Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Photoelectrochemical oxidation assisted air purifiers; perspective as potential tools to control indoor SARS-CoV-2 Exposure

Ajeet Kumar Kaushik a,1,*, Jaspreet Singh Dhau b,2

a NanoBiTech Laboratory, Health Systems Engineering, Department of Environmental Engineering, Florida Polytechnic University, Lakeland, FL, USA
b Research and Development, Molekule Inc. Tampa, USA

ARTICLE INFO

Keywords:
- Clear indoor air
- Air purification technology
- Photoelectrochemical oxidation
- Viral-infection
- SARS-CoV-2 transmission control
- COVID-19 pandemic management
- SARS-CoV-2 exposure

ABSTRACT

Coronavirus diseases 2019 (COVID-19), a viral infection pandemic, arises due to easy human-to-human transmission of severe acute respiratory syndrome coronavirus (SARS-CoV-2). The SARS-CoV-2 causes severe respiratory disorders and other life-threatening diseases (during/post-infection) such as black mold disease, diabetes, cardiovascular, and neurological disorders/diseases. COVID-19 infection emerged challenging to control as SARS-CoV-2 transmits through respiratory droplets (> 10 µm size range), aerosols (< 5 µm), airborne, and particulate matter (PM1.0, PM2.5, and PM10.0). SARS-CoV-2 is more infective in indoor premises due to aerodynamics where droplets, aerosols, and PM1.0,2.5,10.0 float for a longer time and distance leading to a higher probability of it entering upper and lower respiratory tracts. To avoid human-to-human transmission, it is essential to trap and destroy SARS-CoV-2 from the air and provide virus-free air that will significantly reduce indoor viral exposure concerns. In this process, an efficient nano-enable photoelectrochemical oxidation (PECO, a destructive approach to neutralize bio-organism) assisted air purification is undoubtedly a good technological choice. This technical perspective explores the role of PECO-assisted Air-Purifiers (i.e., Molekule as a focus example for proof-of-concept) to trap and destroy indoor microorganisms (bacteria and viruses including Coronavirus), molds, and allergens, and other indoor air pollutants, such as volatile organic compounds (VOCs) and PM1.0,2.5,10.0. It is observed through various standard and non-standard tests that stimuli-responsive nanomaterials coated filter technology traps and destroys microbial particles. Due to technological advancements according to premises requirements and high-performance desired outcomes, Molekule air purifiers, Air Pro Air -Rx, Air Mini, and Air Mini+, have received Food and Drug Administration (FDA) clearance as a Class II medical device for the destruction of bacteria and viruses.

1. Introduction

The viral infections such as Ebola virus, Zika virus, influenza (H1N1) and coronavirus have always been a concern worldwide as their associated pandemics, endemics, and/or both affect human health and global economy [1]. Therefore, investigating effective management strategies and their successful execution is crucial to manage such severe viral infections efficiently [2-4]. In this direction, efforts were and are being made to understand viral infections via exploring the nature of virus pathogenesis and investigating rapid selective diagnostics along with therapeutics of higher efficacy [5]. Since Jan 2020, the world is facing a very potent viral infection, COVID-19 pandemic, caused by a new type of human Coronavirus known as Severe Acute Respiratory Virus-2 (SARS-CoV-2) [6]. This viral infection exhibits very high infectivity and morbidity due to easy human-to-human transmission and interaction with host-cell receptors [3]. The SARS-CoV-2 affects respiratory systems and causes serious respiratory disorders and affects biological functions of important body organs such as the heart, kidney, eye, brain, which in some severe cases may cause death [5].

Health agencies such as the World Health Organization (WHO), Centers for Disease Control and Prevention (CDC), National Institutes of Health (NIH), etc. are making efforts to explore SARS-CoV-2 pathogenesis, structures mutations, virology, and biological function to manage the COVID-19 pandemic. Despite the efforts of these agencies,
SARS-CoV-2 has been tough to manage due to its nature of transmission and infection. Approaches, such as the use of masks, self-health monitoring, hygiene, and social distancing have helped to some extent in cutting the transmission chain [3,7,8]. Food and Drug Administration (FDA) - approved techniques such as 1) selective early-stage diagnostics (rapid screening sensing and detection of SARS-CoV-2 Spike-protein) and high-efficacy therapies (antibodies, anti-retroviral drug, vaccines) have also emerged functional in managing COVID-19 infection [6,9,10]. Besides, the SARS-CoV-2 mutations are making COVID-19 infection more challenging as new virus strains have been found to be more infectious and deadly. The new strains are more robust allowing them to dodge the recently developed anti-COVID-19 treatments [6].

Keeping these challenges into consideration, additional re-designed efforts and approaches are needed to fight against this dreadful viral infection. Recent reports demonstrated SARS-CoV-2 spread as airborne transmission [11]. Therefore, a virus-free clean indoor air obtained via trapping, eradication, and destruction of SARS-CoV-2 is one of the emerging approaches to tackle this problem. It is now an established fact that the SARS-CoV-2 transmission primarily occurs through respiratory droplets, aerosols, particulates (PM2.5), or airborne [10-16], as illustrated in Fig. 1. For a better understanding of air purifiers’ role in managing SARS-CoV-2 transmission, we need to understand various transmission modes [11].

A. SARS-CoV-2 transmission through droplets. Droplets are micro-sized (> 10 µm) drops of respiratory fluids, mainly saliva. These droplets are large enough to carry respiratory pathogens such as SARS-CoV-2 that can easily survive for several hours in open space and on surfaces (Fig. 1B) [17]. These droplets can move three feet in distance and settle out of the air onto the surfaces within minutes. Large droplets have a higher probability of carrying a virion than smaller droplets. Large droplets can convert into tiny droplets by evaporation and remain suspended for an extended period. Viruses can be transferred by touching the mucous membrane in the mouth, nose, and eyes with hands soiled with viruses from the contaminated surfaces (fomite transmission). Droplets of size ranging from 10 to 100 µm can carry many virus particles and be responsible for severe COVID-19 disease. Thus, it is crucial to take necessary precautions to stop droplet-based SARS-CoV-2 transmission. Fortunately, droplet-based transmission, due to large droplet size, can be controlled and avoided using an ordinary mask (not necessarily N-95) and sanitizing the contaminated surface using disinfectants (Fig. 1C). The coating of surfaces using antiviral or antibacterial materials (Cu, Ag, TiO2, etc.) is an excellent approach to prevent fomite transmission [18].

