PEOAS: Plasma Electrolytic Oxidation Air Sterilizer

Abstract
Indoor air quality, often overlooked in the broader discourse on pollution, has emerged as a critical concern, not only in densely populated urban areas but also in rural settings, where traditional practices and lack of infrastructure contribute to the degradation of air quality. Moreover, the rapid pace of industrialization and urban development has further exacerbated the issue, compromising air quality and, by extension, the quality of life. Traditional air purification systems often struggle with fine particulate matter and microbial decontamination, particularly in high-density environments like hospitals. This paper presentsPlasma Electrolytic Oxidation Air Sterilizer, PEOAS, a novel air purification system developed to address these challenges. The PEOAS's ability to target particles down to 0.001 microns positions it as an ideal solution for environments demanding the highest air quality standards, such as hospitals, clinics, and public spaces. Proposed system is tested in a controlled environment, yielding a reduction of 89.13%for PM10 and 69.23%for PM2.5, alongside decreases in SO_2 and NO_x levels by 84.0% and 23.82% respectively. Remarkably, PEOAS achieved a microbial reduction efficacy of approximately 96% for bacterial and moulds, moreover, over 95% for fungi.

1. Introduction

Air is the essential medium for respiration, a complex mixture of gases that supports life on Earth. The composition of air suitable for breathing includes roughly 1% argon, 21% oxygen, 78% nitrogen, and traces of other gases including carbon dioxide at about 0.04%. The human respiratory system is designed to utilize oxygen from this mixture; we inhale oxygen and exhale carbon dioxide in a vital process called gas exchange. This exchange occurs in the lungs, where oxygen is absorbed by red blood cells and transported to body tissues while carbon dioxide, a by-product of metabolism, is picked up and expelled from the body with exhalation [1].While the body requires only oxygen, the presence of other components in the air does not typically harm humans, as our respiratory system has evolved to filter and utilize air effectively. However, anthropogenic activities have significantly degraded air quality, leading to pollution. Industrial emissions, vehicular exhaust, and other combustion processes release a plethora of pollutants, including fine particulate matter (PM), ranging from 0.01 to 1.0 micron, composed of substances like anthracene, pyrene, and various aromatic hydrocarbons [2]. Additionally, the combustion of carbon-based materials generates gases such as nitrogen oxides (NO_x), sulphur dioxide (SO_2), hydrogen fluoride (HF), and chlorides, which contribute to the formation of smog and acid rain, posing health risks to respiratory and cardiovascular systems [3].These pollutants exist in several forms, including solid particulates generated through sublimation at high temperatures, fumes condensed from gases, fine grains from atomized fluids, and chemical gases produced by heating. Sulphur dioxide, for instance, is a result of burning heavy oils and coal, and it's known to exacerbate asthma and other respiratory conditions [4]. Nitrogen oxides, on the other hand, contribute to ground-level ozone formation and can impair lung function [5].The air can also harbour infectious agents like bacteria, viruses, fungi, and prions, which humans can disseminate via aerosol particles or droplets when coughing or sneezing. These pathogens are responsible for a range of airborne diseases, capable of rapid spread in populated areas, as seen with the influenza virus and other respiratory pathogens [6].The intersection of air pollution and airborne diseases represents a dual challenge for public health. While the body's defences filter many contaminants, prolonged exposure to polluted air can overwhelm these systems, leading to increased susceptibility to respiratory infections and other health complications.

Therefore, maintaining indoor and outdoor air quality is critical for health and well-being.The quality of the air we breathe is of paramount concern, particularly as it becomes increasingly laden with a diverse array of chemical contaminants, pathogens, and viruses. These airborne threats pose a heightened risk to human health, especially in indoor environments where natural airflow is limited, and mechanical circulation predominates. The challenge is exacerbated in areas with high occupancy or limited ventilation, leading to a concentration of pollutants that can contribute to a range of health issues, from respiratory irritation to the spread of infectious diseases.

