Windmill Palm Fiber/Polyvinyl Alcohol Nonwoven Fibrous Polymeric Materials

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ABSTRACT
Three types of wet-laid nonwoven materials with windmill palm fibril (WPF_L), WPF_L/windmill palm fiber bundles (WPFB) and windmill palm fiber (WPF)/polyvinyl alcohol (PVA), were prepared. The morphology and length distribution of WPF_L and WPFB were analyzed by digital microscopy and image processing software. The filtration efficiency, air permeability and sound absorption properties of 12 samples of wet-laid nonwoven materials were tested. Adding PVA improved the porosity and enhanced the filtration efficiency, air permeability and acoustic properties of the nonwovens.

Keywords: Windmill palm fiber; PVA; Filtration efficiency; Air permeability; Sound absorption

INTRODUCTION
Air pollution, a significant environmental problem, has attracted increasing attention due to rapid urbanization and industrialization [1]. In particular, particulates such as airborne bacteria and viruses are increasingly impacting the quality of life of the population [2-3]. Air pollution poses serious health threats to the public, and is a major cause of adverse health effects on the human respiratory tract, as well as a negative influence on climate and ecosystems [3-5]. Additionally, air pollution causes chemical corrosion and staining of fabrics, leather, metal products, construction materials and crops [6].

Among the many different groups of materials used for filter media, textile fabrics play an important role and are widely accepted [7]. In particular, nonwoven fibrous filters made from cellulose produced by a wet-laid process (a modified paper-making process) are frequently used for air filtration applications [8,9]. Nonwovens are especially favored for filtration of sub-micron aerosols because of low production costs and wide ranging functionality[10]. The three-dimensional structure of nonwoven materials can not only improve filtration efficiency but can also increase the flow speed of the carrier phase, which can speed up the overall filtration process [11,12].

Palm fiber is an important lignocellulose fiber. Among the various types of palm fiber, oil palm fiber has been studied in depth is widely used as a reinforcing fiber in composites [13-16]. Though windmill palm is an abundant resource, research on its use as a filter is limited. It is well-documented that the smaller the fibers, the better the filtration performance of the fibrous filter [17]. The average diameter of the windmill palm fibril （WPF_L） extracted from windmill palm is 10 μm [18], while the diameter of natural cotton fiber is 13~15 μm, ultrafine wool is 18~27 μm, ramie is 30~40 μm [19] and silk is 11~13 μm [20]. This indicates that WPF_L is potentially one of the most suitable raw materials for filters.

The main objective of this research is to prepare a potential functional polymeric material based on cellulose that has good performance as a filter and also has good acoustic properties. To that end, three types of wet-laid nonwoven material with WPF_L, WPF_L / WPFB and WPF / PVA were prepared. The filtration efficiency and air permeability of these samples were tested. The sound absorption properties of one type of WPF / PVA nonwoven material with high filtration efficiency and high air permeability was tested.

MATERIALS AND METHODS

Preparation of Materials

The windmill palm fiber used in this study was obtained from Mount Huang, Anhui Province, China. A portion of the fibers was treated with a solution of 4wt.% hydrogen peroxide (H_2O_2) and 1.5 wt.% sodium hydroxide (NaOH) with a 1:50 fiber-to-extracting agent ratio (g/mL) at 90°C for 4 h. The residue was then filtered and put into a blender (Bm252c, Meidi, China) at 250 W and and 20,000 r/min for approximately 30 s to obtain separated windmill palm fibril (WPF_L). The other portion of the palm fibers was treated with a solution of 2 wt.% H_2O_2 and 1 wt.% NaOH with an extracting ratio of 1:50 (g/mL) at 75°C for 3 h to obtain the WPFB, which were nearly free of lignin and hemi-cellulose. As a result, fine fiber with a small diameter can be obtained. More details about the sample preparation can be found in C. J. Chen et. al [21]. The WPFB and WPF_L were then washed with running water and dried in an oven with air circulation at 60°C for 24 hours.

Methods

Preparation of Nonwoven Materials Based on WPF_L.

Three types of nonwoven materials were prepared by means of a wet laid process. The first type was composed of WPF_L only, with the amount of WPF_L was increased from 10 g to 40 g in 10-g intervals to obtain samples with different thicknesses. These samples were denoted 1, 2, 3, and 4, respectively.

The second type was composed of WPF_L and WPFB. The proportions of WPF_L and WPFB were 80/20, 60/40 and 40/60. The total weight of fiber containing WPF_L and WPFB for each sample was 40 g. These samples were denoted 5, 6, and 7.