B. SARS-CoV-2 transmission by aerosolization. The COVID-19 infection via aerosol is one of the critical and most widely investigated modes of transmission. These virus-containing aerosol droplets of respiratory fluids are smaller in size (< 5 µm) and can travel in the air up to 6 feet [17,18]. Aerosols are generated during expiratory events such as coughing and sneezing. In general, these two modes can eject thousands of tiny drops containing millions of virus particles into the air, which could cause severe infection if inhaled by a person in the close vicinity of an infected person. Several environmental factors impact the aerosol-based transmission of the virus. Under certain conditions, aerosols can travel up to 30 feet in distance. In addition, environmental temperature and humidity can enhance the viability of the aerosolized virus and make them survive for a longer duration of time [17,18]. A regular mask may not be sufficient to trap all the virus-containing aerosol. Thus, a better-quality mask (N-95 and nanoparticle supported masks), effective ventilation, and air purification are needed to prevent the aerosol-transmitted virus infection.

C. SARS-CoV-2 transmission as airborne. The aerosol size is a mystery, and it has been calculated as 0.2 µm at genome level in
hospitals. Such small particles can be suspended in the air for a long time, which increases the chances of inhalation, especially in closed premises [8, 10, 13]. This type of situation is the main reason to declare COVID-19 viral infection as airborne transmission. Recent reports are more focused on how this type of transmission can be controlled under different environmental conditions. Airflow in the premises can make virus particles travel a longer distance. Humidity and temperature may also support the survival of virus particles in the room. Therefore, it is necessary to actively remove these particles from the infected air to prevent people from getting infected with this deadly virus. Now the biggest challenge is how to clean the air or how to make air virus-free? A potential solution to managing airborne viruses could be utilizing an efficient air purifier to capture and kill the virus.

**D. PM\textsubscript{1.0/2.5/10.0} - Assisted SARS-CoV-2 transmission.** Particulate assisted virus transmission is also a concern expressed recently by many virologists, which is not surprising [13,14]. As viruses containing aerosols remain suspended in the air, suspended aerosols may get adsorbed onto particulate matter (PM\textsubscript{1.0} PM\textsubscript{2.5} and PM\textsubscript{10.0}) in the air [16]. These particulates, namely, inorganic dust particles, organic particles, and biopolymers such as hair, pet dander, dead skin cells, etc., serve as viable platforms for viruses where they could survive longer. A more detailed investigation is needed to explore the possibilities and consequences of this mode of transmission. Maintaining clean and virus-free indoor air will help in defeating the pandemic. As discussed in airborne virus transmission, an air purifier could be helpful to trap the support particulates and simultaneously neutralize the virus protein.

Overall, aerodynamics plays an essential role in SARS-CoV-2 transmission (Fig. 1B & C), especially in indoor premises. Therefore, precautions and safety aspects must be predicted, optimized, and recommended based on premises and environmental factors. Based on careful and critical analysis, the indoor SARS-CoV-2 transmission is severe and challenging to control [6]. The mode of transmission and the impact of environmental factors alongside airflow are also crucial factors that need to be considered to fight against dreaded COVID-19 infection. In such situations, an efficient air purifier function based on virus trapping and stimuli-response destruction (microorganism, mold, and allergens) is one of the most recommended approaches to generate SARS-CoV-2 free indoor air. Such capabilities are well-demonstrated by the Molekule air purifier, as discussed in the next section.

2. **Molekule air-purifier: State-of-the-art indoor air purification**

Indoor air quality is always a concern to maintain according to international standards but not well highlighted due to lack of awareness and widespread technology. Recent viral infection outbreaks (COVID-19 pandemic) not only forced health agencies globally to develop better medical infrastructure and new policies to deal with infectious diseases but also made the general population understand the value of clean air [21–23]. As a result, the need for virus-free indoor air to avoid virus exposure raised the demand of investigating new technologies which can clean the air in reduced form factors, i.e., with more advantages, affordability, and acceptability. These technological and commercial aspects are the major concerns of air purifier developers. Such systems improve indoor air quality significantly, and improvements in health quality (by controlling airborne diseases) are highly noticeable. The aspects of air purification technologies to remove and destroy viruses, including SARS-CoV-2 are illustrated in Fig. 2A.

An efficient filter that can trap air pollutants is the main component of air purifiers, i.e., the heart of the air purifier unit. The efficacy of such a filter depends on the quality of the fabric, pore membrane, and stability (chemical and mechanical). For decades, significant efforts have been made to improve the air purifier performance by improving filter efficiency and device design to make them suitable according to various premises. Based on significant developments and the need for clean
Indoor air, the USA air purifier market size is increasing every year. It is expected to be multi-billion-dollar by 2027 (4.47 billion dollars) [20], as illustrated in Fig. 2B. The expected compound annual growth is expected to be 12.4% in the years 2020 to 2027 [20].

Besides increasing investment and health benefits, the available air purifiers constantly show various shortcomings such as limited filter efficiency, high power consumption, and inefficacy in larger premises [21]. At the same time, most of these systems only trap pollutants, PM (mainly PM_{2.5/10.0}) and VOCs. Trapping of PM_{1.0} and destroying bio-active compounds (allergens, bacteria, virus, etc.) along with molds is a remaining challenge. Therefore, there is a need to design and develop a new air purifier that can trap pollutants and efficiently destroy harmful bio-active compounds. Such a dual approach must be required but not yet widely considered and understood in air purification technology. However, Molekule is exploring this suggested approach successfully. The capabilities of Molekule air purification technology concerning VOCs, allergens, toxins, PM_{1.0/2.5/10.0}, bacteria, viruses, etc., are illustrated in Fig. 3.