Conventional air purification systems, such as those employing High-Efficiency Particulate Air (HEPA) filters, are adept at trapping particles that are 0.3 microns or larger. These filters operate on the principle of interception, diffusion, and impaction to capture particulate matter, including common allergens like pollen, mould spores, dust mites, and pet dander. However, the efficacy of HEPA filters decreases significantly when confronting particles smaller than 0.3 microns, particularly viruses, which can be as small as 0.001 microns. Viruses such as the influenza virus, rhinoviruses causing the common cold, and other airborne pathogens can easily pass through these filters due to their minuscule size. Moreover, HEPA filters do not inactivate or destroy viruses; they merely capture them, which can lead to virus accumulation and potential secondary release during filter replacement or cleaning. Furthermore, HEPA systems do not address gaseous pollutants such as SO_2, NO_x, HF, and ozone (O_3), which can be harmful to human health. SO_2, a by-product of the combustion of fossil fuels containing sulphur compounds, can exacerbate asthma and contribute to acid rain. NO_x, primarily from vehicle emissions and power generation, can lead to the formation of ground-level $O_3$and smog, while HF and O_3 are known irritants to the eyes, skin, and respiratory system. Table 1 shows some of these technologies along with their drawbacks and how proposed work overcome those issues. This paper proposes Plasma Electrolytic Oxidation Air Sterilizer (PEOAS) which can be used to not only filter but also sterilize the air through multi-layer purification process. The air is first drawn into a main chamber, where it undergoes a series of stages designed to eliminate pollutants effectively. Larger particles are captured in the initial layers, preparing the air for finer purification. Utilizing the adsorptive properties of activated charcoal, this layer removes various organic compounds and odours, providing a crucial step in the purification of gaseous contaminants. In electrostatic precipitation stage viruses, fungi, and ultrafine particles are charged and then captured on oppositely charged plates, effectively removing them from the air. Finally, a photocatalyst activated by UV light decomposes organic and inorganic pollutants at a molecular level, including those as small as 0.001 microns, thereby neutralizing harmful microorganisms.

Table 1: Comparison of different air filtration technology and their downsides

Technology	Description	Particle Removal Efficiency	Limitations	Citation
HEPA Filters	They capture 99.97% of particles of minimum size 0.3 microns.	≥0.3 microns	Ineffective against ultrafine particles, does not neutralize pathogens.	[7-8], [17]
Photocatalytic Oxidation (PCO)	Uses UV light and a catalyst like titanium dioxide to oxidize pollutants.	Effective on molecular level pollutants.	Can produce harmful by-products like formaldehyde if not properly designed.	[9-10],[18]

Electrostatic Precipitators	Charge particles in the air, attracting them to plates with the opposite charge.	Fine particles	Can produce ozone, require regular cleaning of plates.	[11-12], [19]
UV-C Light Systems	Use ultraviolet light to inactivate microorganisms.	Effective on microorganisms.	Only affects microorganisms in direct line of sight, potential UV exposure risk.	[13-14], [20]
Plasma-Based Air Purifiers	Use plasma to break down contaminants in the air.	Broad range, including ultrafine particles.	Potential for harmful by-products like ozone.	[15-16], [21]
PEOAS	Integrates cooled plasma and Electrolytic Oxidation to purify and sterilize air.	As small as 0.001 microns.	-	Proposed work

The PEOAS's ability to target particles down to 0.001 microns positions it as an ideal solution for environments demanding the highest air quality standards, such as hospitals, clinics, and public spaces. By deploying this technology, facilities can significantly reduce the risk of airborne disease transmission, offering a safer and healthier environment for both occupants and visitors.

The remainder of the paper is organized in a systematic manner to provide a thorough understanding of the study and its findings. Section 3 introduces two pivotal research questions, the answers to which are comprehensively detailed in Section 7. Section 4 delves into the intricate multi-layer methodology employed by the innovative PEOAS system, shedding light on its operational framework. A more granular exploration is undertaken in Section 5, which elucidates the subprocesses integral to the air sterilization process, revealing the nuanced mechanics of PEOAS. This is closely followed by Section 6, where the experimental results that substantiate our findings are meticulously presented. The paper reaches its culmination in Section 8, which encapsulates the study's conclusions, drawing together the key insights and implications of the research.

2. Research Questions

This research focuses on giving the answer to the following two research questions through the experimental analysis of proposed PEOAS.

Q1: How effective is the PEOAS in reducing particulate matter of different sizes and gaseous pollutants in indoor environments?

Q2: What is the efficacy of the PEOAS in controlling microbial contamination, specifically bacteria and fungi, commonly present in indoor air? How effective is it in healthcare settings, food preparation areas, and other spaces where air quality is critical for health and safety?

Section 7 presents the answers to these research questions based on the results observation.

