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Review

Reactive Air Disinfection Technologies: Principles and Applications in Bioaerosol Removal

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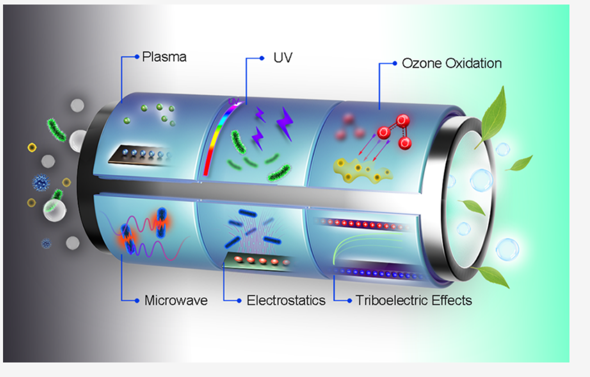

ABSTRACT: As COVID-19 and other infectious diseases continue to spread globally, removing airborne pathogens from confined spaces such as buildings, transportation carriers, and stations is becoming increasingly crucial to curbing transmission and reducing human infection rates. Bioaerosols can act as vectors or media that could store and transport air pollutants and pathogens. To mitigate the adverse effects of bioaerosols and effectively control epidemics, this work reviews the current state-of-the-art air purification processes and technologies available on the market or demonstrated in laboratory and industrial settings, including ozone oxidation, UV disinfection, and photocatalysis. These reactive air purification processes can be used in conjunction with adsorption or filtration-based systems to enhance disinfection besides the physical capture of particulates or the removal of volatile organic compounds (VOCs). This review aims to provide a concise yet comprehensive overview of various reactive air purification technologies. Their principles, applications, and limitations are briefly discussed to provide insight and guidelines for further development of new air purification processes to address emerging airborne contaminant issues.

KEYWORDS: *Air disinfection, Bioaerosol, COVID-19, Catalytic filtration, Viral inactivation*

1. INTRODUCTION

The coronavirus outbreak in 2019 (COVID-19) has been spreading throughout the world and has caused severe respiratory syndrome and other health issues. Similar to other airborne diseases such as Ebola, Middle East respiratory syndrome-associated coronavirus (MERS-CoV), and severe acute respiratory syndrome (SARS), COVID-19 and its recent variants (e.g., Delta and Omicron) can be transmitted through the air or aerosols. As an important vector for airborne pathogens, bioaerosols mostly originate from plants or animals with small sizes ranging from 0.001 to 100 μm, which may contain pathogenic alive or dead microorganisms (e.g., bacteria, viruses, and fungi), as well as nonmicrobial species such as dust, animal biological debris, fungal spores, hyphae, allergens, endotoxins, and mycotoxins. Bioaerosols could migrate in ambient air due to their being lightweight and having small sizes.[1] *Coxsackievirus* A16, *Coxiella burnetii*, and *Mycoplasma hyopneumoniae* were reported to transport over several kilometers by wind.[2,3] Residential environments may expose elevated risks to humans from the indoor bioaerosol contamination presented by those infected groups when sneezing or coughing, which is estimated to spray an average virus density to 10^6−10^8 PFU·mL^{-1} (approximately 37% of 50 μm droplets before dehydration may carry one or more viruses).[4−6] Health implications may include respiratory distress and sensitization (e.g., eczema and asthma), microbial infection, allergenic reaction, and fatal diseases such as SARS outbreak in 2003, the H1N1 viral infection in 2009, and the COVID-19 pandemic starting in 2019. The estimated minimum infective dose of COVID-19 virus for trigging severe acute respiratory syndrome is 1.26−7 × $10^{6.25}$ PFU (about 1−10^7 droplets of 50 μm in diameter).[7]

To mitigate airborne infection, many countries, such as the United States, have launched social distancing policies or advisory practices such as maintaining at least 6 feet between people to avoid contact with the potential airborne virus or aerosols from coughs, sneezing, and even normal breathing or speaking. Generally, the viral concentration in bioaerosols and residence time of bioaerosols could exponentially decay with time of travel or droplet size.[8] However, high concentrations of bioaerosols may still occur and accumulate in public places or confined environments such as hospitals, train stations, airports, classrooms, and offices. For example, Park et al.

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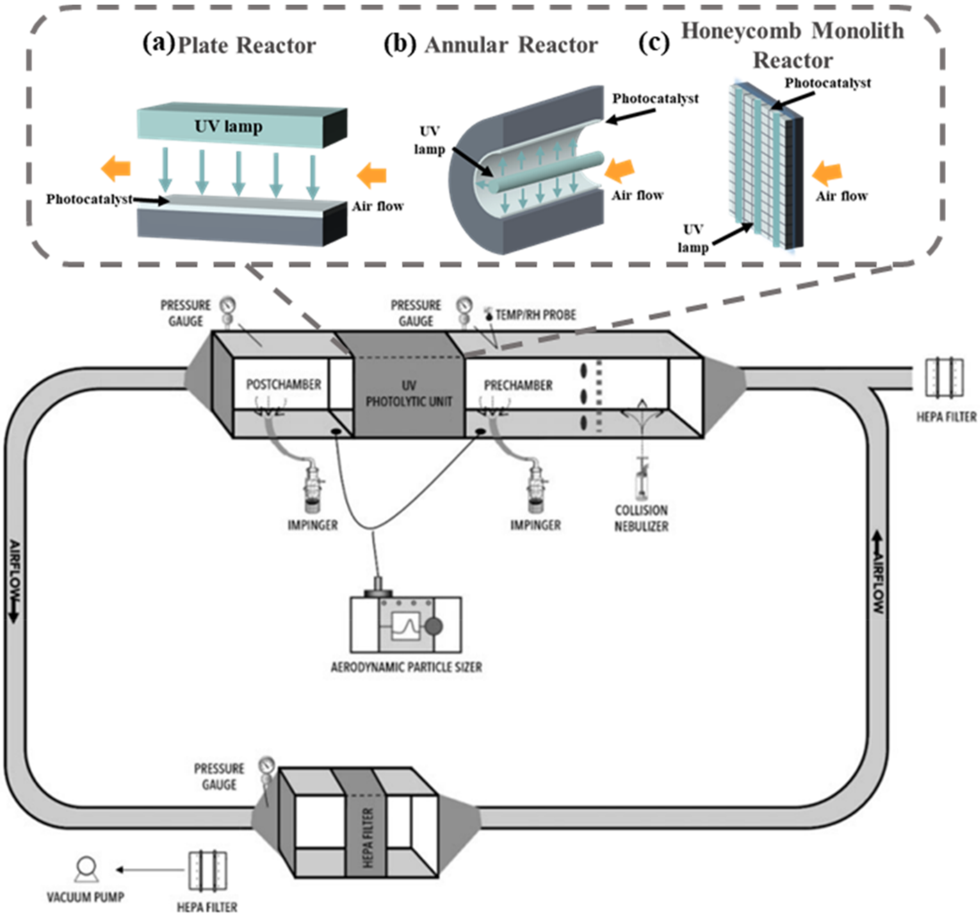