The third type was composed of WPF_L and WPFB (60/40, w/w), joined by PVA at concentrations of 0.1 wt.%, 0.5 wt.%, 1.0 wt.%, 1.5 wt.% and 2.0 wt. percent. The total weight of fiber containing WPF_L and WPFB was 40 g. These samples were denoted 8, 9, 10, 11 and 12. For purpose of description, the material that contained WPF_L and WPFB is called WPF throughout the remainder of this paper.

The wet laid process was used to prepare bamboo fiber, flax fiber and cotton nonwoven mats weighing 40 g. These three samples were denoted 13, 14 and 15, respectively.

$WPF_{L,}$ WPFB and 500 ml of deionized water or 500 ml of PVA with various concentrations were added to a blender. After blending, the compounded materials were formed into a mesh filter. The materials were then dried in an oven at 75°C.

Characterization of Windmill Palm Materials

The morphologies of WPF_L and WPFB were observed using a digital microscope (VHX-100, Keyence, Japan). Image processing software (Image-Pro Plus 5.0) was used to measure the diameter of WPF_L and WPFB. More than 500 samples of each type of fiber were characterized.

Air Permeability Measurement

The air permeability test was carried out on an air permeability testing apparatus (YG461E, Hongda, China). The air permeability was tested at a pressure differential of 100 Pa between the two surfaces of the nonwoven materials. Five different parts of each sample were tested, and the average was used as the air permeability.

Aerosol Filtration Efficiency Measurement

The aerosol filtration efficiency was measured with an automated filtration testing unit (8130-1, TSI, America). NaCl aerosol particles of 260 nm average diameter and 75 nm count median diameter were prepared by an aerosol particle generator. Samples with an effective area of 100 cm^2 were tested at room temperature.

Sound Absorption Measurement

The normal incidence absorption coefficient was measured by means of two microphone impedance tubes (SW463, Shengwang, China) using the transfer function method. The test specimens for testing were circular with an effective area of 100 cm^2 and 8.41 cm^2. Samples were tested over frequency ranges from 60 Hz to 1.6 kHz and 1.6 kHz to 6.3 kHz.

RESULTS AND DISCUSSION

Morphology and Diameter Distribution of WPF_L and WPFB

Morphology and Diameter Distribution of WPF_L

The average WPF_L diameter and diameter distributions were characterized. A frequency distribution diagram is commonly used for describing the diameter distribution. Origin 8.0 software was used to analyze these data, and the results are shown in *Figure 1*. The diameter distribution of WPF_L is a normal distribution, with diameter between 8 and 14 μm in more than 90%, and the average diameter is 10.26 ±2.1 μm. The minimum and maximum diameters of WPF_L are 5.37 μm and 17.82 μm, respectively. The wide range of the diameter distribution creates a distribution of fabric pore sizes.

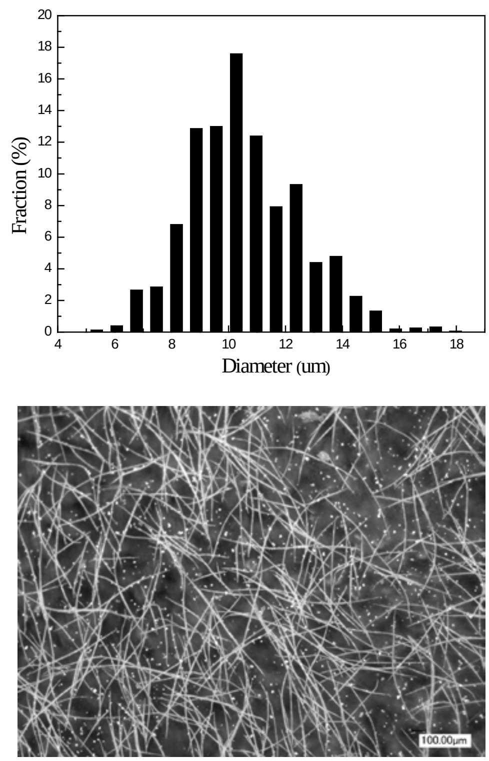

FIGURE 1. Morphology and diameter analysis of WPF_L.

Morphology and Length Distribution of WPFB

The diameter of WPFB is shown in *Figure 2*, and it ranges from 40 μm to 290 μm. While the diameter distribution is nearly a normal distribution, fibers with a diameter between 70～170 μm comprise more than 90% of the total distribution. Additionally, the average diameter is 123.61±12.6 μm, which indicates that the diameter of WPFB is almost 10 times larger than that of WPF_L, which takes the form of millimeter pores more easily. When combing these two types of materials to make nonwoven fabrics, a distribution of pores ranging from the micrometer to millimeter size is possible.