3. Methodology

The sequential process of PEOASdevice is shown in figure 1. It shows various layers that are embedded in the filter for purification of air.

3.1. Pre-Filtration Layer

The air is initially drawn through one or more pre-filters that capture large particulate matter. These pre-filters can remove various pollutants, such as dust, pollen, and other allergens, preventing them from entering the core purification system. This stage extends the life of subsequent filters and ensures higher efficiency for finer filtration processes.

3.2. Activated Charcoal Filtration Layer

Following pre-filtration, the air passes through a layer of activated charcoal. This material is chosen for its high adsorption capacity, thanks to its extensive pore structure. The activated charcoal effectively traps a variety of volatile organic compounds (VOCs), as well as odours and gases produced from industrial activities and urban pollution. This includes complex organic molecules, which can be harmful when inhaled over long periods.

3.3. Electrostatic Precipitation Layer

In the electrostatic precipitation stage, the air is exposed to an electric field, which imparts a charge to the particles. These charged particles are then attracted to plates with an opposite charge, effectively removing them from the air. This method is particularly effective for capturing ultrafine particles that might elude other types of filters, including viruses, bacteria, and mould spores.

3.4. Cooled Plasma Generation Layer

The cooled plasma generator is a critical innovation in this system. Plasma is often called the fourth state of matter and involves ionizing gases to create a field of charged particles. This plasma field interacts with airborne pollutants, breaking down their molecular structure without the need for high temperatures. It provides an effective means to neutralize pathogens and chemical contaminants while maintaining ambient air temperature for comfort. This device utilizes plasma technology as a core component of its air purification process. Plasma is generated and maintained at lower temperatures suitable for safe operation within inhabited spaces. Thus, air sterilization process does not contribute to heat within the environment where the device is operating.

3.5. Electrolytic Oxidation (PCO) Layer

At this stage, a photocatalyst, typically titanium dioxide (TiO_2), is activated by ultraviolet light to produce super-oxide ions andhydroxyl radicals. These highly reactive species interact with pollutants such as bacteria, viruses, and VOCs, breaking them down into harmless substances such as carbon dioxide and water vapor. The PCO process is effective against a variety of organic and some inorganic compounds and is a key step in ensuring that the air is not just filtered but sanitized.