Figure 1. (a) The incorporation of UV lamps into air filtration. (b) Annular and (c) multiannular UV photoreactors. The bottom graph is reproduced with permission from Barnewall et al.[35] Copyright 2021, Cambridge University Press, licensed under https://creativecommons.org/licenses/.

reported that bacterial concentration in the air reached 720 CFU·m^{-3}, and fungi was at a level of 77 CFU·m^{-3} in hospital lobbies.[9] Health authorities report approximately 500,000 health care workers in the U.S. could be regularly exposed to aerosols from surgery annually.[10] Traditional adsorption- or adsorbent-based air filters are usually effective for capturing bioaerosols and reducing the transmission of infectious viruses in heating, ventilation, and air conditioning (HVAC) systems. For example, high minimum efficiency reporting value (MERV) rated filters and face piece respirators (FFRs) are commonly used in healthcare facilities. However, they have limited capacities to capture and inactivate airborne pathogens, particularly small viruses that pass through the filter, and the collected bioaerosols are not inactivated but may accumulate on the filter surface and spread for long periods at higher humidity, potentially becoming a new source of contamination and pathogen reproliferation, posing a secondary risk to human health.

Effective air sterilization and purification are critical to mitigating the challenges of airborne pathogen transmission and protecting the public health. There are many types of air purification technologies that are reported and even commercialized in industrial and household applications such as adsorption by activated carbon adsorbents and photocatalysis for disinfection and volatile organic compound removal.[11,12] Additionally, for industrial waste gas treatment, other technologies such as electrostatic precipitator for particulate removal and catalytic conversion to reduce nitrogen and sulfur oxides were all reported previously, which are not the focuse of this review. Besides, some review articles also reported other technologies or processes, such as lysozyme technology[13] and disinfectant spraying,[14] which are also not within the scope of this review. Instead, this review article presents a comprehensive survey of air cleaning technologies that employ reactive disinfection processes such as UV photolysis, ozonation, and electrically and microwave-driven reactions. The present review article aims to elucidate the basic mechanisms of such chemical or catalytic disinfection processes. Their principles, applications, and limitations are briefly discussed to provide insight and guidelines for the further development of new air purification processes to address emerging airborne contaminant issues.

2. REACTIVE AIR DISINFECTION TECHNOLOGIES

2.1. UV Disinfection and Photocatalysis. Ultraviolet (UV) light has widely been used in both water and air disinfection.[15,16] Under UV irradiation (especially under the germicidal UV wavelength of 254 nm), microorganisms absorb UV photons that cause damage to their deoxyribonucleic acid (DNA), and the main mechanism of inactivation is the formation of pyrimidine dimers from the absorption of photons between adjacent thymine residues, which prevents the microbe from replicating.[17−19] Vacuum UV (VUV) with wavelengths <200 nm demonstrates stronger germicidal effects

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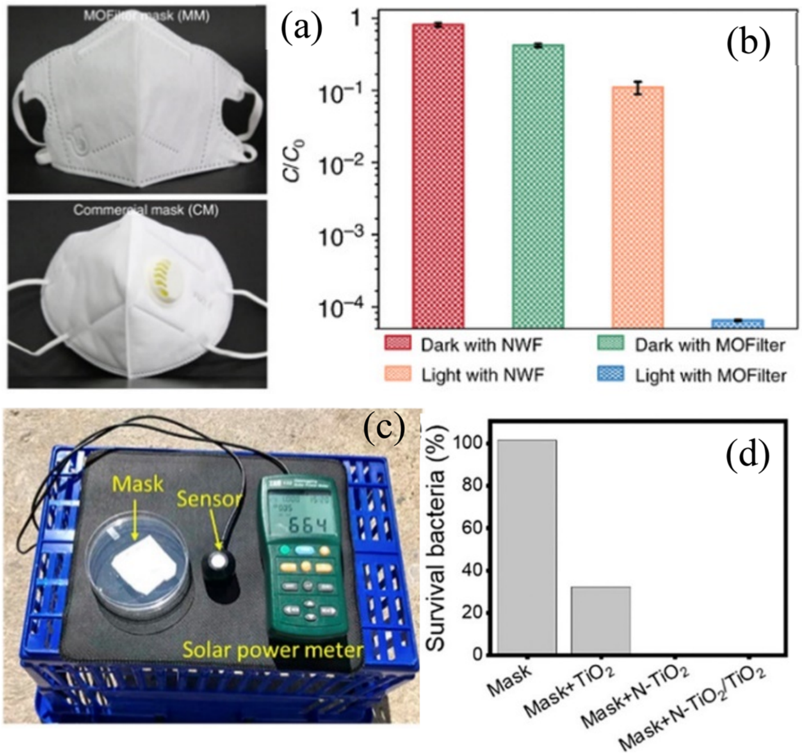

Figure 2. (a) Photo of the ZIF-8-loaded nonwoven fabrics (MOFilter) mask and a commercial nonwoven fabrics (NWF) filter mask. (b) Comparison of the ratio of the residual *E. coli* cells (C) over the initial bacterial level (C_0) in the air that passed through the two types of filter masks under light and dark conditions, respectively. (c) Disinfection performance test of the filter mask under real sunlight irradiation. (d) Survival ratio of bacteria on TiO_2-, N-TiO_2-, and TiO_2/N-TiO_2 (7:3 weight ratio)-loaded masks and unloaded masks. Reprinted with minor modifications and permission from Li et al.[44] Copyright 2021, American Chemical Society.

