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# Efficient and reusable polyamide-56 nanofiber/nets membrane with bimodal structures for air filtration

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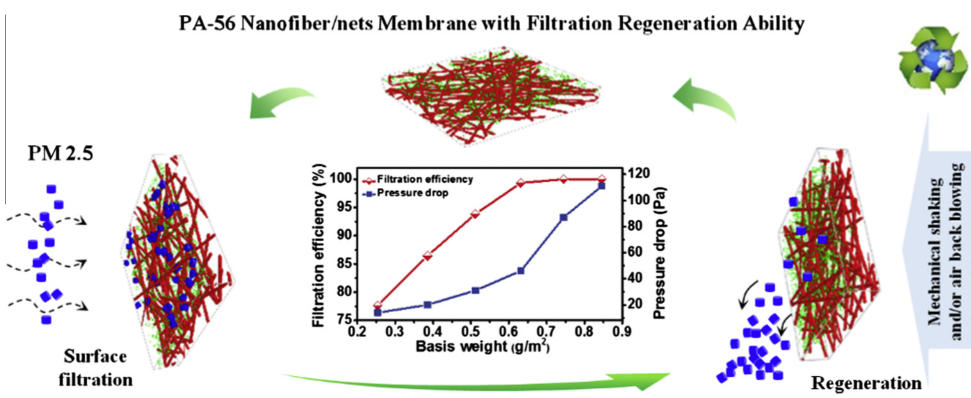
## HIGHLIGHTS

- Bio-based PA-56 NF/N membrane was fabricated via one-step electrospinning/netting.
- 2D nanonets (~20 nm) and stable cavity structures were synchronously constructed.
- Superlight weight and mechanical robustness.
- High filtration efficiency (99.995%) and low pressure drop (111 Pa).
- Surface filtration and dust-cleaning regeneration ability.

## GRAPHICAL ABSTRACT

Bio-based PA-56 membrane composed of the ultrathin 2D nanonets and stable cavity structures can effectively filtrate ultrafine airborne particles with high filtration efficiency, low air resistance, and long service life.

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## ABSTRACT

Nanofibrous media that both possess high airborne particle interception efficiency and robust air permeability would have broad technological implications for areas ranging from individual protection and industrial security to environmental governance; however, creating such filtration media has proved extremely challenging. Here we report a strategy to construct the bio-based polyamide-56 nanofiber/nets (PA-56 NFN) membranes with bimodal structures for effective air filtration via one-step electrospinning/netting. The PA-56 membranes are composed of completely covered two-dimensional (2D) ultrathin (~20 nm) nanonets which are optimized by facilely regulating the solution concentration, and the bonded scaffold fibers constructed cavity structures which are synchronously created by using the $CH_3COOH$ inspiration. With integrated properties of small aperture, high porosity, and bonded scaffold, the resulting PA-56 NFN membranes exhibit high filtration efficiency of 99.995%, low pressure drop of 111 Pa, combined with large dust holding capacity of 49 g/m$^2$ and dust-cleaning regeneration ability, for filtrating ultrafine airborne particles in the most safe manner involving sieving principle and surface filtration. The successful synthesis of PA-56 NFN medium would not only make it a promising candidate

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for air filtration, but also provide new insights into the design and development of nanonet-based bimodal structures for various applications.



## 1. Introduction

With rapid urbanization and industrialization the particulate matter (PM) pollution in air, especially the notorious $PM_{2.5}$, causes growing impact on people's living quality, and it poses serious health threats to the public, fatally interferes with equipment operation, as well as influencing climate and ecosystems [1–3]. Moreover, stricter emission limits for fine particle emissions from industrial processes and automotive exhaust have also contributed to the urgent need for high performance filters with high filtration efficiency, low energy cost, and long service life [4,5]. Fibrous filters are attractive for airborne particle filtration by virtue of their integrated characteristics of cost-effective, ease of scalable synthesis from various materials, universality across a wide range of air filtration fields, etc [6,7]. Generally, the fibrous media for air filtration are designed based on two criteria: (i) fiber diameter, which has a decisive effect on the capturing efficiency of airborne particles [8,9]; (ii) cavity structure, which can facilitate the air flow penetration across the medium and reduce the energy cost [7,10].

