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Short communication

Antimicrobial nanoparticle-coated electrostatic air filter with high filtration efficiency and low pressure drop

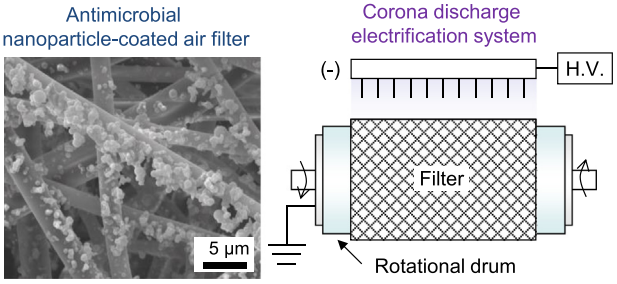
Kyoung Mi Sim [a], Hyun-Seol Park [b], Gwi-Nam Bae [c], Jae Hee Jung [c,*]

[a] Department of Integrated Biomedical and Life Science, Korea University, Anam-ro 145, Seongbuk-gu, Seoul 136-701, Republic of Korea
[b] High Efficiency and Clean Energy Research Division, Korea Institute of Energy Research, 152 Gajeong-ro, Yuseong-gu, Daejeon 305-343, Republic of Korea
[c] Center for Environment, Health and Welfare Research, Department of Energy and Environmental Engineering, Korea University of Science and Technology (UST), Korea Institute of Science and Technology (KIST), Hwarang-ro 14-gil 5, Seongbuk-gu, Seoul 136-791, Republic of Korea

HIGHLIGHTS

- An antimicrobial *S. flavescens* nanoparticle-coated electrostatic (ES) filter was prepared.
- A corona discharge electrification process enhanced the filtration efficiency of the air filter.
- The antimicrobial ES filter had high filtration efficiency and a low pressure drop.
- This study provides useful information about the development of a hybrid air purification system.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, we demonstrated an antimicrobial nanoparticle-coated electrostatic (ES) air filter. Antimicrobial natural-product *Sophora flavescens* nanoparticles were produced using an aerosol process, and were continuously deposited onto the surface of air filter media. For the electrostatic activation of the filter medium, a corona discharge electrification system was used before and after antimicrobial treatment of the filter. In the antimicrobial treatment process, the deposition efficiency of *S. flavescens* nanoparticles on the ES filter was ~12% higher than that on the pristine (Non-ES) filter. In the evaluation of filtration performance using test particles (a nanosized KCl aerosol and submicron-sized *Staphylococcus epidermidis* bioaerosol), the ES filter showed better filtration efficiency than the Non-ES filter. However, antimicrobial treatment with *S. flavescens* nanoparticles affected the filtration efficiency of the filter differently depending on the size of the test particles. While the filtration efficiency of the KCl nanoparticles was reduced on the ES filter after the antimicrobial treatment, the filtration efficiency was improved after the recharging process. In summary, we prepared an antimicrobial ES air filter with >99% antimicrobial activity, ~92.5% filtration efficiency (for a 300-nm KCl aerosol), and a ~0.8 mmAq pressure drop (at 13 cm/s). This study provides valuable information for the development of a hybrid air purification system that can serve various functions and be used in an indoor environment.

* Corresponding author.
E-mail address: jaehee@kist.re.kr (J.H. Jung).

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1. Introduction

Microorganisms are ubiquitous in the environment. They are present in water, soil, air, plants, animals, and humans. In particular, as indoor air quality (IAQ) management has become an important issue for modern society, interest in microorganisms has mainly focused on their presence in the air, where they are referred to as bioaerosols (Goyer, 2001; Nazaroff, 2014). Bioaerosols are airborne particulate matter with a biological origin, and include viruses, bacteria, fungi, and a variety of living materials. They can travel freely with airflow movement and can spread over a wide area in a short period of time (An et al., 2004; Smith et al., 2009). Exposure to high concentrations of these airborne pollutants can have harmful effects in humans, including contagious infectious diseases, acute toxicity, allergies, and cancer (Larsson et al., 2004; Morawska and Zhang, 2002; Pöyhönen et al., 2004). Therefore, controlling exposure to bioaerosols is important for disease control and prevention, and there is a growing research interest in microbiological indoor pollutants.

Aerosol filtration is the most widely used technique for the control and removal of hazardous bioaerosols, and is applied in a variety of residential and industrial air conditioning systems for indoor air cleaning (Fisk, 2013; Hinds, 2012; Li and Hopke, 1992). Fibrous filters have been widely used to separate solid matter from particulate laden airflow streams because of their simple structure and low material costs. There are four physical mechanisms of particle filtration by which an aerosol particle can be deposited onto a fiber in a filter: inertial impaction, gravitational sedimentation, interception, and diffusion (Podgórski et al., 2006). Fiber filters can be classified as pre filters, medium filters, high-efficiency particulate air (HEPA) filters, or ultra-low particulate air (ULPA) filters, according to their particle filtration efficiency (Ahn et al., 2006; Schroth, 1996). The filtration efficiency of a medium filter is 60–90% and the corresponding pressure drop is 15–30 mmAq. A HEPA filter can eliminate 99.97% of particles with a particle diameter of 0.3 μm with a pressure drop of 25–50 mmAq. A ULPA filter removes more than 99.999% of 0.12–0.17-μm particles, with a similar pressure drop to a HEPA filter (Chuaybamroong et al., 2010; Hanley et al., 1994; Jamriska et al., 1997). HEPA and ULPA filters are often used in cleanrooms, electronic semiconductors, or as indoor air purifiers to remove unwanted particles from the air. The filtration efficiency of a general fiber filter is increased as the solidity of the filter increases, which is directly proportional to the air pressure drop. Therefore, for a general air filter, a high pressure drop is unavoidable, which in turn requires a large loss of energy to achieve a high filtration efficiency (Fisk et al., 2002).