due to its higher photon energy (6.70 eV) than those (4.88 and 3.40 eV) of UV irradiation (254 and 365 nm), despite its high potential for ozone generation in air or water.[20]

Compared to other disinfection (e.g., ozonation and photocatalysis), UV air filtration is the most common and highly commercialized technique for inactivating a wide spectrum of bacteria, spores, molds, and viruses.[21] UV disinfection requires proper exposure intensity and time (e.g., UV dose) to warrant the microbial inactivation rates or efficiency. For example, it takes 36 s of irradiation with 254 nm low-pressure mercury vapor (LP-Hg) lamps at 20.06 mJ·cm^{-2} to reduce the concentration of SARS-CoV-2 by 99.99% (3 log) on plastic and stainless steel surfaces.[22] Exposure or contact time also varies with different pathogens species. Some UV-resistant bacterial and mold spores may require a high dosage of UV light (e.g., 7−59 mJ·cm^{-2}).[23,24] For instance, 23−28 mJ·cm^{-2} is usually required to reach 90% (1 log) removal of bacterial spores such as strains Sterne and Ames.[25] However, UV lamps are relatively energy consuming (80−120 W·cm^{-2}) with short life spans (800−1000 h) and are not as widely and conveniently available as visible light sources (natural sunlight or room lights). Thus, visible-light driven photocatalysis is emerging and gaining increasing interest along with the development of visible-light-driven photocatalysts such as Ag_3AsO_4 and carbon- or nitrogen-doped titanium dioxide (TiO_2).[26] Some commercial photocatalysts used in air purification systems between 1999 and 2018, such as TiO_2 and modified TiO_2, have been proven effective against a wide range of microorganisms.[27]

Moreover, a low exposure time in most UV disinfection technologies or processes (e.g., a few microseconds or seconds) could reduce the effectiveness of air disinfection. For instance, the efficacy of UVC irradiation in killing microorganisms may decrease when relative humidity and air dust levels increase, as they can absorb or block UV and provide shelter to airborne microorganisms.[28,29] Additionally, the efficiency of bioaerosol deactivation is highly dependent on the distribution patterns of irradiance and the degree of air mixing.[30,31] Therefore, a well-designed UV reactor and configuration are crucial for sufficient UV exposure. Figure 1a−c demonstrates three common configurations of UV reactors (i.e., plate, annular, and honeycomb reactors), respectively, that could be coupled with an air filtration system. The UV disinfection efficacy could be limited by environmental factors (humidity, irradiation distance, or exposure time) and UV resistance or self-healing of some microorganisms.[32,33] For example, following 3 h of UV (254 nm) irradiation, the repair phenomenon of airborne MS2 phage was observed, with a photoreactivation percentage ranging from 18.98% to 35.54%.[34] The combination of high-efficiency particulate air (HEPA) filtration and UVC light (254 nm) has been used in the removal of SARS-CoV-2 bioaerosols with a removal rate of 93% reducing the particle count from 79 to 5 particles.[35]

Photocatalysis can be achieved under UV (180−365 nm) and visible light (400 nm and above). Compared to visible light, UV irradiation has greater photon energies and photogeneration efficiency, which typically enable greater efficacy of disinfection.[36] For example, UVA photocatalysis (λ = 350−400 nm; I = 0.65 mW·cm^{-2}) inactivated 99.8% of influenza virus H3N2 within 30 min on Pt/TiO_2-coated glass.[37] UVC photocatalysis (λ = 254 nm; I = 4.5 mW·cm^{-2})

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inactivated 99.97% of murine norovirus within 10 min in a TiO_2 photocatalytic reactor.[38] Photocatalysis reactions under VUV (vacuum ultraviolet light) conditions with 0.004−0.125 s irradiation times removed airborne MS2 viruses from the air that passed through an air purifier with a flow rate of 33 L·min^{-1}.[39] The aerosol microbial suspensions made of Gram-negative bacteria (*Pseudomonas aeruginosa*), Gram-positive bacteria (*Staphylococcus aureu*, methicillin-resistant *Staphylococcus aureus*, *Aspergillus fumigatus*), and fungi (*A. fumigatus*) were injected at a flow rate of 1500 mL·min^{-1} and 0.3 min residence time into a photoreactor with a honeycomb structure of UVA/TiO_2 and yielded removal rates of 92.0%, 88.0%, 93.0%, and 80.7%, respectively.[40] Besides, visible-light-driven photocatalysis is also reported for air disinfection.[41,42] For example, simulated sunlight at the intensity of 100 mW·cm^{-2} was applied to inactivate all the filtered *E. coli* cells in the air on nonwoven fabrics coated with bactericidal ZIF-8 (MOFilter) and nitrogen-doped titanium dioxide (N-TiO_2).[43,44] Figure 2 illustrates the fabrication of the commercial mask N95 with modifications of photocatalysts and the corresponding air disinfection efficiency comparisons.[44] For example, the ZIF-8-loaded nonwoven fabrics (MOFilter) exhibited high photocatalytic activity and disinfection power as indicated by the lowest survival under light exposure (Figure 2a, b). By contrast, the pristine nonwoven fabrics (NWF) mask caused a slight reduction of the bacterial level in filtered air. Furthermore, coating with visible-light-responsive photocatalysts such as N-TiO_2 led to 100% of bacteria on the mask under real sunlight exposure (Figure 2c, d). Nevertheless, photocatalysis or photocatalysts are subjected to surface fouling or inactivation, which is inevitable in practical implementations due to the deposition of dust or other particles. Thus, cleaning the photocatalyst coating is essential for maintaining the catalyst activity. Photocatalysis disinfection may suffer the same limitations as UV disinfection, such as light penetration and exposure time.