Nowadays, benefiting from the relatively small diameter, the nanofiber based filtration media evoke more and more attentions due to their enhanced filtration performance (especially the filtration efficiency) in actual operating environments [11–13]. Compared with various routes including melt-blown [14], template synthesis [15], sea-island spinning [16], phase-separation [17], plasma treatment [18], etc., electrospinning has emerged as the most versatile and effective technology for large-scale fabricating nanofibers with controlled morphologies and functional components from various materials [19,20]. And, many electrospun filtration media (usually with diameter of 100 nm to 1 μm), such as polyacrylonitrile (PAN) [21], PAN/poly(acrylic acid) [22], PAN/polyurethane (PU) [23], polyvinyl chloride/PU [7], polyetherimide [24], polysulfone [25], poly(lactic acid) [26], and polyamide-66 (PA-66) [27] , have been successfully prepared and exhibit effectively enhanced filtration performance. However, they still suffer from some drawbacks: inadequate filtration performance, weak mechanical property, and short service life caused by the deep bed filtration manner, all of which can be ascribe to the limited structural controllability involving thick fiber diameter (not real nanoscale of <100 nm) and easy-collapsed cavity structure.

Electrospinning/netting [28], which evolves from the electrospinning technique, has gained an increasing appeal due to its capacity for one-step fabricating 2D ultrathin (~20 nm) "nanonets" with large quantities and uniform size. In view of their intriguing characters, ranging from extremely small diameter, high porosity, and 2D pore structures to enhanced interconnectivity, the resulting nanonets stand out from the conventional nanomaterials as an ideal air filtration medium [29]. Previously, the novel PA-66 NFN filtration membrane was prepared in our group for the first time, and exhibited relatively high filtration efficiency of 99.9%; however, its air resistance was extremely high (~200 Pa) owing to the limited nanonet coverage rate, together with the inadequate and unstable cavity structures [27]. Considering the previously acquired success and the original theory of that larger void in the medium can substantially reduce the friction induced air resistance [10,30], the combination of 2D ultrathin nanonets and stable cavity structures can be an effective strategy to enhance the filtration performance for the filter materials. Bio-based polymer PA-56, as one kind of alternatives to petroleum-based polymers, is derived from renewable sources; and it exhibits broad prospects for various applications in the sustainable society, owing to their excellent performance related to high-temperature and chemical resistance, toughness and easy processability [31,32]. To date, considerable efforts have been devoted to the synthesis of polymer PA-56, however, nearly no effort has been given to the development of the PA-56 nanofibers, let alone the PA-56 NFN membranes with novel 2D nanonets and stable cavity structures for the airborne particle filtration.

Herein, we have designed and fabricated the bio-based PA-56 NFN membranes with bimodal structures, including novel nanonets comprising of interlinked ultrathin nanowires (~20 nm) and stable cavity structures built by the bonded scaffold fibers for air filtration via one-step electrospinning/netting. The coverage rate and pore structure of the nanonets in PA-56 membranes are finely controlled by tuning the solution concentration, and their effect on the filtration performance of the membranes was systematically studied. Moreover, PA-56 NFN membranes composed of 2D nanonets and stable cavity structures are thoroughly designed and optimized based on the facile acetic acid ($CH_3COOH$) inspiration. Additionally, the pore structures, mechanical properties, and filtration performance (especially the dust holding capacity) of the PA-56 NFN membranes are carefully investigated and compared with typical high-efficiency particulate air (HEPA) filters; and, filtration simulations based on two different filtration manners are proposed to elaborate the contribution of 2D ultrathin nanonets and stable cavity structures on enhancing the service performance in air filtration.

## 2. Experimental section

### 2.1. Materials

PA-56 chips were supplied by Shanghai Kaisai Biotechnology Research And Development Center Co., Ltd., China. Formic acid (>88%) (HCOOH), $CH_3COOH$ (>99.5%), and hydrophobic silicon dioxide ($SiO_2$) nanoparticles (7–40 nm) were purchased from Shanghai Chemical Reagents Co., Ltd., China. The Hollingsworth & Vose (H&V) HB7613 and HC4683 glass media (78 g/m$^2$), as two kinds of Standard Glass Grades US used as HEPA and Sub-HEPA filters respectively, were supplied by Hollingsworth & Vose (Asia Pacific) Co., Ltd., China. The nonwoven polypropylene substrate with negligible filtration performance (filtration efficiency of 3% and pressure drop of 1 Pa under the face velocity of 32 L/min) was kindly provided by Shandong Huaye Nonwoven Fabric Co., Ltd., China. All chemicals were of analytical grade and were used as received without further purification.

### 2.2. Preparation of PA-56 solutions

PA-56 solutions with solo solvent were prepared by dissolving PA-56 chips in HCOOH with a vigorous stirring process for 24 h at room temperature. The concentration of PA-56 was adjusted to 12, 15, 18, 21, and 24 wt%, respectively. While the PA-56 solutions (18 wt%) with mixed solvent were obtained by using the HCOOH/$CH_3COOH$ mixture with stirring for 24 h. The solvent weight ratio of HCOOH/$CH_3COOH$ in the mixed solutions were 3/1, 1/1, and 1/3, respectively. The detailed compositions and properties of the relevant solutions were shown in Table S1.