with restricted pore connectivity, which reduces permeability and increases pressure drop, despite potentially higher particle retention [29]. Compared to PN fibres, BN fibres form a more densely packed, channel-like structure due to their rigid morphology, resulting in more stable airflow pathways and enhanced mechanical strength. In contrast, PN fibres are more sensitive to binder-induced densification, leading to greater reductions in porosity and water absorption. These structure–property–performance relationships are consistent with recent studies that emphasize the importance of binder-induced pore evolution and surface modification in natural fibre-based filtration media. Optimal performance is achieved by balancing pore accessibility, surface functionality, and network integrity [28–31].

With respect to water absorption according to binder ratios, the structural evolution observed via SEM directly explains the experimentally observed decline in water absorption with increasing binder ratios. Fundamentally, the high moisture uptake at lower binder concentrations (5 wt%) is driven by the inherent biochemical structure of the lignocellulosic fibers. Cellulose macromolecules possess abundant equatorial hydroxyl (-OH) groups, rendering the uncoated fiber surfaces highly hydrophilic and prone to hydrogen bonding with water molecules. As the binder concentration is incrementally increased to 20 wt%, the polymeric binder forms a continuous film that physically encapsulates the fiber network. This binder coverage acts via a dual mechanism: chemically, it masks the exposed hydrophilic hydroxyl sites on the cellulose surface, preventing direct moisture interactions; physically, it fills the inter-fiber voids, effectively blocking the capillary pathways that would otherwise facilitate bulk water ingress [28]. While fundamental micro-chemical analyses

(such as FTIR or contact-angle goniometry) are often used to quantify these specific surface energy changes, the macroscopic bulk water absorption data obtained in this study provides robust functional evidence of this encapsulation effect. The profound reduction in bulk water uptake at higher binder loadings confirms that the binder successfully neutralizes the inherent hydrophilicity of the cellulose network

Filtration Performance Evaluation

Figures 7 and 8 demonstrate the water absorption and moisture content of air filter sheets fabricated using the PN and BN methods with varying fibre quantities (100, 200, and 300 grams) and binder concentrations (5% to 20%). The results demonstrate a consistent decreasing trend in both water absorption and moisture content as binder concentration increased. Regarding air filter sheets produced using the PN method, initial water absorption levels at a 5% binder ratio were approximately 66.97%, 66.85%, and 62.40% for fiber weights of 100, 200, and 300 grams, respectively. As the binder ratio increased to 20%, water absorption correspondingly declined to 62.40%, 56.23%, and 44.75%. This reduction can be attributed to increased binder coating on fibre surfaces, which blocks hydrophilic sites and reduces pore accessibility, thereby decreasing the material's capacity to retain water, thereby limiting water penetration and retention. Similar trends have been reported in recent studies on natural fibre–biopolymer composites, where increased polymer or crosslinking density reduces porosity and restricts moisture uptake [14, 29, 31]. The denser fibre-binder matrix likely restricted the availability of hydrophilic sites on the fibres, thereby minimizing capillary action. This trend was similarly observed in sheets prepared with the BN method, although the overall water absorption levels were slightly higher than those of the PN samples across all binder ratios and fibre quantities.

The superior performance of PN filter sheets in terms of lower moisture retention can be explained by the intrinsic properties of pineapple leaf fibres. These fibres are less hygroscopic and possess a denser microstructure compared to bamboo fibres, which tend to exhibit higher porosity and greater moisture affinity [2, 8, 10].

This characteristic is crucial in air filtration applications, where excessive moisture can not only impair filtration efficiency but also facilitate the growth of microorganisms. The lowest water absorption and moisture content were observed in the PN300/20% sample. This suggests that this formulation is optimal for minimizing water retention. Minimizing water retention benefits filter durability and performance. High moisture content can reduce airflow, promote clogging, and degrade filter materials over time.

Particulate Matter Removal Efficiency

Figure 9 illustrates that particulate matter (PM) removal efficiency positively correlates with binder concentration for both PN and BN filter media. PN filters consistently demonstrated superior filtration performance, increasing from approximately 60% at 5 wt% binder to a peak of 70% at 20 wt%. However, BN filters exhibited significantly lower capture efficiencies, ranging from 42% to 52% across the same binder loadings.