When filter fibers have been charged, the electrostatic force between particles and fibers can significantly augment the filtration efficiency without increasing the filter pressure drop. This is particularly useful for improving the filtration of particles in the size range of 0.15–0.5 μm (Aussawasathien et al., 2008). A charged fiber creates an electric field in its vicinity that exerts a force on a charged particle. The field created by a charged fiber can also polarize a particle, and the force on a polarized particle has an important role in increasing the filtration efficiency of small particles. Normally, electret (or electrostatic) filters are made of dielectric polymer fibers that have a quasi-permanent electrical charge. Also, the fibers gain an electric charge from their surroundings, depending on various electrical charging processes such as corona charging, triboelectric charging, or induction charging (Gu and Schill, 1997; Romay et al., 1998; Tsai et al., 2002). Because of its advantages, electrostatic (ES) filters have been widely used in residential and industrial air conditioning systems (Boelter and Davidson, 1997; Grass et al., 2004).

Although air filtration systems can be used to improve IAQ, they can become a source of contamination by microorganisms harmful to human health. Antimicrobial filters can provide significant benefits, because they can rapidly inactivate captured microorganisms and minimize the number of live/viable particles resuspended from the filter by passing air (Pyankov et al., 2008). Various techniques have been investigated to impart antimicrobial activity on filter media. Filter coating techniques, using an antimicrobial material such as silver (Ag) and copper (Cu) nanoparticles, carbon nanotubes (CNT), and biocidal chemicals are considered to be promising methods for imparting antimicrobial ability with relatively little cost (Ji et al., 2007; Lee et al., 2010). Recently, extracts of natural products with antimicrobial activity have been considered as novel, efficient, and cost-effective materials for the development of antimicrobial filter media (Dixon, 2001). Plant extracts, such as *Melaleuca alternifolia* (tea tree), *Eucalyptus*, and *Sophora flavescens*, in particular, can be used as a coating for filters to inactivate fungal spores, bacteria, and influenza viruses (Huang et al., 2010; Hwang et al., 2015a, 2015b; Pyankov et al., 2008; Pyankov et al., 2012). The treatment of filter surfaces with nanosized particles of a natural product is an effective method for enhancing their antimicrobial activity, because the nanosized natural products provide the maximum possible specific surface area to contact surrounding agents.

In this study, we developed an antimicrobial natural-product nanoparticle-coated ES air filter. Antimicrobial natural-product *S. flavescens* nanoparticles were produced using an aerosol process consisting of nebulization–thermal drying, and were continuously deposited onto the surface of air filter media. For the electrostatic activation of the surface of the filter medium, a corona discharge electrification system was used before and after the antimicrobial treatment of the filter media. We evaluated the antimicrobial ES air filter in terms of the deposition efficiency of antimicrobial nanoparticles, the filtration efficiencies of nanosized KCl aerosols and submicron bacterial bioaerosols, the filter pressure drop, and its antimicrobial activity against bacterial bioaerosol. Additionally, we compared the filtration performance before and after the additional charge re-activation process.

2. Materials and methods

2.1. Preparation of the antimicrobial nanoparticle-deposited ES filter

Dried *S. flavescens* roots were purchased from the Kyung-dong Oriental Herbal Market, Seoul, Korea (Jung et al., 2013; Sim et al., 2014a, 2014b). A voucher specimen is on record at the Functional Food Center, Korea Institute of Science and Technology (KIST), Gangneung Institute, Korea. Dried *S. flavescens* roots (600 g) were extracted three times with pure ethanol (1 L) by refluxing for 3 h. After filtration, the ethanol extract was evaporated in *vacuo* and freeze-dried. A 0.25-g sample of *S. flavescens* powder was dissolved in 40 mL of ethanol and sonicated for 10 min. The solution was then filtered through a cellulose acetate membrane filter with a pore size of 0.24 μm to eliminate any insoluble residue.

To prepare an antimicrobial ES air filter, *S. flavescens* nanoparticles generated using the nebulization–thermal drying process were deposited onto the fiber surfaces of an ES filter (Fig. 1(a)). Twenty milliliters of the *S. flavescens* solution were poured into a one-jet Collison nebulizer (BGI Inc., Waltham, MA, USA). The nebulizer was supplied with 1 L/min of HEPA-filtered clean air. The resulting *S. flavescens* aerosol was passed through both an activated carbon absorber tube and a thermal glass quartz tube heater (75°C temperature and ~3 s residence time) to remove the ethanol. Activated carbon is a form of carbon processed to have small, low-volume pores that increase the surface area available for adsorption or chemical reactions. The size and number concentration of the nanoparticles generated were measured using a scanning mobility particle size (SMPS) system consisting of a differential mobility analyzer (DMA 3081; TSI Inc., Shoreview, MN, USA) (Chen et al., 1998; Siefert, 1984) and a condensation particle counter (CPC 3010; TSI Inc.) (Gamero-Castano and de la Mora, 2000; Kaufman, 1998) based on the electrical mobility of the particles in the range of 14–673 nm. The *S. flavescens* nanoparticles were deposited on ES filters (polyurethane fiber filter; fiber diameter = 2 μm; thickness = 0.6 mm). The quantity of deposited *S. flavescens* nanoparticles on filters was