Air filtration improvement of konjac glucomannan-based aerogel air filters through physical structure design

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Abstract

This study presents two methods to improve the air filtration performance of konjac glucomannan (KGM)-based aerogel air filters through physical structure design by changing the pore-size distribution and the surface area, using an air purifier. Results indicated that KGM-based aerogels had a comparable filtration effect with the commercial air filter with a longer purification time. This purification time could be shortened by over 50%, by changing the pore-size distribution from large size to small size or increase the surface area with the fold structure. This should boost the development of polysaccharide-based aerogel used as the air filter.

Keywords: konjac glucomannan; aerogel air filter; pore-size distribution; structure design; particulate matter

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1. INTRODUCTION

Air quality greatly affects human life, travel and ecosystems. The average breathing times of a person was over 20,000 per day with 10,000 L of air exchanged \([1]\), which makes clean air a basic necessity for a healthy life. Currently, air pollution caused by increasing industrial and automotive exhaust seriously threatens people's health \([2]\). As the main pollutant of the air, particulate matter (PM) caused about 4.1 million deaths in 2016 \([3]\). Currently, the generation of PM relates to a lot of fields such as fuel quality, combustion efficiency \([4, 5]\). Although many governments and research institutions are making efforts to reduce the PM generation by traffic control \([6]\), fuel quality improvement \([7]\) and emission standard upgrade \([8]\), it still takes a long time to reach the desired air quality. Given the fact that the respiratory health of human needs protection urgently, it is of great importance to reduce the PM concentration in the living environment and protect people's respiratory health through active protection such as using an air purifier \([9]\).

The key function element of an air purifier is the air filters inside the machine. The air filters can be made by activated carbon fibers, nanofibers, photocatalytic materials \([10, 11]\) such as fiberglass and quartz fiber \([12]\) and Nano-TiO\(_2\) \([13]\). However, most of them are not environmentally friendly. In recent years, there are growing interests in the exploitation of biodegradable air filter materials to be used as the air filter, such as nano protein-functionalized hierarchical composite air filter \([14]\), silk nanofibers \([15]\) and polysaccharide-based aerogels \([16]\). As one of the classical porous materials, aerogel is considered as one kind of good air filtration materials with continuous three-dimensional network structure, which is formed by the replacement of the liquid solvent in a gel by air without substantially altering the network structure or the volume of the gel body \([17, 18]\). Currently, aerogel made of polysaccharides such as cellulose \([19]\), starch \([20]\) and konjac glucomannan (KGM) \([21]\) attracted a lot of researchers due to the characteristics of abundant sources, ideal sustainability, excellent biodegradability and strong safety \([22]\).
KGM is one kind of highly linear polysaccharide isolated from the tubers of the *Amorphophallus konjac* plant. Recently, it was used as the main component for green or biodegradable functional materials such as air filtration materials [23–25], food packaging materials [26–28], sound absorption materials [29] and thermal insulation materials [30, 31]. Previous studies [23, 24] indicated that KGM-based aerogels containing gelatin, potato starch and wheat straw could have good air filtration properties with unique pore structure and size distribution, revealing its high potential to be used as alternative biodegradable air filters. A practical investigation with aerogel as the air filter in a commercial air purifier should further reveal the air purification application potential and capability of KGM-based aerogel. Therefore, this study aimed to investigate the feasibility of using KGM-based aerogels as the real air filter with different filter structure designs including pore-size distribution and aerogel structure, as a continuation of the previous laboratory investigation [23–25]. The results should boost the development of polysaccharide-based aerogel used as the air filter.

## 2. MATERIALS AND METHODS

### 2.1. Materials

KGM (Mw = 9.67 × 10^5 Da) was purchased from Qingsen Biological Technology Co., Ltd (Wuhan, China). Potato starch was purchased from Wuhan Lin He Ji Food Co., Ltd (Wuhan, China). Gelatin (ref. 10010328) was purchased from Sinopharm Chemical Reagent Co., Ltd (Shanghai, China). The joss stick was purchased in a local supermarket in Wuhan. Raw wheat straw was obtained from local farmers in Wuhan. After being cut into small segments and washed more than 5 times, raw wheat straw was completely dried in an oven at 90 °C. The dried straw segments were mechanically milled into particles by a cereal pulverizer. The wheat straw powder was sieved through a 160 mesh Tyler screen before being used.