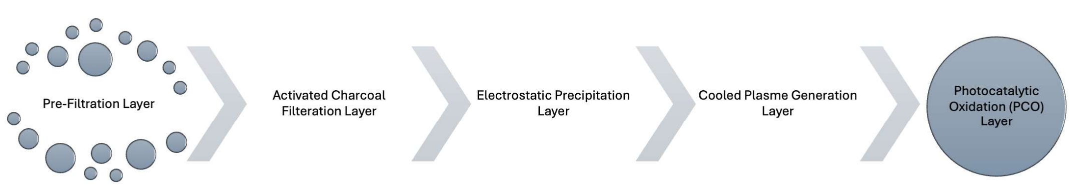


Figure 1: PEOAS Sequential Process

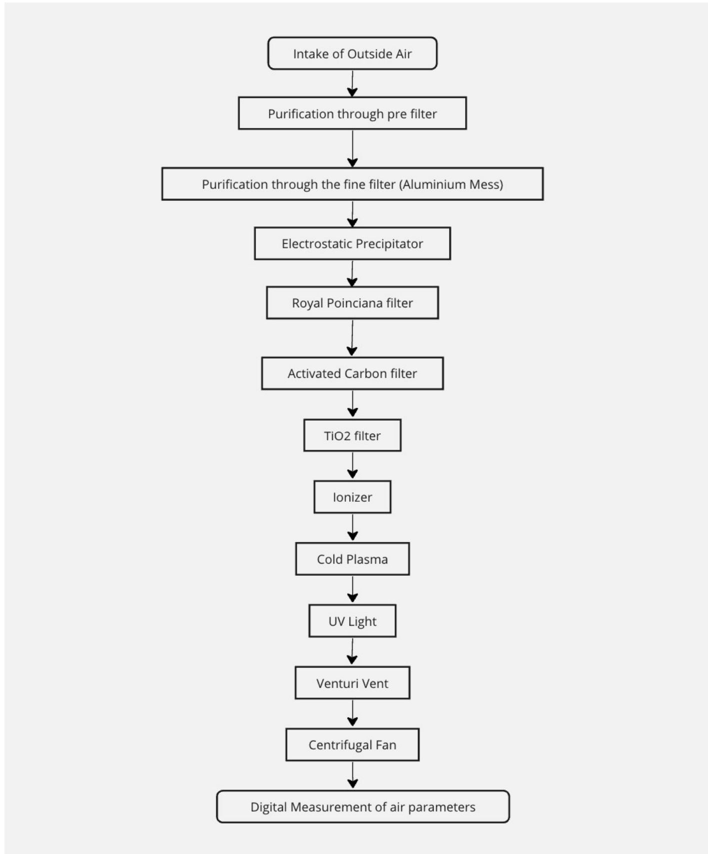


Figure 2: Subprocesses in PEOAS

4. Purification Process

This comprehensive air sterilizer uses a multi-stage purification process as shown in figure 2 that utilizes both physical filters and chemical processes to clean the air of particulates, microorganisms, and other pollutants. Each sub-process contributes to the overall effectiveness of the system, ensuring that the air released back into the environment is clean and safe to breathe. This section discusses each of these subprocesses in more detail.

4.1. Intake of Outside Air

The system begins by taking in air from the outside environment. This is the first step in the purification process where raw, unfiltered air enters the chamber for treatment.

4.2. Purification through Pre-Filter

The initial stage of filtration involves a pre-filter that captures larger particulate matter such as dust, pollen, and hair. This early interception is crucial for protecting the more refined filters downstream and ensuring their longevity and efficiency.

4.3. Purification through Fine-Filter (Aluminium Mess)

Following preliminary filtration, the air is further refined through a fine aluminium mesh filter. This stage targets smaller particles not captured by the pre-filter, enhancing the overall particulate removal efficiency of the system.

4.4. Electrostatic Precipitator

Next, the air is subjected to an electrostatic precipitator that employs an electric charge to attract and trap extremely fine particulate matter. This technology is particularly effective in removing smoke and microscopic pollutants, significantly improving air quality.

4.5. Royal Poinciana Layer

The incoming air is then passed through a nano-layer made from the fabric of Royal Poinciana tree.This layer possesses natural air purification properties, contributing to the removal of additional contaminants and enhancing air freshness.

4.6. Activated Carbon Layer

After initial purification, the air is subjected to an electrostatic magnetic field. This process generates negative ions, which are known to attach to and neutralize airborne particles like bacteria and fungi, effectively removing them from the air.

4.7. Titanium Dioxide Layer

Next, the air passes through an outer layer of Titanium dioxide (TiO_2).It acts as a photocatalyst when exposed to UV radiation, breaking down contaminants at a molecular level.

4.8. Ionizer Layer

The air is then filtered through layers of activated charcoal and carbon. These materials are highly porous and have a large surface area, making them effective at trapping pollutants like PM 2.5 and PM 10.0, which are particulate matter with diameters of 2.5 and 10 micrometres, respectively.

4.9. Cold Plasma Layer

The cold plasma layer employs plasma technology to deactivate a wide range of pathogens, including bacteria, viruses, and mould spores, without the need for high temperatures. This energy-efficient method ensures the air is not only clean but also safe for indoor environments.

4.10. Ultraviolet Filtration

Along with the antibacterial layer mentioned in process 7, the air is exposed to ultraviolet rays. UV light has the ability to dismantle and inactivate bacterial and fungal elements, adding another level of purification.