Molekule Air purifiers function on the photoelectrochemical oxidation (PECO) approach. The PECO technology is designed to drastically lower the atmospheric oxidation energy barrier using a specially designed catalyst coated on an air-cleaning filter. This technology combines the decades-old approach of mechanically sifting particles from the air with accelerating the atmospheric fate of pollutants by reaction with reactive oxygen species. The PECO technology was developed over 25 years of research by Dr. Yogi Goswami, founder of Molekule, who utilized semiconductors studied in energy production to instead produce photoreactions on the surface of the semiconductor, i.e., photovoltaic physics.

The electrons in solar cell semiconductors absorb photons and are excited to a higher valence state from their ground state, leaving behind a positive charge virtual hole. By structuring the photocell with very specific layers of doped semiconductors, the electrons can be directed to the surface. The holes are balanced by charge migration through the material. Oxidation mediated by the hydroxyl radical is the eventual fate of reactive compounds in Earth’s atmosphere, with a few exceptions. This includes species like ozone and virtually every compound altered by living organisms such as VOCs, allergens, mycotoxins, and viruses. In the stratosphere, oxidation is a process that ultimately serves to quench free radicals and other highly reactive species such as carbon monoxide and sulfur dioxide. As a result, an atmosphere that has reached redox equilibrium, in that its oxygen compounds are predominantly O_2 and H_2O, is the “freshest,” least contaminated, and a goal for clean air.

In the absence of electrodes, the excited electrons may recombine with holes to dissipate their energy as heat or take part in photoreactions with the atmosphere [24]. These photoreactions result in catalytic oxidation of organic and inorganic species. On a titanium dioxide (TiO_2) surface, as an example [25], there are a variety of reactions that lead to the catalytic formation of short-lived reactive oxygen species common in nature, such as hydroxyl radicals and superoxide ions:

\[
\text{TiO}_2 (hv) \rightarrow \text{TiO}_2 (e^- + h^+) \\
\text{TiO}_2 (h^+) + RX \rightarrow \text{TiO}_2 + RX^- \\
\text{TiO}_2 (h^+) + H_2O \rightarrow \text{TiO}_2 + \text{HO}^- + H^+ \\
\text{TiO}_2 (h^+) + OH^- \rightarrow \text{TiO}_2 \cdot \text{HO} \\
\text{TiO}_2 (e^-) + O_2 \rightarrow \text{TiO}_2 + O_2^-. 
\]

Photochemical oxidation (PCO) air-cleaning technology has been met with skepticism due to relatively low reaction rates [26-28]. In the

![Fig. 3. The state-of-art indoor air cleaning performance of Molekule Air purifier. Indoor pollutants trapped in nano-enabled filters and bio-organism eradicate and or neutralize by photo-electro-chemical-oxidation (PECO) mechanism.](image-url)
absence of well-structured layers of semiconductors that direct electron flow, recombination could dominate, leading to a relatively low population of reactive oxygen species. Much like the difference between smoldering and flaming, incomplete oxidation can lead to chemical species bearing reactive aldehyde groups released into the atmosphere. In addition, high-energy light, such as UV-C, which in many cases is used to activate the catalyst leads to counter-productive emission of ozone [29]. The design of a photocatalytic air purification system is complex and is dependent on a wide variety of factors, including intensity of the light falling on the catalyst, chemical makeup and concentration of pollutants, the air flow rate through the device, moisture levels in the air, properties of the specific catalyst used, pollutant residence time, and how the device itself is configured.

The PECO technology of Molekule air purifiers seeks to solve these challenges in several ways. The first is with surface area. The catalyst is coated onto efficient filtration media with fine fibers resulting in high surface area for the photocatalytic reactions. As a result, there are many small domains for any pollutants passing through the filter to be slowed and exposed to catalytic oxidation. In addition, this provides many semiconductor surfaces on which the UV-A can be absorbed [30,31]. PECO is also influenced by the design of solar cells (photoactive materials). Awareness of the oxidative power of photoactive semiconductor materials is at least a century old, but just using a block of metal oxide materials could dominate, leading to a relatively low population of reactive oxygen species. Much like the difference between smoldering and flaming, incomplete oxidation can lead to chemical species bearing reactive aldehyde groups released into the atmosphere. In addition, high-energy light, such as UV-C, which in many cases is used to activate the catalyst leads to counter-productive emission of ozone [29]. The design of a photocatalytic air purification system is complex and is dependent on a wide variety of factors, including intensity of the light falling on the catalyst, chemical makeup and concentration of pollutants, the air flow rate through the device, moisture levels in the air, properties of the specific catalyst used, pollutant residence time, and how the device itself is configured.

The PECO technology of Molekule air purifiers seeks to solve these challenges in several ways. The first is with surface area. The catalyst is coated onto efficient filtration media with fine fibers resulting in high surface area for the photocatalytic reactions. As a result, there are many small domains for any pollutants passing through the filter to be slowed and exposed to catalytic oxidation. In addition, this provides many semiconductor surfaces on which the UV-A can be absorbed [30,31]. PECO is also influenced by the design of solar cells (photoactive materials). Awareness of the oxidative power of photoactive semiconductor materials is at least a century old, but just using a block of metal oxide and bright light is not sufficient, as mentioned above. Solar cells are intricate layers of differently doped materials designed to directly generate electrons-hole pairs with excellent specificity. PECO was developed to allow an overabundance of photoactive electrons on the catalyst’s surface. Hence, a very high degree of hydroxyl radicals is present to speed the oxidative fate of reactive chemical species.