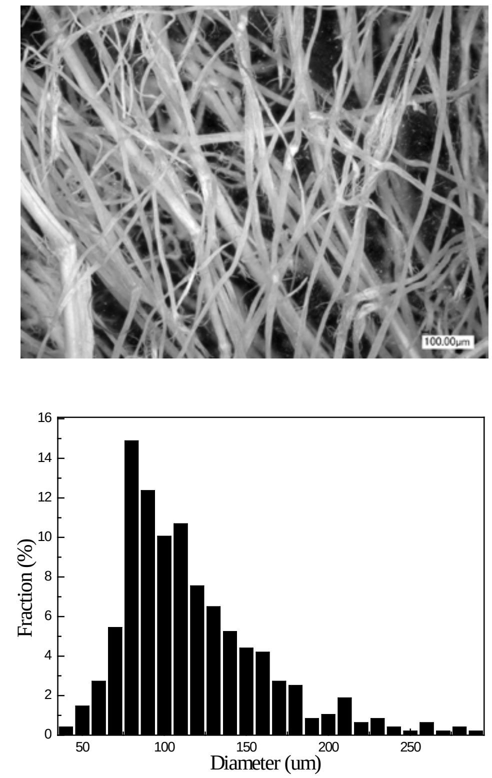

FIGURE 2. Morphology and diameter analysis of WPFB.

Filtration Efficiency and Air Permeability of WPF_L Nonwoven Materials

As the amount of WPF_L increases, the thickness of nonwoven materials increases, as illustrated in *Table I*. The filtration efficiencies and air permeabilities of nonwoven materials with different amounts of WPF_L are shown in *Figure 3*. The filtration efficiency increases as the thickness of nonwoven materials increases, and a linear correlation can be observed in *Figure 3a*. The R squared is 0.866, which indicates a good correlation. However, the air permeability decreases as the thickness of the nonwoven materials increases, and a linear correlation and a high R squared of 0.95 can be observed in *Figure 3b*. The interaction between filtration efficiency and air permeability is approximately a linear correlation, with an R squared of 0.75 as shown in *Figure 3c*.

Ideally a filter should have a combination of high filtration efficiency and high air permeability. However, the negative correlation between filtration efficiency and air permeability shown in *Figure 3c* means that an increase in the filtration efficiency will decrease the air permeability. Further results can be observed in *Figure 4.* When the filtration efficiency increases from 45.15±2.19% to 67.40±1.05%, then the air permeability decreases from 137.55±7.08 mm^3/mm^2s to 72.47±5.67 mm^3/mm^2s. Increasing the thickness to improve the filtration efficiency is not possible because the air permeability will become unacceptable. This relationship indicates that high filtration efficiency with high air permeability may not be possible for a material containing WPF_L.

TABLE I. Thickness of nonwoven materials with different amounts of WPF_L.

Samples	1	2	3	4
Areal density ($g.m^{-2}$)	80	160	240	320
Thickness (mm)	2.07	3.81	7.31	10.26

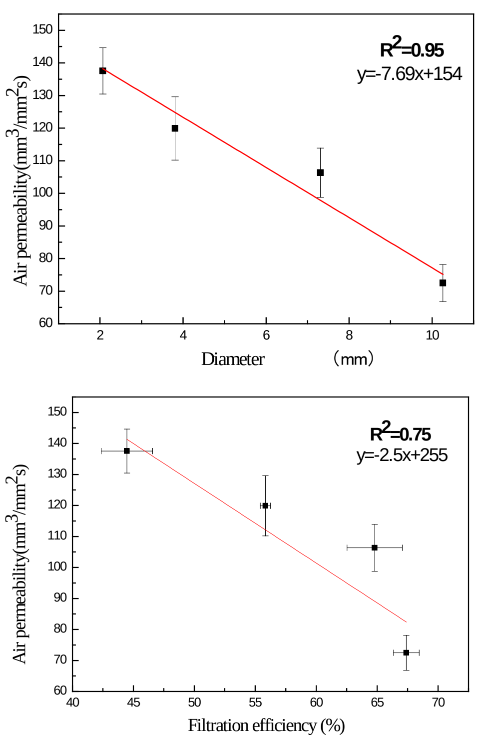

FIGURE 3. Correlation analysis among (a) diameter and filtration efficiency; (b) diameter and air permeability; (c) filtration efficiency and air permeability.