2.2. Ozone Disinfection. Ozone disinfection is a widely used technique in various industries, including food disinfection, water treatment, and tooth cleaning.[45] Ozone could be generated by splitting oxygen molecules into reactive oxygen atoms that reform into ozone under a dielectric barrier discharge (DBD).[46,47] The triatomic molecule of oxygen (O_3) is unstable and quickly degrades to the stable state (diatomic oxygen), giving rise to formation of secondary oxidants (hydroxyl radicals) that have high reactivity and short reaction time.[48] Thus, ozone is a strong oxidant with a standard redox potential of 2.07 V[49] and nonselectively oxidizes organic matter without producing chemical residuals and microbial resistance. As a result, its antimicrobial activity is nearly 3000 times that of chlorine with its oxidation capacity about 600 times that of chlorine. Furthermore, superior to UV disinfection, ozonation could effectively inactivate airborne pathogens without the issues of penetration.[50] Ozone can not only inactivate enveloped viruses by oxidizing their outer envelope but can also inactivate nonenveloped viruses by peroxidation of their outer proteins[51−53] and thus impairing viral adhesion to host cells. Besides, the unsaturated fatty acids present in the lipid envelope could be oxidized by ozone, leading to destruction of single-stranded RNA.[54,55]

A typical ozone reactor in Figure 3 was shown to remove greater than 99% of four model phages: MS2, φ6, PR772 and φX174, which represent norovirus, influenza, adenovirus, and single-stranded DNA phage, respectively, under 1.23 ppm

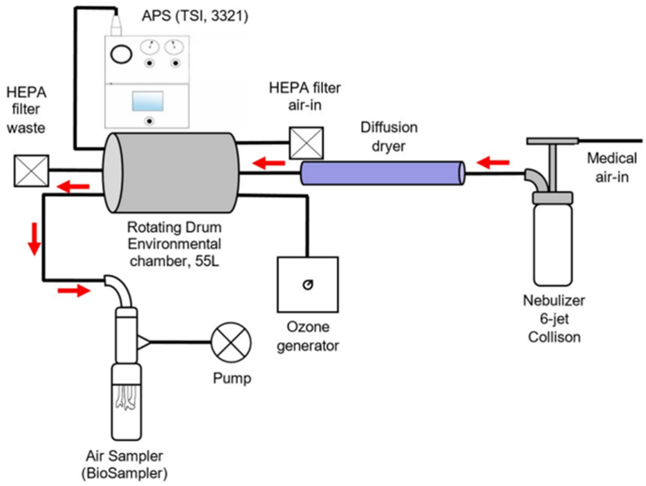

Figure 3. Schematic of a typical aerosol disinfection reactor assembly for ozonation. Reprinted with permission from Dubuis et al.[56] Copyright 2020, Public Library of Science, licensed under Attribution 4.0 International (CC BY 4.0) and https://creativecommons.org/licenses/by/4.0/.

ozone exposure for 40 min at a relative humidity of 85%.[56] Under an ambient environment, ozone was able to achieve over 99.9% inactivation of influenza virus (an enveloped virus) and Feline calicivirus (a nonenveloped virus) on the glass surface.[54] Ozone oxidation had achieved approximately 99.89%, 99.49%, and 98.74% inactivation of the total aerobic mesophilic bacteria, *Enterobacteriaceae*, and yeast mold, respectively.[57] In addition to effectively inactivating bacteria and viruses, ozone oxidation can inhibit the germination of fungal spores. Germination of *Botrytis cinerea* (*B. cinerea*), a necrotrophic fungus spore, was inhibited at C × T product of 700 μL·L^{-1} × h dose of ozone.[58] Ozone gas also significantly prevented the growth and development of aspergilli from inoculate.[59] Recently, Wang et al.[61] combined ozone with photocatalysis to achieve the inactivation efficiency of 99.99% for *E. coli* cells in aerosol with an ultrashort retention time of 8.07 s (relative humidity = 90%) via the significant improvement of reactive oxide species (ROSs) with ozone compared to only photocatalysis. The inactivation rate of viruses and other microorganisms increased with the long exposure times, high ozone concentration, humidity, and temperature.[60] However, prolonged exposure to ozone in ambient air (e.g., 1 ppm for 4 h at 37 °C) is considered harmful to human lungs and can cause inflammation and impaired lung function.[61] This means that for many areas with high cleanliness requirements (e.g., ICU wards in hospitals), good ventilation is required to reduce the remaining ozone and prevent human exposure.[62] Moreover, the ozone cost and production yield vary in the range of 35−110 eV·molecule^{-1} and 15−55 g·kwh^{-1}. Besides this, high capital, operation, and maintenance costs (ca. 10 kW·kg^{-1} O_3) in many ozonation contacting systems (e.g., bubble columns, injectors, spray chambers, or diffusers) also hold back wide applications. Therefore, ozone for bioaerosol purification may still be in an infant stage compared to the widespread use of ozone in water treatment and food industry disinfection.

2.3. Electrically Driven Air Disinfection. Different electrified technologies have demonstrated effective microbial pathogen inactivation in water,[63] but this approach is not commonly studied for air or bioaerosol disinfection. One such

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method is electrochemical disinfection, which relies on the generation of powerful oxidants such as H_2O_2, O_3, or radicals on the electrode surface when water or other substances (e.g., Cl^-) react with anodic or cathodic materials.[64,65] It is reported that 10−13 mg·L^{-1} of mixed oxidants can be generated electrochemically in water and achieved more than 99.999% (>5 log) inactivation of MS2 and *E. coli* cells within 90 min.[66] The inactivations of *Cryptosporidium parvum* oocysts and *Clostridium perfringens* spores by electrochemically produced mixed oxidants at a dose of 5 mg·L^{-1} were over 99.9% (>3 log) in 4 h.[67] Air disinfection could possibly be operated by passing the feed gas through a solution containing electrochemically produced mixed oxidants. For instance, the SARS-CoV-2 viruses were rapidly inactivated by over 95% in only 30 s and 99.99% in 5 min at a voltage of 5 V via formed O* on the lattice oxygen ($O_{lat}O^*$) of an in situ-formed nickel oxide hydroxide (NiOOH) anode surface that can oxidize the peptide chains and decompose the peptide backbone of the receptor binding domain (RBD) of spike glycoprotein. Moreover, electrically conductive carbon coatings made of graphene could achieve ∼99% inactivation of *Pseudomonas aeruginosa* bacteria and 100% inactivation of T4 virus under a current density of 4.5 mA·cm^2 (a voltage potential of 0.3 V).[68] This type of conductive air filter is widely demonstrated using different coating materials such as Co_3O_4/Ag nanoparticles,[69] copper nanowire,[70] ZnO nanospines,[71] and iron oxide nanowires,[72] which achieved a 7 log inactivation within 10 s toward *S. epidermidis* of indoor bioaerosols. Combined effects of hydroxyl radicals, electroporation, and Joule heating are responsible for the inactivation mechanisms of bacteria. Figure 4a−d illustrates a schematic of air filtration with the laser-induced graphene (LIG)-coated filter mounted on a vacuum filtration system, where a poly(ether sulfone) (PES) filter coated with LIG could achieve surface heating or joule heating for sterilization when charged by a DC current.[73] The electrified filters could be Joule heated to 100−380 °C depending on the coating materials (Figure 4e).