According to the premises requirements, Molekule designed and offers various devices a) Molekule MINI (up to 250 sq. ft), b) AIR-MINI+ (up to 250 sq. ft), c) AIR PRO (up to 1000 sq. ft), and d) AIR-Pro-RX (more than 800 sq. ft). All these devices are based on the PECO technology and capable of cleaning indoor air via optimizing airflow dynamics and optimum light parameters for varied indoor conditions, such as hospitals, malls, homes, etc. The air purification working principle based on trapping and destruction is illustrated in Fig. 4. The Molekule air purifiers-based indoor air cleaning approach has two components 1) nano-enabled filter (pre-filter), which can trap gasses and particulate matters, and 2) PECO-filter based degradation or neutralization of VOCs and bio-active compounds such as bacterial, molds, viruses, allergens, proteins, toxins, etc. Besides, ensuring 360° based air intake and spreading of clean air is also instrumental in getting a better air purification performance.

3. Molekule air-purifier potentials to clean indoor air

As a combination of nano-enabled filter and photo-stimulation responsiveness PECO technology, Molekule air purification technology functions based on 1) trapping of pollutants (mainly gasses and particulates) and 2) eradication or neutralization of bio-microorganism (allergens, bio-actives, virus, etc.). These devices are designed by considering various premises (such industries, households, and commercials) and maximum possible occupancy (such as schools, offices, malls, and homes) [32]. Besides, optimization of air dynamics based on-premises is also considered crucial in selecting a Molekule air purifier device supported by the PECO working mechanism (Fig. 4). Over the time advancement in Molekule Air purifiers of tunable performance according to the need of various premises are illustrated in Fig. 5.

As demonstrated, many components of air pollution are detoxified by an oxidation mechanism. All the toxins of biological origin rely on structures made of C–C bonds. Breaking these bonds via oxidation results (A) and destroy (eradicate and neutralize) indoor air pollutants involve droplets (> 10 µm), aerosols (< 5 µm), airborne (0.2 µm at genome level), and particulate matter (PM1.0, PM2.5, and PM10.0). The molecule takes air from every angle (Stage 1. 360° Air Intake), and air flows through the outer filter, which traps large particles like Dust, PM, and dander (Stage 2. Particle Capture). Further, a chemical reaction occurs when a nanoparticle-coated filter is activated by light breaking down viruses and bacteria to their most basic molecular components (Stage 3. PECO Process means purification at its best). At last, the Molekule device releases harmless molecules that are meant to be in the air (Stage 4. 360° of clean air) means reducing the presence of harmful particles.
impacts the ability of allergens to cause reactions or for pathogens to infect. The VOCs are also subject to disruption by an oxidation process. The conversion of stable toxins like formaldehyde or benzene into carbon dioxide and water curbs their ability to bind to our tissues. Oxidation of outdoor pollutants driven by solar radiation in the atmosphere may be different from oxidation of indoor pollutants caused by PECO. Not only is the general chemical makeup of stratospheric air different from that of household air, but there are sources of pollutants indoors that do not exist outdoors. The PECO is an innovative technology that uses free radicals—the same radicals used to destroy cancer cells to

Fig. 5. Specifications of Molekule’s AIR MINI, AIR, AIR-PRO, and AIR PRO-RX.

Fig. 6. A) Schematics of showing free radical assisted denaturation of micro/bio-organism, B) hybridization of PECO technology with device developments, filter technology, and environmental factor to achieve high-performance in terms of trapping and degradation of pollutants.
break down pollutants at a molecular level, including viruses, bacteria, mold, allergens, and chemicals.

Using nanotechnology, PECO can destroy pollutants 1000 times smaller than the standard filters. One of the significant benefits of PECO technology is that it oxidizes the pollutants in the air. This process renders biologically active compounds into less reactive oxidized components of the atmosphere, such as CO$_2$ and H$_2$O (Fig. 6A). Various VOCs such as benzene and formaldehyde are considered by the US Environmental Protection Agency (EPA) as air toxins. To assess the capability of PECO technology for removing these compounds, all the Molekule air purifiers were challenged with a cocktail of different VOCs. There are thousands upon thousands of volatile and semi-volatile organic compounds in outdoor and indoor air, so the components of the VOC cocktail need to be representative of many different VOCs. The practical approach to utilize PECO-assisted air purification supported by top-ranked engineering and smart-functionalized multi-model materials has emerged very efficiently (Fig. 6B). The performance of PECO technology has been demonstrated at the microscopic level, where capturing, oxidation and destruction are systematic step-by-step processes. The PECO technology destroys pollutants at a microscopic scale, including VOCs and viruses 1000x smaller than what the standard filter tests for. With no ozone byproduct, Molekule air purifiers safely destroy a vast range of indoor air pollutants. As a science company, Molekule conducts extensive testing of its technology through its own labs as well as certified third-party laboratories.

Additionally, oxidation is generally known to decrease the toxicity of targeted organic compounds. Indoor air is likely to be polluted by many of the same pollutants as in outdoor air. These would include the pollutants put forth by the EPA as criteria air pollutants—PM, ozone, NO$_x$, SO$_2$, and CO. Although, the indoor air needed to be more classified for better understanding. Further, the PM should be classified to represent not just harmful inert particles like smoke and Dust but also bioaerosols such as viruses, bacteria, mold spores, and allergens. Additionally, chemicals such as those defined by the EPA as air toxins need to be considered. These included pollutants such as formaldehyde and other VOCs. The PECO can oxidize pollutants, dropping their reactivity and, therefore, their toxicity.

Some pollutants, such as inorganic components of the Earth’s crust, are not meaningfully changed by oxidation reactions and are better captured and disposed of. This made PECO technology-supported nanofiltered systems more efficient to clean indoor air. The functional capabilities of Molekule air purification technology (AIR MINI, AIR-MINI+, AIR PRO and AIR PRO-RX) to reduce the potential of SARS-CoV-2 exposure concerns in indoor premises discussed briefly.

The scientific experiments discussed in this report were conducted by third-party labs. The related procedure and outcomes of these experiments are in public domain and published on the website of Molekule Inc. Therefore, the experimental detail and procedures are not required to be discussed in this mini review article.