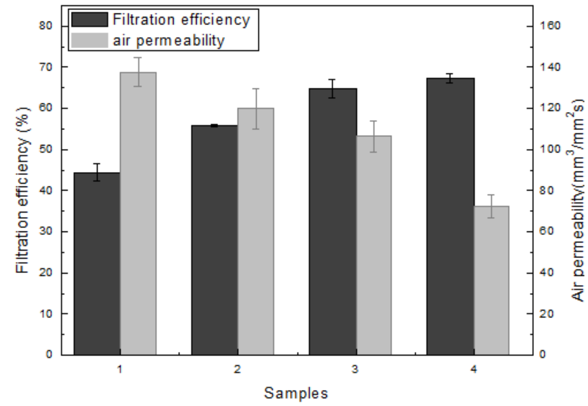

FIGURE 4. Filtration efficiency and air permeability of nonwoven materials with different amounts of WPF_L.

Filtration Efficiency and Air Permeability of WPF_L /WPFB Nonwoven Materials

WPFB has a larger diameter than WPF_L, as shown in *Figure 1* and *Figure 2*. With increasing content of WPFB, more fibers with a diameter of approximately 126.31 μm have been added into the nonwoven materials, and as a result, the air permeability increases. When the concentration of WPFB reaches 60 wt.%, the air permeability increases to the peak of approximately 125.18 ± 7.12 mm^3/mm^2s. Filtration is a separation and purification process and filtration efficiency is one of the most critical measurements for filtration [22]. With the content of WPFB increasing from 0 wt.% to 40 wt.%, the filtration efficiency increases. However, when the content of WPFB is above 40wt. %, a clear decline can be observed in *Figure 5*. The highest filtration efficiency is 77.17 ± 2.06%, while the air permeability is 88.22 ± 4.97 mm^3/mm^2s.

Increasing fiber diameter decreases the filtration efficiency because due to decreased particle impact probability resulting from a lower number of fibers [23,24]. The WPFB with a large diameter can increase the fiber surface roughness, which can improve the particle collection efficiency due to the presence of asperities [25]. The fibrillation of WPFB during the alkali treatment not only increases the surface asperities but also increases the micro pores, which can filter small particles. These characteristics all have a positive effect on the filtration efficiency. However, increasing the level of large diameter WPFB in nonwovens can increase the macro pores and the particles may go through the materials freely. As a result, the filtration efficiency will decrease. This effect is evident from *Figure 5* as filtration efficiency is observed to decrease in Sample 7, where the WPFB level reaches 40 percent.

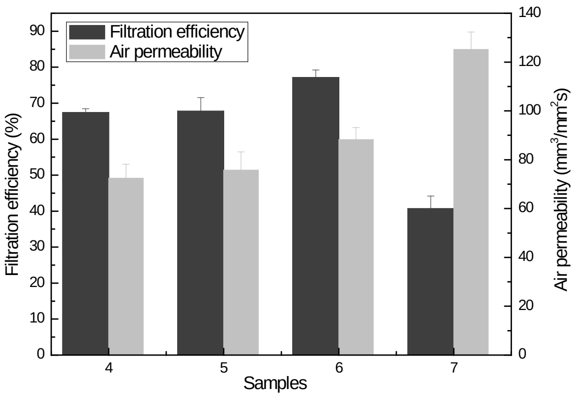

FIGURE 5 Filtration efficiency and air permeability of nonwoven materials with different WPFB contents.

Filtration Efficiency and Air Permeability of WPF / PVA Nonwoven Materials

The filtration efficiency and air permeability of nonwoven materials with different concentrations of PVA are shown in *Figure 6*. As the concentration of PVA increases from 0.1 wt.% to 1.0 wt.%, the filtration efficiency and air permeability increase. The film-forming tendencies of PVA in conjunction with mechanical blending produce many bubbles during the process of wet laying [26]. After drying, some of the bubbles remain, effectively increasing the porosity and improving the filtration efficiency and air permeability. As PVA concentration increases, it becomes more difficult for the PVA to form bubbles, which causes the number of pores in the materials decrease. As a result, a decrease in the filtration efficiency is observed when the PVA concentration becomes greater than 1.5 wt. percent. However, when PVA concentration increases above 1.0 wt.%, a film forms on the surface. As PVA concentration increases further, a more and more complete film is formed. Hence, a decrease in the air permeability is observed. The highest filtration efficiency is 88.87 ± 1.75%, with anair permeability is 92.18 ± 3.59 mm^3/mm^2s. The filtration efficiencies of the bamboo fiber nonwoven mat of sample 13, flax fiber mat of sample 14 and cotton mat of sample 15 are 63.90 ± 2.13%, 61.41 ± 1.68 and 67.80 ± 0.96% respectively, much lower than those of WPF / PVA nonwoven materials. Meanwhile, the air permeabilities of the three mats are more than 120 mm^3/mm^2s, significantly higher than that of WPF / PVA.