### 2.2. Methods

#### 2.2.1. Aerogel preparation

KGM-based composite aerogel air filter was prepared according to the previously reported method for aerogel preparation with modifications [32]. Gelatin was first dissolved in distilled water in a water bath at 60 °C and stirred at 400 rpm for 0.5 h. Then the potato starch and KGM flour were added gradually and mixed at stirring speed 800 rpm at 90 °C for 1 h to form a mixed sol. Subsequently, the obtained sol was aged at 4 °C for 24 h and transferred into an aluminum tray (570 mm × 650 mm × 30 mm) before frozen at −20 °C for 10 h in an ultra-low temperature freezer. Then the samples were freeze-dried in a freeze drier (FD100, Jiangsu BLK Refrigeration Technology Development Co., Ltd, China) at −35 °C under a vacuum of 5 Pa for 22 h. The obtained aerogel was cut into 350 mm × 250 mm × 5 mm to fit the size of the commercial filter in an air purifier (AC2886, Philip, Netherlands). Five aerogel formulae with different pore-size distribution (Table 1) were chosen according to the previous investigation [25].

#### 2.2.2. Aerogel air filter preparation

The structure and pore-size distribution of filters are of great importance to achieve the optimum air filtration performance. To investigate the purification effect of aerogel in an air purifier, an aerogel air filter with a different structure (Figure 1) were prepared to fit the exact size of the commercial filter to allow it to be put inside the air purifier:

- **a. Flat-structure aerogel air filter with even pore-size distribution**

  The flat-structure aerogel air filter with even pore-size distribution was prepared by combining three pieces of the same kind of aerogels. Some small pieces were inserted between the different aerogel layers as the aerogel cushion. Three kinds of this aerogel air filter were prepared, including K1G2, K1G2S3 and K1G2S3WS1.

- **b. Flat structure with the pore-size distribution from large size to small size**

  According to the previous study [25], the pore-size distribution of KGM-based aerogel could be controlled through the total solid concentration, and the higher the total solid concentration, the smaller the aerogel pore size. Therefore, 50%-K1G2S3, 70%-K1G2S3 and K1G2S3 were used to prepare the flat-structure aerogel air filter with the pore-size distribution from large to small, similar to the previous aerogel air filter with even pore-size distribution.

- **c. Fold-structure aerogel filter preparation**

  The sample of 70%-K1G2S3 was used to prepare the aerogel filter with fold structure by inserting the aerogel piece into a self-made plastic mold.

#### 2.2.3. Air purification effect evaluation

To evaluate the aerogel purification efficiency, a transparent acrylic hood (110 × 60 × 70 cm) was made (Figure 2). Before the test, and the air purifier with different air filter was put inside the hood together with a PM2.5 detector (LB-S08, Lanbaoeyuan Co., Ltd, China) and an air fan. Then one joss stick was burned and...
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Fig. 1. KGM-based aerogel air filter (a, flat-structure aerogel air filter with even pore-size distribution (all three layers had the same pore-size distribution); b, flat structure with the pore-size distribution from large to small (the pore-size distribution were from large size to small size); c, fold-structure aerogel filter preparation (the aerogel were folded to increase the surface area and only one layer was used); d, example photo of the aerogel air filter with flat structure; e, example photo of the aerogel air filter with fold structure; f, original aerogel air filter in the air purifier).

Fig. 2. Schematic diagram (left) and example photo (right) for the air purification effect evaluation.

put into the hood through the operation hole. Immediately, the air fan was switched on to allow the fast and even PM distribution in the hood, and the PM$_{2.5}$ detector became to detect the real-time PM values of the hood, with the operation hole closed. When the PM values of the hood reached over 500 $\mu$g/m$^3$, the joss stick would be taken out and extinguished. Subsequently, the air purifier would be turned on immediately to purify the air in the hood. The PM$_{2.5}$ concentration was recorded every 30 s until the PM$_{2.5}$ concentration reached $<30$ $\mu$g/m$^3$. Each kind of air filter was tested in quadruplicate. To evaluate the purification stability, the optimum aerogel air filter would be used to run the purification test in continuous five cycles.

3. RESULTS AND DISCUSSION

3.1. Purification effect of the flat-structure aerogel air filter with even pore-size distribution

The purification performance of different air filters showed significant differences (Figure 3). The time needed to reduce the PM$_{2.5}$ concentration from 500 $\mu$g/m$^3$ (heavy air pollution) to $<50$ $\mu$g/m$^3$ for K1G2, K1G2S3 and K1G2S3WS1 were 15, 21 and 13 minutes, respectively. Therefore, for the aerogel air filters, the purification capability of K1G2S3WS1 was the best, K1G2 was in the middle and K1G2G3 was not good. A previous study indicated that starch addition could improve the air filtration property as it
Fig. 3. The purification performance of air purifier with different air filters (K1G2, K1G2S3, and K1G2S3WS1 were flat-structure air filters).

Fig. 4. Air purification performance of aerogel filters with pore-size distribution difference.