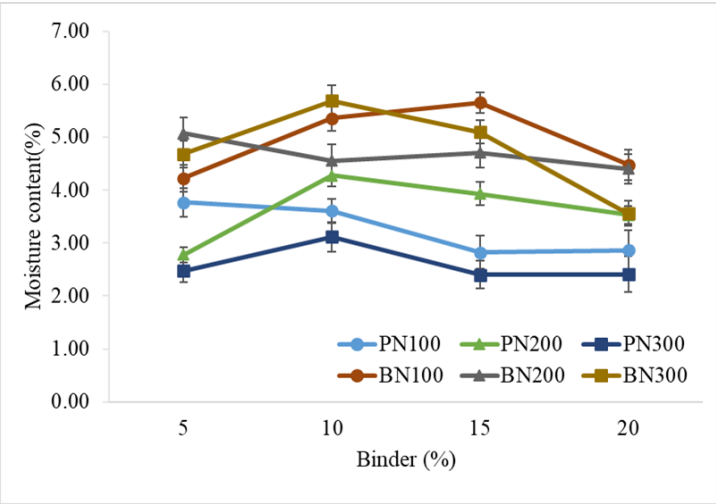


Figure 7 The water absorption of PN and BN air filter as a function binder concentration

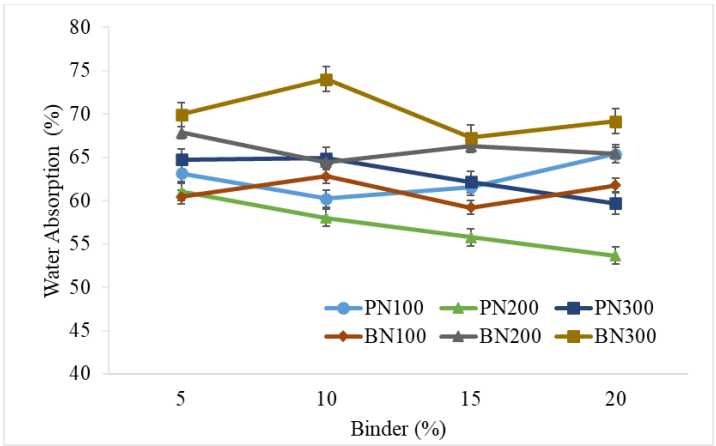


Figure 8 The moisture content of air filter sheets from PN and BN as a function binder concentration

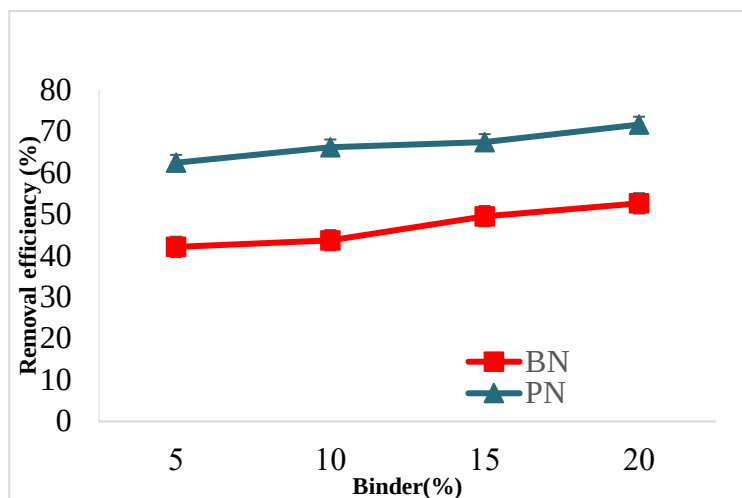


Figure 9 The particulate matter removal efficiency of air filters fabricated using 300 gram of Pineapple fiber and Bamboo fiber

The progressive improvement in efficiency at higher binder concentrations is attributed to microstructural densification. As the binder bridges inter-fibre gaps, effective pore diameters decrease, thereby enhancing PM capture via mechanical interception and inertial impaction [29]. Furthermore, the marked performance disparity between the two materials stems from their inherent fibre morphologies. The highly fibrillated, flexible nature of PN creates a dense, tortuous network that maximizes surface area and effectively traps fine particulates [14]. Conversely, the inherently rigid, tubular structure of BN forms a more ordered, channel-like architecture [30]. While this ordered structure likely improves airflow permeability, it provides fewer physical obstacles for traversing particles, resulting in higher aerosol bypass and lower overall capture efficiency.