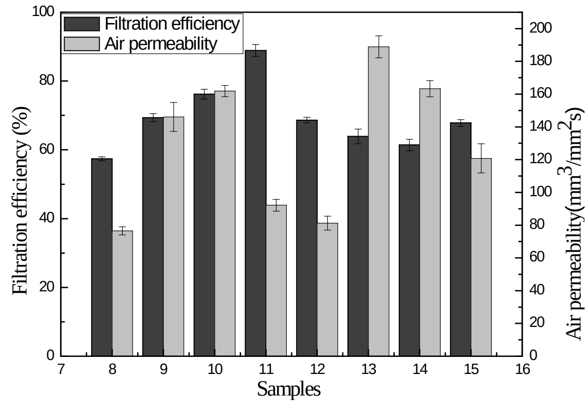

FIGURE 6. Filtration efficiency and air permeability of nonwoven materials with different concentrations of PVA.

Sound Absorption Properties of WPF / PVA Nonwoven Material

As shown in *Figure 7*, the WPF / PVA nonwoven material with an areal density of 320 g/m^2 does not absorb sound because the sound absorption coefficient was below 0.2 at the frequency range of 80 to 800 Hz. With increasing frequency, the sound absorption coefficient increases initially and reaches a peak of approximately 0.95 at a frequency of 4000 Hz. This increase with frequency has been observed by others. For example, a 16.38-mm thick commercial glass fiber needle-punched mat [27] and a 12-mm thick nature luffa fiber mat [28] reach peaks of 0.62 and 0.6 respectively, both at a frequency of 6300 Hz. However, further increases in the frequency led to a slight decrease in the sound absorption properties. This result indicates that WPF / PVA nonwoven material has better sound absorption properties than do glass fiber and luffa fiber. The average sound absorption coefficient of sample 11, at 12-mm thick, is calculated by averaging the absorption coefficients at frequencies of 250, 500, 1000, 2000, and 4000 Hz, and the result is approximately 0.36. Meanwhile, the sound absorption coefficient of 20-mm thick kapok fibrous material is approximately 0.24 [29].

Factories in most cases face both air particle and multi-frequency noise pollution. The WPF / PVA nonwoven material exhibits good combination of particle filtration and noise absorption properties and is attractive from the standpoint of sustainability being cellulose based. The material should be of high interest in industrial environments where such combinations of particle and noise reduction are required.

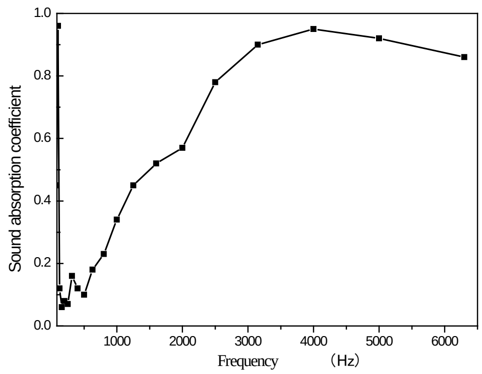

FIGURE 7. Sound absorption coefficient of WPF / PVA nonwoven materials.

CONCLUSION

Different diameters of WPF_L and WPFB and polymeric material PVA were used to prepare tree types of nonwoven materials. The average diameter of WPF_L is 10.26 ± 2.1 μm, with a distribution from 5.37 μm to 17.82 μm. Meanwhile, the average diameter of WPFB is 123.61 ± 12.6 μm, with a distribution from 40 μm to 290 μm. Increasing the level he larger WPFB fibers increases the air permeability of the resulting nonwovens, and increases filtration efficiency until the loading reaches 40%, at which point filtration efficiency begins to decrease.. When the content of WPFB reaches 40 wt.%, the highest filtration efficiency of 77.17 ± 2.06% achieved, while the air permeability is 88.22 ± 4.97 mm^3/mm^2s. The material with 1.5 wt. % PVA has the best balance of properties, with filtration efficiency at 88.87 ± 1.75%, air permeability is 92.18 ± 3.59 mm^3/mm^2s, and an average sound absorption coefficient of approximately 0.36.

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