4.11. Venturi Vent

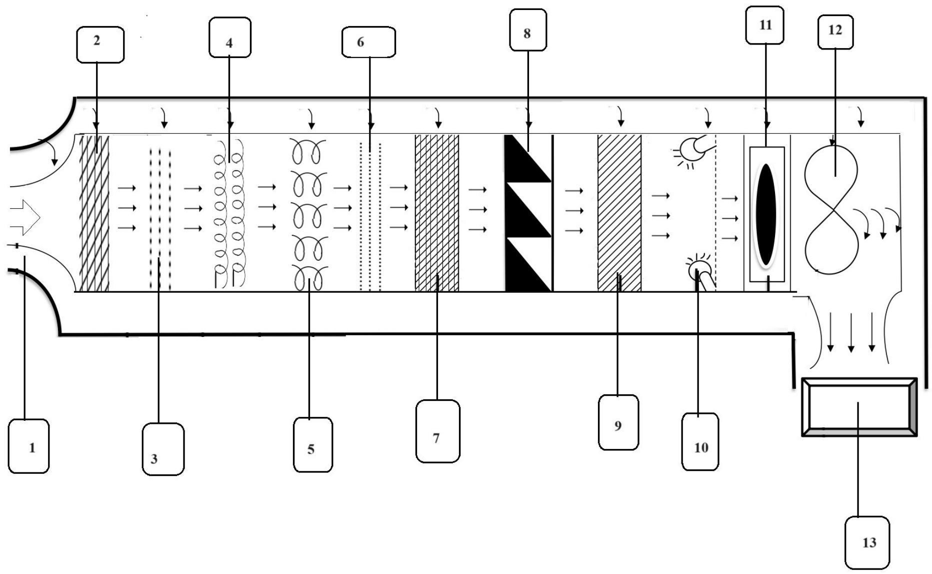
Air then passes through a venturi vent made of copper and brass. The venturi effect creates a lower pressure zone that helps to propel the air with greater force through the system.

4.12. Centrifugal Fan

A centrifugal fan is used to pull air from the outside to the inside of the system and then thrust it back out. This ensures a continuous flow of air through the purifier.

4.13. Digital Measurement of Air Parameters

This process involves sensors and digital systems to monitor the quality of air, such as measuring levels of various pollutants, to ensure the system is functioning correctly and effectively improving air quality.



5. Results and Observation

Proposed PEOAS sterilizer is tested in NABL authorized laboratory and results have been presented in table 2.

Table 2: Reduction Efficiency of PEOAS for Particulate and Gaseous Pollutants

Parameters	**Before Result**	**After Result**	**% Reduction**	**Test Method**
Particulate matter (<10 µm) in µg/m³	46	5	89.13%	IS: 5182 (Part-23) -(RA-2017)
Particulate matter (<2.5 µm) in µg/m³	13	4	69.23%	USEPA CFR-40, Part-50, Appendix-L
Sulphur dioxide (SO2) in µg/m³	25.0	<4.0	84.0%	IS: 5182 (Part-2)-2001, (RA-2017)
Nitrogen dioxide (NO2) in µg/m³	16.58	12.63	23.82%	IS: 5182 (Part-6), (RA-2017)
Carbon Dioxide (CO2) in %	<0.2	<0.2	0.0%	IS:13270-1992, Reaf: 2014
Ozone (O3) in mg/m³	<18.54	<18.54	0.0%	IS 5182 (Part 9): 2014
V.O.C in mg/m³	<0.1	<0.1	0.0%	IS 5182: Part.11:2006 (RA-2012)
Formaldehyde in µg/m³	<300	<300	0.0%	NIOSH-2016-15th March,2003
Total Bacterial Count in CFU/90mm Plate/Duration of exposure	<16	<0.5	96.88%	ISO 14698-1:2003(E):2003
Mould Count in CFU/90mm Plate/Duration of exposure	<13	<0.5	96.15%	ISO 14698-1:2003(E):2003
Fungi in CFU/m³	<9	<0.4	95.56%	EPA Method

We made the following observations from the results.

Significant Reduction in Particulate Matter: The results show a substantial reduction in particulate matter, with PM10 levels decreasing from 46 µg/m³ to 5 µg/m³ and PM2.5 levels from 13 µg/m³ to 4 µg/m³. This indicates the system's effectiveness in removing fine and ultrafine particles from the air, which are known to pose significant health risks.

Decrease in Sulphur Dioxide and Nitrogen Dioxide Levels: The concentrations of SO2 and NO2 have also decreased, with SO2 levels dropping from 25.0 µg/m³ to less than 4.0 µg/m³ and NO2 levels from 16.58 µg/m³ to 12.63 µg/m³. This demonstrates the system's capability to reduce gaseous pollutants, contributing to improved air quality.

Stable Levels of Carbon Dioxide and Ozone: The levels of CO2 and O3 remained below the detectable limits before and after the test, indicating that the system maintains safe levels of these gases without increasing their concentration.

Volatile Organic Compounds (VOC) and Formaldehyde: The concentration of VOCs and formaldehyde remained below detectable limits before and after the purification process, suggesting the system's efficiency in controlling chemical pollutants.