To elucidate the observed filtration performance, a simplified mechanism is proposed that considers the combined effects of mechanical sieving, interception, and adhesion within the fibrous matrix. At low binder content (5%), the filter exhibits large pore sizes and weak fibre–fibre interactions, allowing fine particles to traverse the open network and diminishing the efficacy of mechanical sieving. As binder content increases to 10-15%, enhanced fibre cohesion leads to smaller pores and a more interconnected

network, thereby improving particle capture through interception as particles following airflow trajectories encounter fibre surfaces. The intrinsic surface roughness and molecular structure of lignocellulosic fibres further facilitate adhesion, enabling particles to attach via van der Waals forces. The binder amplifies this effect by increasing the number of fibre contact points and stabilising the overall structure. At high binder content (20%), excessive densification and pore blockage enhance particle capture by sieving, but also restrict airflow and elevate pressure drop. Thus, filtration performance is determined by the interplay between structural characteristics and capture mechanisms, with optimal results achieved at intermediate binder levels where a balance between pore structure and fibre bonding is maintained. These findings align with recent studies emphasising the significance of microstructure and surface properties in natural fibre-based filtration systems [30-31].

Application of air filter media

In the long-term application test, microbial growth was observed on the surface of the filter media after extended use, highlighting a potential limitation for practical deployment. The exposure conditions during this test were typical of a tropical environment, with ambient temperatures of approximately 25-32 °C and relative humidity in the range of 70-85%, under natural airflow

without controlled ventilation. Post-exposure evaluations revealed an increase in moisture content relative to the initial state. The presence of microbial contamination was identified through visual observations, including surface discoloration, spot formation, and localized colony-like growth on the filter sheets. Although specific microbial species were not characterized in this study, these findings suggest that the lignocellulosic nature of the fibers, combined with high humidity conditions, can promote microbial colonization over time [28, 31]. To enhance the durability and hygienic performance of the developed filter media, the incorporation of antimicrobial agents such as chitosan, silver nanoparticles, or plant-derived essential oils is recommended. These additives have been widely reported to inhibit microbial growth and improve the functional performance of natural fiber-based materials [14, 29].

These findings highlight the potential of pineapple leaf fiber as a promising candidate for sustainable air filter production, particularly when paired with optimized binder concentrations. However, improvements in moisture resistance and the incorporation of antimicrobial agents are recommended for enhancing long-term performance under ambient environmental conditions.

Conclusions

This study establishes the fundamental structure-property relationships of agricultural waste-derived lignocellulosic fibers for use in sustainable air filtration media. By shifting away from synthetic polymers, we demonstrated that the intrinsic morphological and chemical properties of natural fibers dictate their functional aerodynamic performance. Specifically, pineapple leaf (PN) fiber demonstrated superior mechanical integrity and particulate filtration performance, a result directly driven by its highly fibrillated, denser network architecture and inherently lower hygroscopicity. Conversely, while bamboo leaf (BN) fiber exhibited higher structural flexibility and uniform binder dispersion, its greater moisture sensitivity and rigid, tubular morphology limited its overall filtration efficacy. Despite these promising structural capabilities, extended operational evaluations

highlighted the inherent vulnerabilities of untreated cellulosic matrices, namely moisture accumulation and subsequent microbial proliferation. Therefore, while this study validates the strong baseline potential of pineapple leaf fibers, future development must address these biological and environmental limitations prior to real-world deployment. Subsequent research directions should focus on engineering hybrid fiber composites to balance permeability and strength, as well as integrating targeted surface hydrophobization and active antimicrobial modifications to ensure long-term operational durability and safety.

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