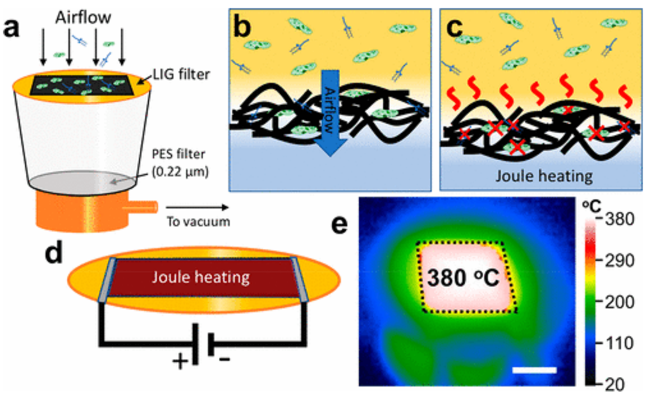

Figure 4. (a) Air filtration with the laser-induced graphene (LIG)-coated filter. (b), (c) Schematic of filtration with/without Joule-heating. (d) Schematic of the Joule heating setup in which a potential is applied across the filter for Joule heating. (e) Infrared image of a LIG filter. The figure and caption are used with permission from Stanford et al.[73] Copyright 2019, American Chemical Society.

Electrostatic air cleaners, also known as electrostatic precipitators (ESP), are most widely used to remove air pollutants, primarily charged particles such as pollens and dust, from air and exhaust gases generated by industrial sites and coal-fired power plants. ESPs can be categorized based on the number of stages used to charge and collect particles from the polluted gas as shown in Figure 5. Single-stage ESPs (Figure 5a) apply a high voltage to charge and collect particles within the same chamber on surfaces with the opposite charge. Two-stage ESPs (Figure 5b) consist of an ionization stage that uses thin wires equidistant from parallel or cylindrical grounded plates or tubes to create an electric corona discharge and ionize the particles in the airflow and a collection stage that involves the use of parallel metal plates to collect negatively (positively) charged particles on positively (negatively) charged plates.

ESPs are primarily designed for the collection of bioaerosols with certain chemical inactivation of microbes in bioaerosols,[74] because the high-voltage corona discharge could produce reactive species including ozone that may inactivate bacteria, bacterial endospores, and viruses.[10,75−78] For example, Park et al. demonstrated airborne bacterial removal efficiency of up to 75%−100% for air samples when they flow through micro-organism-ionizing respirators at a rate of 10−20 L·min^{-1}, where built-in miniaturized corona ionizers can generate ozone.[79] Yao et al. reported that under an electric field of 15 kV·cm^{-1} for around 30 min, more than 90% of the vegetative cells of *Pseudomonas fluorescens* were inactivated on the surface of nonconductive filters.[80] Similarly, more than 90% of the bioaerosol was removed using a charged droplet electrified scrubber and an opposite polarity electrified scrubber with a liquid-to-gas ratio of 2.4 L·m^{-3}.[81] Xia achieved a greater than 2.3 log reduction of the infective virus across the packed-bed dielectric barrier discharge reactor.[82] Of course, ESPs may generate harmful ozone that could cause adverse effects if not properly managed.

2.4. Triboelectric Effects and Applications in Air Purification.

Triboelectric air purifiers have recently emerged as superior to traditional electrostatic precipitation and fibrous filtering.[83] These purifiers utilize ambient mechanical energy to generate high voltage through coupling of the triboelectric effect and electrostatic induction, which enables absorption and degradation of air-phase pollutants.[84,85] To generate highly localized electric fields, nanowires (NWs) such as Ag, CuO, and ZnO are applied to significantly enhance the field at the wire tip (>10^7 V m^{-1}) and reduce drive voltages to several volts.[86,87] Triboelectric air filters and commercialized products have been employed for the removal of sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), formaldehyde, and $PM_{2.5}$.[88] However, few studies have explored their efficacy against airborne pathogens, such as viruses. One of the major disinfection mechanisms is electroporation which applies a sufficiently strong electric field (>10^7 V m^{-1}) to induce reversible structural changes on the outer surfaces of the microbes (bacterial membranes and viral capsids) and inactivation occurs.[89] Electroporation-based microbial disinfection has demonstrated effectiveness against bacteria, protozoa, and viruses. Figure 6 depicts a design of air disinfection powered by a triboelectric nanogenerator (TENG) that could harvest energy from ambient vibration sources, such as vibration of the ventilators in buildings.[90] The three-electrode filter comprises a macro-mesh negative electrode and integrated positive/ground electrodes. Airborne microbes (bacteria and viruses) acquire negative charges when passing through the macro-mesh electrode, and they are subsequently trapped and inactivated on the positive electrode surface by electrostatic attraction and electroporation. This triboelectric air filtration achieved >99.99% microbial

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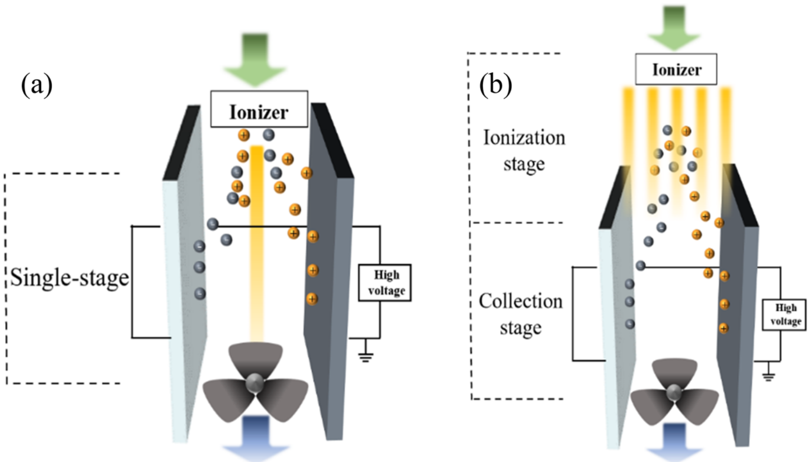

Figure 5. Schematic illustration of (a) single-stage ESPs and (b) two-stage ESPs.