As a note, every experiment reported in this report was performed using a Molekule device in the highest optimized and standardized setting. Every device operation was performed in identical conditions against every targeted pollutant. Air purifiers were tested at Aerosol Research and Engineering Laboratories (ARE) in a 16 m$^3$ chamber on MS2 Bacteriophage aerosolized droplets. Precaution: Pollutants were not re-released into the chamber after the initial introduction. Just note that no air purifier can prevent you from getting a virus. Air PRO removes airborne viruses like MS2 bacteriophage (Fig. 7A) by 99% within 30 min, a proxy virus for SARS-CoV-2, which travels in tiny droplets that can linger for hours before settling on surfaces.

Air Mini was tested at Intertek-Columbus in a 30 m$^3$ chamber on ΦX174 Bacteriophage aerosolized droplets. Precaution: Pollutants were not re-released into the chamber after the initial introduction. Just note that no air purifier can prevent you from getting a virus. AIR-MINI Vs. DNA Virus. Molekule AIR MINI successfully removed viruses (ΦX174 Bacteriophage, DNA virus PhiX174: 98.7% removed in 2 h*, as illustrated in Fig. 7B) which otherwise could linger for hours in the air.

In this testing procedure, the PECO-Filter was also cut, sampled, and...
incubated to measure viable virus count. The results of the studies confirmed zero viable viruses present on the filter after the procedure.

4. Discussion: Molekule devices to manage COVID-19 infection

It has been demonstrated that controlling of COVID-19 infection pandemic is not a unidirectional approach. In the current situation based on evidence, where efficient diagnostic tools and therapeutic (drugs and vaccines) are performing well, another approach of having a virus-free indoor air is also getting significant attention [3,4,7]. In this direction, indoor and outdoor cases are of equal attention. The WHO suggested precautionary guidelines that outdoor virus transmission is manageable, but indoor air virus transmission is a serious concern, where environmental factors such as aerodynamics, temperature, humidity, etc., play a significant role in supporting virus transmission. It has been a long time; people are either in their homes, working from home, or attending offices under the guidelines (Fig. 8A). In all these conditions, if someone brings a virus from the outdoors, everyone in the same premises has a higher probability of getting the infection.

Thus, to work and live indoors, it is essential to have virus-free air. This looks challenging when it is evident that indoor virus transmission is through droplets, aerosol, airborne, and PM<sub>1.0/2.5/10</sub>. Thus, a technology that can trap the virus carriers and neutralize the virus has become a need. In this direction, Molekule air purifiers, function on PECO approach where a nano-based filter, the heart of the device, have successfully demonstrated trapping of pollutants (VOCs, Dust, etc.) and neutralize microorganisms, including DNA virus (MS2 Bacteriophage - >99%) and DNA virus (ΦX174 Bacteriophage- > 98%). The performance of Molekule Air purifiers to clean indoor air is summarized in Fig. 8B.

Molekule Air purifier is capable to capture and deactivate aerosolized virus droplets in a room-size chamber. To test destruction, a swatch of the filter was removed, placed in a flask with sterile phosphate-buffered-saline (PBS), and shaken to generate an elution of viable virus particles. This elution was plate counted and it was found that there were zero detectable viral phage counts. This result points to the finding that destruction of the captured Φ174 bacteriophage droplet particle was completed [33,34]. PhiX174 was used as a surrogate virus for SARS-CoV-2 to observe oxidation. The Φ174 bacteriophage has a polyhedral morphology with high assay sensitivity, rapid growth, and high titer, and has a limit of detection that approaches a single virus particle [33-35]. Both Corona virions (including SARS-CoV-2) and Φ174 bacteriophage have proteins (capsid and spiked proteins) and genomic materials that have C–C, C–H, and C–N bonds, and the test and swatch analysis demonstrate that the PECO filter degrades these bonds.

Testing on microorganisms of different strains, sizes, and shapes was conducted, e.g., E. coli is a Gram-negative, rod-shaped bacteria (negatively charged). Bacillus subtilis is a Gram-positive, rod-shaped bacteria (negatively charged), Aspergillus niger, and Aspergillus brasiliensis (with negative and positive charges on the surface) are filamentous fungi. The tested viruses include the MS2 bacteriophage having an icosahedral virus. The MS2 Bacteriophage is a single-stranded RNA virus that is commonly used to simulate Influenza [35]. The novel coronavirus

![Fig. 8. The scenario of closed premises with contaminated air (A), a wind tunnel system utilized for Recirculating air purification technologies (B), summary performance outcomes of Molecule air purification technology (C), and RT-qPCR based viability evaluation of BCoV, PRCV, & influenza A virus (IAV) tested with reference to performance Molecule air purifiers (D) [32].](image-url)
walls (e.g., Aspergillus niger and E. coli) or are harder to entrain due to infection. Hence, the demonstration of significant inactivation of these phage lack a lipid envelope which makes them more resistant to disinfection. The hemagglutinin-esterase dimer (HE), a membrane glycoprotein (M), an riophage, bacteria, and mold destruction supports that PECO oxidation science on filtration and entrainment of particles using the MERV scale. The larger size suggests that entrainment would be easier to accomplish than with MS2 Bacteriophage, given the existing aerosol in size. The larger size suggests that entrainment would be easier to accomplish than with MS2 Bacteriophage, given the existing aerosol in

Overall, the Molekule testing that demonstrated MS2, Φ174 bacteriophage, bacteria, and mold destruction supports that PECO oxidation is effective across size, shape, surface characteristics, and charge differences. The structure of coronavirus has a spike protein (S), hemagglutinin-esterase dimer (HE), a membrane glycoprotein (M), an envelope protein (E), a nucleocapsid protein (N), and RNA. It also has Nucleocapsid protein (N) which is found in MS2 Bacteriophage. Both MS2 (positive-sense single-stranded RNA virus) and Φ174 bacteriophage lack a lipid envelope which makes them more resistant to disinfection. Hence, the demonstration of significant inactivation of these small, tough-to-destroy viruses is a strong indicator that the technology can inactivate coronaviruses. The PECO technology has been demonstrated to range against a surrogate that either have tougher envelopes/cell walls (e.g., Aspergillus niger and E. coli) or are harder to entrain due to size (MS2 Bacteriophage) than coronaviruses.