Dramatic Reduction in Microbial Counts: There is a notable decrease in total bacterial count, mould count, and fungi, with bacterial count reducing to less than 0.5 CFU/90mm plate from less than 16, and mould and fungi counts also showing similar reductions. This points to the system's high efficacy in reducing microbial presence, significantly lowering the risk of airborne infections.

The results from the table indicate that the PEOAS is highly effective in reducing both particulate and microbial contamination in the air. The device demonstrates a strong capacity to refine indoor air quality by significantly lowering the concentrations of various pollutants and pathogens.

6. Discussion

In this section we provide the answer to the proposed research questions.

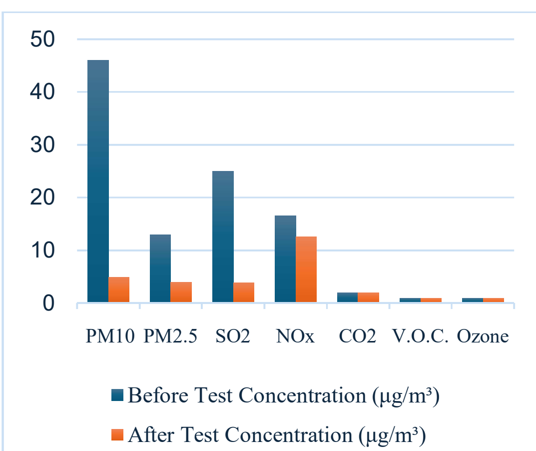


Figure 3: Before and After results of PEOAS for particulate and gaseous pollutants.

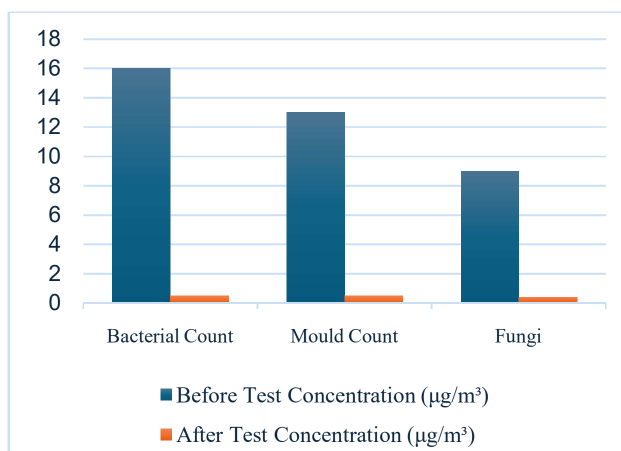


Figure 4: Before and After results of PEOAS for Microbes.

*A1:*It can be seen from figure 3 that proposed PEOAS demonstrates considerable effectiveness in reducing particulate matter, with PM10 levels decreasing by 89.13% and PM2.5 levels by 69.23%. This indicates a strong capability of the system to capture fine and ultrafine particles, which are known to have adverse health effects. Furthermore, the system effectively reduces concentrations of common gaseous pollutants such as SO_2 and NO_x by 84.0% and 23.8%, respectively. These reductions are significant because these gases can exacerbate respiratory conditions and contribute to environmental pollution.

*A2:*From figure 4 it is evident that the air purification system exhibits high efficiency in controlling microbial contamination in indoor air. It shows a 96.88% reduction in total bacterial count and a 96.15% reduction in mould count, with fungi showing a 95.56% reduction, which can significantly decrease the risk of allergenic and pathogenic infections. These results suggest that the PEOAS could be a powerful tool in reducing the transmission of infectious diseases and in maintaining a sterile environment, making it highly suitable for healthcare settings, food preparation areas, and other spaces where air quality is critical for health and safety.

7. Conclusion

With its innovative combination of physical filtration, electrostatic precipitation, cooled plasma technology, and Electrolytic Oxidation, the PEOAS offers a superior solution to indoor air quality challenges. Its ability to address pollutants down to 0.1 microns in size makes it particularly suitable for healthcare settings, where the highest standards of cleanliness are required to protect the health of patients and staff. This technology not only purifies the air but also creates a healthier indoor environment by actively eliminating the biological and chemical contaminants that contribute to indoor air pollution. While the reduction in TOC and VOCs is lower compared to other contaminants, the results are still positive. The substantial reduction in airborne pathogens, including bacteria and fungi, underscores the potential of this technology for application in settings where sterility and air quality are of utmost importance, such as hospitals, clinics, and public spaces.

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