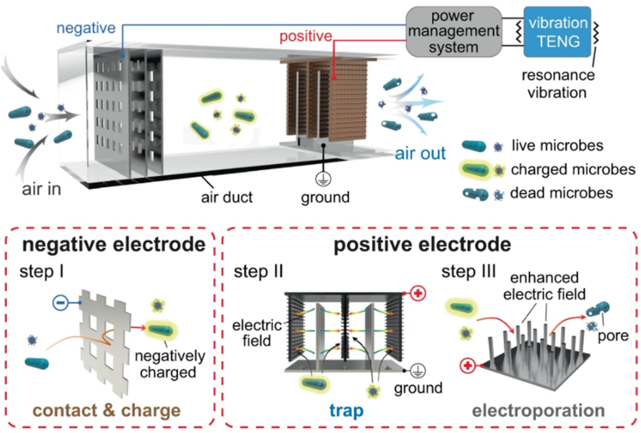

Figure 6. Conceptual design of air disinfection by charged electrode filters powered by a triboelectric nanogenerator. Reprinted with permission from Huo et al.[90] Copyright 2021, Springer Nature, licensed under https://creativecommons.org/licenses/.

inactivation within 0.025 s in a fast airflow (2 m·s^{-1}) with low pressure drops (<24 Pa).

2.5. Plasma Air Disinfection. Plasma is considered the fourth state of matter after solid, liquid, and gas and is defined as a partially or fully ionized gas generated by a variety of electric discharges such DBD, corona discharge, plasma jet, and gliding arc discharge as shown in Figure 7a–d.[91] It can be applied directly or indirectly, with the former involving the sample as one of the electrodes and the latter remotely producing plasma components delivered to the target via a carrier gas such as plasma jets. Energetic electrons in plasma can generate ROSs and reactive nitrogen species (RNSs) by exciting, dissociating, and ionizing gas molecules, leading to the inactivation of biological species.[92] Atmospheric cold plasma (CAP), working under atmospheric conditions below 40 °C, has emerged as an effective technology for water treatment,[93] deodorization,[94] and air purification.[95] Compared with other airborne bioaerosol removal technologies, CAP achieves high effectiveness in a very short period. For example, over 98% of *Bacillus subtilis* in aerosols was inactivated within the 0.12 s treatment by CAP with a power density of 0.38 W·m^{-2}, while there was 100% inactivation of *Pseudomonas fluorescens* aerosols.[96] Here, 1.5 and 5.5 log reductions of airborne *E. coli*, respectively, were obtained after 10 s and 2 min of single exposure with CAP with a power density of 3.6 W·m^{2}.[97] CAP is also effective against coronavirus (COVID-19) and avian influenza virus (AIV).[98,99] A 2.19 log reduction for the spores of *Aspergillus flavus* was achieved with CAP at 0.79 W·cm^{-2} for 120 s of exposure time, and complete inactivation was achieved in 480 s.[100] The porcine reproductive and respiratory syndrome virus (PRRSv) was inactivated with up to a 1.3 log inactivation rate at an air flow rate of 12 cfm under 20 kV.[101] However, using high-voltage plasma for residential disinfection raises safety concerns due to the use of high-voltage electricity, and the formation of secondary pollutants such as ozone, CO, or NO_x may negatively impact treated air quality.[102]

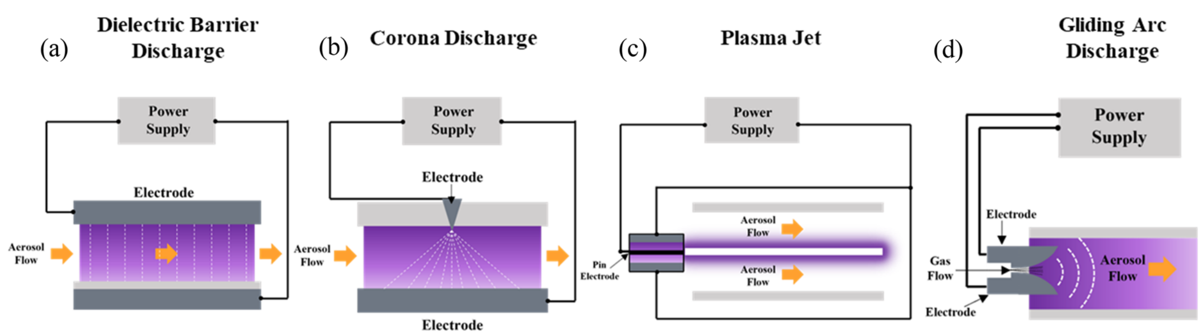

Figure 7. Schematics of the different plasma applications for bioaerosol disinfection: (a) dielectric barrier discharge, (b) corona discharge, (c) plasma jet, and (d) gliding arc discharge.

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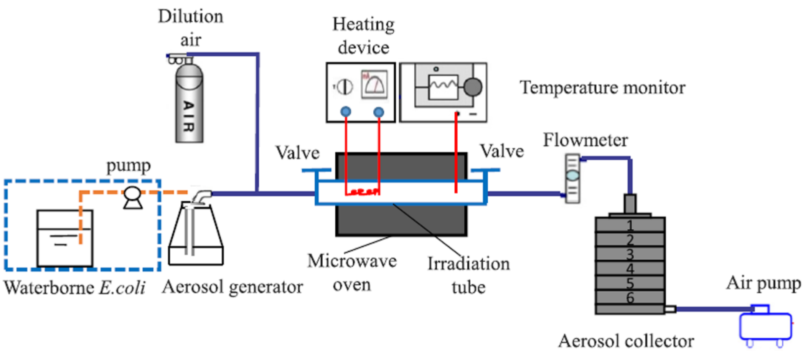

Figure 8. Schematic of an experimental setup of microwave-enabled aerosol disinfection. Reprinted with permission from Wang et al.[117] Copyright 2019, Elsevier.