Additionally, complete oxidation of entrained matter on the PECO filter, gas-phase VOCs injected in room-size chambers with Molekule air purifier tests were completed. Bond dissociation energies of amino acids, the building unit of proteins, are in the range of 319 kJ/mol to 527 kJ/mol. Some of the VOCs tested for effective destruction have bond dissociation energies in the range of 337 kJ/mol to 731 kJ/mol. This is indicative of the fact that VOCs destruction can be a surrogate for the destruction of trapped viruses on the PECO filter. Molekule Air has been tested for VOCs destruction at Lawrence Berkeley National Laboratory and Intertek against varying concentrations of VOCs (Formaldehyde, p-Limonene, and Toluenes) as shown in Figs. 7 & 8.

Based on the principle of recirculating air purification phenomena, a wind-tunnel (Fig. 8C) based performance of PECO technology was demonstrated to evaluate the viability of bovine coronavirus (BCoV, a beta coronavirus), porcine respiratory coronavirus (PRCV, an alpha-coronavirus), and influenza A virus (IAV) [22], as shown in Fig. 8D. In this process, PECO supported Molekule air purifiers were utilized and exhibited efficacy above 95.8% based on RT-qPCR studies. However, collection efficiency was observed as > 99% (in the case of BCoV, PRCV, & IAV) in the case of super micrometer particles. These results suggested a successful inactivation of viruses and projects the application of Molekule purifier for bigger premises like hospitals.

Hospitals predominantly rely on high minimum efficiency reporting value (MERV) rated filters to maintain air filtration through the central heating, ventilation, air conditioning (HVAC) system. Despite the use of these filters, airborne-related infections continue to be problematic within the hospital system. The hospital central HVAC system and MERV-rated filters is a generalized approach to erodeuce bacteria and fungi in the air, but other airborne microbes and toxins can exist in localized indoor environment at very high levels. This may be due to the pathogens or pollutants carried by the patient or hospital workers, those disturbed by movement in the room, or otherwise those that are not effectively filtered by the central HVAC system [21,22]. Patients and hospital workers may be at a higher risk due to pathogenic complications in the air. These risks may be reduced using the freestanding Molekule air purifiers, which is a targeted approach in cleaning indoor air.

Many healthcare facilities rely on HEPA filters, which capture viruses and other microbes. However, health care professionals who change these filters risk exposure to microbes when they do so because the microbes are not destroyed. This could be a potential source of infection. In the Molekule air purifiers because the virus is destroyed on the filter, the risk of exposure during filter changes is drastically reduced. Major problems with current mechanical air filtration, even using high-efficiency particulate air filters and the HVAC systems used in hospitals, include the ability of micro-organisms to proliferate on the filter surfaces themselves and the inability of existing technology to effectively stop the spread of small particles such as viruses and other toxins. With the portable PECO units, in addition to physical filtration, a photo-electrochemical reaction takes place on the surface of a nano-coated filter leading to the oxidation of organic matter. These processes allow for the destruction of organic material 1000 times smaller than the traditional HEPA filter size standard. Thus, PECO can efficiently destroy airborne organic matter, bacteria, viruses, mold, and volatile organic compounds converting them into their trace elements.

The above discussed results of studies suggest that Molekule devices are capable of trapping organic pollutants (as a feature of nano-based filter membrane) and degrade (make them inactive via PECO as a feature of light-stimulated nano-system). Therefore, such devices can efficiently remove viruses from the indoor air via trapping SARS-CoV-2 carrying droplets, aerosol, airborne, and PM1.0/2.5/10.0 and further neutralizing the captured virus through PECO destruction technology. High-performance Molekule Air purifiers can produce virus-free indoor air that is much needed in this unprecedented scenario to run businesses - a need to bring the global economy on track (Fig. 9A).

Recently, Air Pro-RX received FDA clearance for medical applications. This is the first commercially available PECO-technology-based air purifier with the FDA 510(k) Class II Medical Device Clearance for medical purposes where destroying viruses and bacteria is crucial. Air Pro-RX also satisfies outlined performance criteria as per FDA guidelines for use in helping to reduce the risk of potential microbial (bacteria and virus) exposure via controlling one of the major transmission modes of airborne pandemics. Such a system emerged as a set-up of disease control during the current public health emergency. Outside of medical settings, Air Pro-RX offers frontline protection to schools, hotels, offices, and other high-traffic spaces. At the same time, AIR MINI and AIR-MINI+ have also received FDA clearance [clearance as FDA 510(k) Class II medical devices] for the medical use at it can efficiently destroy virus and bacteria in the small space up to 250 sq. ft which is like a studio apartment and kid’s bedrooms. Some of the recent accomplishments of Molekule air purifiers based on high and desirable performance outcomes are illustrated in Fig. 9B.

5. Conclusion and viewpoint

This technical perspective explores the potential of Molekule air purification technology for efficient and effective (~99%) trapping and destruction of microorganisms such as viruses (MS2 and ΦX174 Bacteriophages, Porcine and Bovine Coronaviruses and H1N1 viruses), bacteria, fungi, mold, etc. A destructive approach based on the synergy of nano-assisted efficient photoelectrochemical oxidation and filter membrane, Molekule Air Purification technology, is unique and capable of producing clean indoor air free from pollutants and microorganisms, a need for better health.

Regarding the aspects of personalized health wellness based on novel materials for diagnostic, treatment, and antibacterial performance [18,36-39], everyone should pay special attention to indoor air quality as we do for water and food quality. The health consequences in case of contaminated air are noticeably serious and now are well-explored. The best way to manage these consequences is precautions and adopting technology-supported air purification approaches, where Molekule air purifiers are curtailling, a critical supporting factor. The global scaling-up capability and technological advancement considering aerodynamics and dimension of premises made these devices suitable for application ranging from small rooms to homes to malls to schools to hospitals. The Molekule Air purifiers have received FDA approval for medical application based on its tendency to remove pollutants of concern from indoor air. Engineers and scientists of Molekule are
dedicated to investigating better chemistries, optimum packaging, and device design to develop high-performance Molekule air purifiers according to the needs of every class of consumer, including for developing countries.