Fig. 5. Air purification performance of the aerogel filter with the flat structure and fold structure.

Fig. 6. Purification stability of aerogel air filter with fold structure.

reduced the average pore size and benefit close pore formation [30]. This may provide the purification advantages of K1G2S3 at the beginning compared to that of K1G2, but it also showed high air resistance and this may lower its air purification rate later. The further added WS could bring the aerogel pores some unique cavity structure and benefit the pore communication with each other [24, 30], which could make the airflow route complex. Therefore, the particulates would not pass the pores easily and the absorption success rate was significantly increased. The commercial air filter showed superior air filtration performance, and it took only 3 minutes to reduce the PM2.5 concentration from 500 μg/m³ (heavy air pollution) to <50 μg/m³. This was due to its much higher surface area with a multi-folded structure and also the lower pressure drop, which strengthened the airflow speed. However, all KGM-based aerogel filters could reach the same good air quality after a certain purification time, and proper structure design may help to improve their air purification rate.

3.2. Purification effect of the flat-structure aerogel air filter with the pore-size distribution from large size to small size.

One method to improve the aerogel purification efficiency could be the proper combination of the pore-size distribution, which would let the big PM be intercepted by the outer layer with large pore size, medium PM be intercepted by the middle layer with medium pore size and small PM was intercepted by the small pore size. Results (Figure 4) indicated this method brought significant improvements, and the time needed to reduce the PM_{2.5} from ≈500 μg/m³ to <50 μg/m³ for the aerogel air filter reduced...
from 21 minutes (flat structure with even pore-size distribution using K1G2S3) to 8 minutes. At the same time, the air resistance property was significantly improved, and this could explain the very fast air purification rate especially at the early stage, i.e. in the first 10 minutes.

3.3. Air purification performance of aerogel air filter with fold structure

3.3.1. Purification rate
To increase the surface area would be another way to improve air filtration performance. This would require the aerogel samples with good flexibility and 70%-K1G2S3 was chosen. The aerogel with fold structure showed significant air purification improvement compared with the aerogel air filter with flat structure also made by 70%-K1G2S3 (Figure 5), as the purification time to reduce the PM$_{2.5}$ from $\approx$500 μg/m$^2$ to $<50$ μg/m$^2$ was 30 minutes (flat structure) and 11 minutes (fold structure). Their difference was very large, especially in the first 15 minutes. Within the testing time of 30 minutes, the aerogel air filter with fold structure could finally reduce the PM$_{2.5}$ concentration from 500 μg/m$^2$ to 7 μg/m$^2$, while the flat-structure air filter could only reach 46 μg/m$^2$. This should be accredited to their surface difference (fold structure $\approx$ 4023 cm$^2$; flat structure $\approx$ 1961 cm$^2$). Furthermore, the fold-structure air filter had only one layer, and therefore the airflow rate was much faster, reducing the air purification time. Thus, aerogel samples with the fold structure showed a better effect than the flat-structure samples.

3.3.2. Purification stability
As the aerogel air filter with the fold structure had only one layer, its purification stability would be important and five continuous cycle tests were run (Figure 6). Results showed that the air purification time needed to reduce the PM$_{2.5}$ concentration from about 500 μg/m$^2$ to 50 μg/m$^2$ was about 11 minutes for all 5 cycles, indicating good purification stability. This was explained by that the filtration of aerogel filter materials for PM$_{2.5}$ relied on a physical interception, and its action was not affected by the environmental factors [33]. Besides, the strong adsorption between the aerogel surface and the particulate could also prevent the particulate from escaping from the aerogel surface.

4. CONCLUSION

The KGM-based aerogel was used as the air filter in a commercial air purifier and the impacts of the structure and pore-size distribution on the filtration performance were investigated and compared with the commercial air filter. Results indicated K1G2S3WS1 showed the best air filtration property among the three kinds of aerogel air filter, which was explained by that the addition of wheat straw could increase the complexity of the pore path. The filter structure could result in significantly different filtration results. To reduce PM$_{2.5}$ concentration of the test chamber from about 500 μg/m$^2$ to $<50$ μg/m$^2$, the filtration time of flat-structure aerogel filter could be decreased to 8 minutes by changing the size distribution from large size to small size. The fold-structure aerogel filter could have 11 minutes purification time with one piece of aerogel used, and it also showed good purification stability within five purification cycles. Therefore, in addition to the formulae optimization to achieve high filtration performance, physical structure design, like changing pore-size distribution and increasing surface area by making fold-structure aerogel samples, was also of great importance to improve aerogel air filtration property.

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CONFLICT OF INTERESTS

The authors declare they have no conflict of interests.

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