2.6. Microwave Air Disinfection. Microwave disinfection has been extensively studied in the field of food disinfection[103−105] and sludge digestion[106] and moisture reduction in the food industry[107] over the last few decades. Microwaves are electromagnetic waves with frequencies between 300 MHz and 300 GHz and could inactivate microorganisms through thermal and nonthermal effects.[108] The thermal effect results from the absorption of microwave energy by intra- and extracellular fluids, causing polar molecules to vibrate and generate heat. Nonthermal effects occur due to a direct stabilizing interaction of electric field with specific (polar) molecules in reaction medium with a rise in temperature.[14,109,110]

Microwave inactivation of airborne microorganisms has long been studied on diverse bacteria, bacterial endospores, fungi, allergen aerosol, and viruses.[109,111−114] For instance, airborne *E. coli* cells decreased by 100% at a microwave exposure at an energy density of 7.4×10^3 kJ·m^{-3} for 20 s.[115] Here, 54% and 87.8% of the airborne *Bacillus subtilis* varniger spore and *Pseudomonas fluorescens* were inactivated after exposure to a 500 W microwave (2.45 GHz) at for 90 and 108 s, respectively.[113] Also, 90% of the airborne MS2 virus was inactivated after exposure to microwaves at 700 W for 120 s.[116] Microwaves generally have a greater inactivation efficiency on airborne bacteria than waterborne bacteria because there is no significant energy loss due to the low energy absorption by air moisture. Wang et al. reported that the inactivation rate constant for airborne *E. coli* (0.29 s^{-1}) was nearly 20 times higher than that of waterborne species (0.014 s^{-1}).[117] MS2 bacteriophage was aerosolized through a Collison nebulizer and was fed into the microwave irradiation system (125−375 W), which achieved log inactivation efficiencies of 0.8, 1.0, and 1.3 at relative humidities of 30%, 60%, and 90%, respectively.[112] Figure 8 shows a typical configuration of a microwave-assisted air filtration system.[112,118] Microwave power, microwave frequency, and exposure time are the main factors affecting the efficacy of microwave disinfection of bioaerosols.

Besides direct microwave exposure, researchers also combine filtration with microwave irradiation to achieve airborne virus inactivation.[112] Previous research indicates that microwave treatment of FFRs at 1250 W for 2 min induced a 5 log IE for H1N1 virus.[119] A microwave-assisted PAN/SiC air filtration system effectively inactivated *B. subtilis* endospores and *E. coli* under 500 W microwave irradiation in less than 90 s via a high temperature SiC disk under microwave irradiation.[111] Woo et al. applied 375 W microwave irradiation to an HVAC filter supported on a SiC disk to achieve log removal of 3.62 for aerosol MS2 removal in 10 min, and 90 °C was identified as the threshold temperature to characterize microwave irradiation power and application time.[112]

3. COMPARISON OF ENERGY EFFICIENCIES OF DIFFERENT AIR PURIFICATION PROCESSES

Electrical energy per order (E_{EO}) is a "figure of merit" for evaluating the cost of chemical processes following first-order kinetics.[120] E_{EO} (kWh·m^{-3}·order^{-1}) is defined as the number of kilowatt-hours of electrical energy needed to decrease the concentration of a pollutant by 1 order of magnitude (90%) in 1 m^3 of the treated media such as water or air, which permits the comparison of energy efficiency among different reaction systems,[121,122] as shown in eq 1.

$$E_{EO} = \frac{P \cdot t}{V \times \log(C_0/C_f)} \quad (1)$$

where P is the input power to the disinfection reaction (kW), t is the reaction time (h), V is the volume of the treated aerosol (m^3), and C_0 and C_f are the initial and final aerosol pathogens concentrations (CFU·mL^{-1}), respectively. Typically, the operational parameters such as oxidant or irradiation doses, pollutant concentrations, and pollutant characteristics (e.g., resistance to disinfection) may affect the E_{EO} values.[123−126] The E_{EO} values were calculated by eq 1 for different air disinfection technologies we surveyed from the literature (Table 1). Figure 9 shows the calculated E_{EO} values vary from 1.0×10^{-4} to 1.2. For the airborne bacteria (e.g., *E. coli* cells), the E_{EO} values increase in the order of electrified disinfection, triboelectric air purification, UV disinfection and photocatalysis, ozone disinfection, plasma disinfection, and microwave disinfection. Microwave disinfection renders high inactivation rate constants (0.46 s^{-1}) but the highest E_{EO} value (>0.5 kWh·m^{-3}·order^{-1}). By contrast, UV photocatalysis and photocatalysis, ozone disinfection, and plasma disinfection yielded much lower E_{EO} values (1.3×10^{-4} to 4.59×10^{-2} kWh·m^{-3}·order^{-1}) than microwave disinfection. However, they all achieve less than 50% of the inactivation rate constant for microwave disinfection, highlighting the effective or efficient disinfection power of microwave deposits of its high energy consumption. Electrified disinfection via electroporation costs the least energy consumption, but the disinfection kinetics tend to be lowest with the rate constant near 10^{-3} s^{-1}. To improve the disinfection power and energy efficiency, some combinations of different air purification technologies were explored. For example, Zadi et al. combined plasma and

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Table 1. Comparison of E_{EO} Values Reported or Calculated on Different Air Disinfection Technologies