The outcomes of this analytical perspective suggest that PECO assisted air purifiers can successfully manage indoor air microbial exposure and support the objectives of policies and legislation planned or proposed to manage indoor respiratory infection caused by pollutants, water, food, etc [40]. A virus-free and clean indoor air is more crucial in a scenario when SARS-CoV-2 is mutating often [[41,42] and known to affect the neuronal function to cause and facilitate neurodegenerative disorder and the brain injury [43].

Author contributions

All authors contributed equally.

Notes and declaration

A.K. declares no competing financial interest J.D. is affiliated with Molekule Inc as a Sr. Research & Development Director.

Declaration

The scientific experiments discussed in this article were conducted by a third-party agreement. The related procedures and outcomes reported in this article are published on the Molekule website. Keeping these points into consideration, this article is not a research article as author only summarized the outcomes of findings which are in public domain.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors acknowledge respective institutions and departments for providing facilities and resources.

References

[1] A. Kaushik, Manipulative magnetic nanomedicine: the future of COVID-19 pandemic/endemic therapy, Exp. Opin. Drug Del 18 (2021), 18:531–534.
[2] P. Paliwal, S. Sargolzaei, S.K. Bhardwaj, V. Bhardwaj, C. Dixit, A. Kaushik, Grand Challenges in Bio-Nanotechnology to Manage COVID-19 Pandemic, Front. Nanotechnol. 2 (2020), 571284.
[3] A.K. Kaushik, J.S. Dhau, H. Gohel, Y.K. Mishra, B. Kateb, N.Y. Kim, D.Y. Goswami, Electrochemical SARS-CoV-2 Sensing at Point-of-Care and Artificial Intelligence for Intelligent COVID-19 Management, ACS Appl. Bio. Mater. 3 (2020) 7306–7325.
[4] S.P. Varahachalam, B. Lahooti, M. Chamanee, S. Bagchi, T. Chhibber, K. Morris, J. F. Bolanos, A. Kaushik, Kim, Nanomedicine for the SARS-CoV-2: state-of-the-Art and Future Prospects, Int. J. Nanomedicine. 16 (2021) 539–560.
[5] V. Yamamoto, J.F. Bolanos, J. Fiallos, et al., COVID-19: review of a 21st Century Pandemic from Etiology to Neuro-psychiatric Implications, J. Alz. Dis. 77 (2020) 459–504.
[6] A. Gage, K. Brunson, K. Morris, S.L. Wallen, J. Dhau, H. Gohel, A. Kaushik, Perspectives of manipulative and high-performance nanosystems to manage consequences of emerging new severe acute respiratory syndrome Coronavirus 2 variants, Front. Nanotechnol. 3 (2021) 45.
[7] A. Ahmadivand, B. Gerislioglu, Z. Ramezani, A. Kaushik, P. Manickam, S. A. Ghoreishi. Functionalized terahertz plasmonic metasensors: femtomolar-level detection of SARS-CoV-2 spike proteins. Biosens. Bioelectron. 177(177), pp. 112971.
[8] T. Bouzid, I. Anees-Maersano, B. Alahmad, C.N. Maersano, M.-A. Bind, The impact of outdoor air pollution on COVID-19: a review of evidence from in vitro, animal, and human studies, Eur. Resp. Rev. 30 (2021), 200242.

Fig. 9. The proposed position and role of Molekule Air purifiers to clean the air efficiently via trapping, eradicating, and neutralizing virus protein (A), and acknowledgement of Molekule Air Purifier’s accomplishments (B).
A.K. Kaushik and J.S. Dhau

[9] M.A. Sadique, S. Yadav, P. Ranjan, S. Verma, S.T. Salamam, M.A. Khan, A. Kaushik, R. Khan, High-performance antiviral nano-systems as a shield to inhibit viral infections: SARS-CoV-2 as a model case study, J. Mater. Chem. B. 9 (2021) 4620–4642.

[10] J.W. Tang, W.P. Bahnfleth, P.M. Blyuyssen, G. Buonanno, J.L. Jimez, J. Kuriniski, Y. Li, S. Miller, C. Sekhar, L. Moraweska, L.C. Marr, Disrupting myths on the airborne transmission of severe acute respiratory syndrome coronavirus (SARS-CoV-2), J. Hosp. Infec. 110 (2021) 89–96.

[11] M. Klopas, M.A. Baker, C. Rhre, Airborne Transmission of SARS-CoV-2: theoretical Considerations and Available Evidence, JAMA 324 (2020) 441–442.

[12] Z.S. Fachangrazi, G. Sancini, A.C. Hunter, S.M. Moghimi, Airborne particulate matter and SARS-CoV-2 Partnership: virus hitchhiking, stabilization and immune cell targeting—a hypothesis, Front Immunol 11 (2020) 579352.

[13] N.T. Tung, P.C. Cheng, K.H. Chi, T.C. Hsiao, T. Jones, K. Bérubé, K.F. Ho, H. Chuang, Particulate matter and SARS-CoV-2: a possible model of COVID-19 transmission, Sci. Tot. Env. 750 (2021), 141532.

[14] N.S.M. Nor, C.W. Yip, N. Ibrahim, M.H. Jaafar, Z.Z. Rashid, N. Mustafa, H.H. Abd Hamid, K. Chandru, M.T. Latif, P.E. Saw, C.Y. Lin, Particulate matter (PM 2.5) as a potential SARS-CoV-2 carrier, Sci. Rep. 11 (2021) 2508.

[15] B. Wang, J. Liu, Y. Li, S. Fu, X. Xu, L. Li, J. Zhou, X. Liu, X. He, J. Yan, Y. Shi, Airborne particulate matter, population mobility and COVID-19: a multi-city study in China, BMC Public Health 20 (1) (2020) 1–10.

[16] T. Barakat, B. Myulikens, B.-L. Su, Is Particulate Matter of Air Pollution a Vector of Covid-19 Pandemic? Matter 3 (2020) 977–980.

[17] S. Huang, COVID-19: why we should all wear masks — there is new scientific rationale, Medium (2020), https://medium.com/@Cancerwarrior/covid-19-why-we-should-all-wear-masks-there-is-new-scientific-rationale-280e06ceee71.

[18] S. Tiwari, S. Juneja, A. Ghosal, N. Bandara, R. Khan, S.L. Wallen, S. Ramakrishna, A. Kaushik, Antibacterial and antiviral high-performance nano-systems to mitigate new SARS-CoV-2 variants of concerns, Curr. Opm. Biomed. Eng. 21 (2021), 100363.

[19] Periodic graphics: comparing how air purification technologies trap and attack viruses. Chem. Eng. News, https://cen.acs.org/biological-chemistry/infectious-disease/Periodic-Graphics-Comparing-how-air-purification-technologies-trap-and-attack-viruses/99/i23.

[20] P. Li, J. Li, X. Feng, J. Li, Y. Hao, J. Zhang, H. Wang, A. Yin, J. Zhou, X. Ma, B. Wang, Metal-organic frameworks with photocatalytic bactericidal activity for integrated air cleaning, Nat. Commun. 10 (2019) 2177.

[21] F. He, W. Jeon, W. Choi, Photocatalytic air purification mimicking the self-cleaning process of the atmosphere, Nat. Commun. 12 (2021) 12:2528.

[22] V.K.H. Bui, T.N. Nguyen, V. Tran Tran, J. Hur, I.T. Kim, D. Park, Y.C. Lee, Photocatalytic materials for indoor air purification systems: an updated mini-review, Env. Technol. Innovation. 22 (2021), 22:101471.

[23] M. Buonanno, D. Welsh, I. Shuryak, D.J. Brenner, Far-UVC light (222nm) efficiently and safely inactivates airborne human coronaviruses, Sci. Rep. 10 (2020) 10:2825.

[24] N. Bono, F. Ponti, C. Punta, G. Clandi, Effect of UV irradiation and TiO2–photocatalysis on airborne bacteria and viruses: an overview, Materials (Basel) 14 (2021) 14:1075.

[25] S. Irvani, Nanopozotocatalysts against viruses and antibiotic-resistant bacteria: recent advances, Crit. Rev. Microbiol. (2021) 1–16, https://doi.org/10.1080/1040841X.2021.1944053.

[26] A. Poormohammadi, S. Bashirian, A.R. Rahmani, G. Azarian, F. Mehri, Are photocatalytic processes effective for removal of airborne viruses from indoor air? A narrative review, Environ. Sci. Pollut. Res. 28 (2021) 43007–43020.

[27] N. Zacharias, A. Haag, R. Brang-Lamprecht, J. Gebel, S.M. Essert, T. Kistemann, M. Exner, N.T. Mutters, S. Engelhart, Air filtration as a tool for the reduction of viral aerosols, Sci. Tot. Env. 772 (2021), 144956.

[28] L. Hosain, M. Malíha, R. Barajas-Ledesma, J. Kim, K. Putera, D. Subedi, J. Tanner, J.J. Barr, M.M.B. Holl, G. Garnier, Engineering laminated paper for SARS-CoV-2 medical gowns, Polymer (Guildf) 222 (2021), 12:2643.

[29] H.R. Kim, S. An, J. Hwang, High air flow-rate electrostatic sampler for the rapid monitoring of airborne coronavirus and influenza viruses, J. Haz. Mater. 412 (2021), 125219.

[30] A. Singh, A. Kaushik, J.S. Dhau, R. Kumar, Exploring coordination preferences and biological applications of pyridyl-based organochalcogenes (Se, Te) ligands, Coord. Chem. Reviews 450 (1) (2022), 214254.

[31] P.K. Sharma, E.S. Kim, S. Mishra, E. Ganbold, R.S. Seong, A.K. Kaushik, N.Y. Kim, Ultra-sensitive and reusable graphene oxide-modified double-interdigitated capacitive (DIDC) sensing chip for detecting SARS-CoV-2, ACS sensors 6 (9) (2021) 3468–3476.

[32] L. Mozawska, J. Allen, W. Bahnfleth, P.M. Blyuyssen, A. Boerstra, G. Buonanno, J. Cao, S.J. Dancer, A. Floto, F. Franchimon, T. Greenhalgh, A paradigm shift to combat indoor respiratory infection, Science 372 (2021) 689–691.

[33] J. Pulc, M. Schreier, C. Janiszewski, Facial mask personalization encourages facial mask wearing in times of COVID-19, Sci. Rep. 12 (1) (2021) 891.

[34] S. Spalich, A. Nath, Nervous system consequences of COVID-19, Science 375 (2022) 267–269 (6578).

[35] M.A. Haidar, Z. Shahkour, M.A. Reslan, N. Al-Haj, P. Chamoun, K. Habashy, H. Kafarani, S. Shahyoub, S.H. Farran, A. Shaito, E.S. Saba, SARS-CoV-2 involvement in central nervous system tissue damage, Neural Regen. Res. 17 (6) (2022) 1228.

[36] E. Mostafavi, A.K. Dubey, L. Teodori, S. Ramakrishna, A. Kaushik, SARS-CoV-2 Omicron variant: A next phase of the COVID-19 pandemic and a call to arms for system sciences and precision medicine, MedComm 3 (2022) e119.

[37] S. Tiwari, S. Juneja, A. Ghosal, N. Bandara, RN. Khan, S. Wallen, S. Ramakrishna, A. Kaushik, Antibacterial and antiviral high-performance nano-systems to mitigate new SARS-CoV-2 variants of concerns. Current Opinion in Biomaterial Engineering, 21 (2022) 21, 100363.