Air disinfection technologies	Catalyst/UV	Bacteria/Virus	E_{EO} ($kWh \cdot m^{-3} \cdot order^{-1}$)	ref.
UV disinfection and photocatalysis	$Ti_3C_2T_x$ and TiO_2/UVA (365 nm) and UVC (254 nm)	*E. coli*	6.6×10^{-3}	129
	N/A/UVA (365 nm), UVC (254 nm), and UVD (185 nm)	*E. coli*	2.0×10^{-4} to 3.3×10^{-3}	130
	N/A/UV-LED	*E. coli*	1.3×10^{-4}	131
	$Ti_3C_2T_x$ and TiO_2/UVA (365 nm) and UVC (254 nm)	*B. subtilis*	1.5×10^{-2}	129
	TiO_2/UVA (365 nm)	Influenza virus	5.1×10^{-3}	132
	TiO_2/UVA (364 nm)	Influenza virus	1.2×10^{-3}	133
	N/A/UVC (254 nm)	Influenza virus	2.4×10^{-3}	134
	N/A/UV-LED	*S. marcescens*	1.5×10^{-4}	131
	N/A/UV-LED	*S. epidermidis*	2.6×10^{-3}	131
	$Ti_3C_2T_x$ and TiO_2/UVA (365 nm) and UVC (254 nm)	*Spore of B. subtilis*	4.5×10^{-2}	129
	Pd-TiO_2/VUV (254 + 185 nm)	MS2	9.2×10^{-4}	39
	TiO_2/UVC (254 nm)	*Legionella pneumophila*	4.06×10^{-2}	135
	TiO_2/UVA (365 nm)	*P.aeruginosa*	2.25×10^{-2}	40
	TiO_2/UVA (365 nm)	*S. aureus*	2.81×10^{-2}	40
	TiO_2/UVA (365 nm)	MRSA	1.51×10^{-3}	40
	TiO_2/UVA (365 nm)	*A. fumigatus*	3.25×10^{-2}	40
Ozone disinfection		MS2	4.59×10^{-2}	56
		Cladosporium spp.	2.7×10^{-2}	136
		Alternaria spp.	3.8×10^{-2}	136
		Penicillium spp.	7.6×10^{-2}	136
		Herpes simplex virus (HSV)	2.8×10^{-2}	54
		E. coli	1.5×10^{-2}	137
		0.5 μm airborne particles	2.0×10^{-2}	138
		Gram-negative bacteria	3.2×10^{-2}	139
Electrified disinfection	Mixed metal oxide (Ti/IrO_2 + TaO_2)	*E. coli*	2.4×10^{-4}	140
	N/A	*E. coli*	1.0×10^{-3} to 2.0×10^{-4}	97
	Ag−Co_3O_4	*E. coli*	1.2×10^{-4}	69
	Laser-induced graphene	T4 bacteriophage	3×10^{-4}	68
Electrostatic precipitation	MnO mesh coated with MnO_2	*E. coli*	8×10^{-4}	79
	Copper-clad plates	*P. fluorescens*	1.2×10^{-4}	80
	Copper-clad plates	*B. subtilis var. niger* bacteria	6.5×10^{-4}	80
Triboelectric air purification	N/A	*E. coli*	4.4×10^{-4}	141
	Cu_3PNW-Cu electrode	MS2	2×10^{-4}	90
Plasma disinfection	N/A	*E. coli*	1.90×10^{-2}	142
	N/A	Porcine reproductive and respiratory syndrome virus	2.11×10^{-2}	101
	TiO_2/Cu^{2+}@perlite	*E. coli*	1.2×10^{-2}	143
	N/A	*E. coli*	7.18×10^{-2}	144
	N/A	*S. epidermidis*	6.25×10^{-2}	144
	N/A	Airborne MS2	5.6×10^{-2}	145
Microwave disinfection	N/A	*E. coli*	2.8×10^{-1}	111
	Fe_3O_4@SiC	*E. coli*	4.6×10^{-1}	115
	MW+HVAC filter	MS2	1.2	112
	N/A	MS2	1.5×10^{-1}	116

photocatalytic technology and demonstrated possible catalyst regeneration with nonthermal plasma.[127] Xie et al. achieved stable and efficient air disinfection performance (E_{EO}= 5.75×10^{-6} $kWh \cdot m^{-3} \cdot order^{-1}$ and rate constant = 10^{-5} s^{-1}) by combining UV and microstatic electricity.[128] A summary of advantages and disadvantages of presented air purification technologies can be seen in Table S1.

4. PERSPECTIVES

The spread and infection of COVID-19 and other legacy airborne pathogens have spurred the development and implementation of effective air sterilization and purification technologies, especially in indoor or enclosed environments with limited ventilation (e.g., residential homes or offices, train stations, airports, and aircrafts), where populated density facilitates the viral spread. Commercially available air purifiers are mostly based on size exclusion or adsorption that is increasingly deficient for viral particle removal because most of the filters are clearly effective at removing micrometer-sized particles (e.g., dust, dander, pollen, fungus, and other common allergens) but may not be able to capture small viruses or bioaerosols, depending on many factors such as the filter

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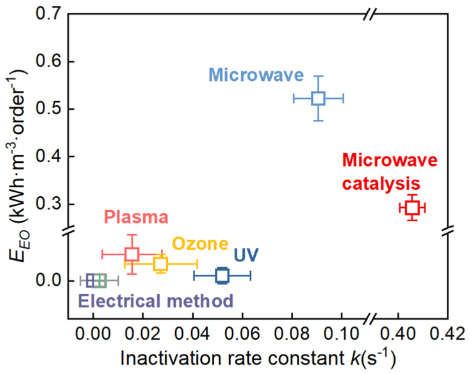

Figure 9. Relationship between the inactivation rate constant of bioaerosol and E_{EO} among different reactive air purification technologies or processes.

materials and pore sizes, the size, shape, and concentration of the airborne particles, and the airflow velocity through the filter. Moreover, poorly maintained air filters in heating ventilation and air conditioning (HVAC) systems could result in accumulation of viable pathogens and secondary viral transmission through air circulation.[146] The resuspension or emission of the bioaerosols captured on the filter is also possible and clearly increases the risk of infection. Some commercial air purifiers may employ UV irradiation for enhanced disinfection. However, the effectiveness of such UV/filter combination toward viral inactivation will significantly be affected by the UV intensity, exposure time, and UV penetration. Therefore, there is a still pressing demand for the development and research studies of novel and cost-effective air disinfection technologies that may hold paramount significance to public health as global communities are back to normal operation with the long-term coexistence of COVID-19 and other infectious disease-causing pathogens. Particularly, this review article focused on the introduction of the chemically or catalytically reactive air disinfection technologies. Successful implementation of these technologies requires innovations of new materials, catalysts, reactor designs, and process operations. For example, chemically doped TiO_2 and novel 2D or flat-sheet nanomaterials such as MXenes are demonstrated for enhanced photocatalytic air disinfection.[34,129] Moreover, owing to the high disinfection kinetics rate, microwave irradiation may become economically viable for airborne pathogen removal by combining with granular activated carbon (GAC) air filters that could provide adsorption/reaction sites for viral particles and enable a trap–heating pathway of air disinfection.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestengg.3c00016.

Additional details regarding advantages and disadvantages of presented air purification technologies (PDF)

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Notes

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