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Pilot Study on the Production of Negative Oxygen Ions Based on Lower Voltage Ionization Method and Application in Air Purification

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Abstract: In the current highly industrialized living environment, air quality has become an increasing public health concern. Natural environments like forests have excellent air quality due to high concentrations of negative oxygen ions originating from low-voltage ionization, without harmful ozone. Traditional negative oxygen ion generators require high voltage for corona discharge to produce ions. However, high voltage can increase electron collisions and excitations, leading to more dissociation and recombination of oxygen molecules and consequently higher ozone production. To address the challenge of generating negative oxygen ions without accompanying ozone production, this study designed and constructed a low-voltage negative oxygen ion generator based on nanometer-tip carbon fiber electrodes. The advantage of this device lies in the high curvature radius of carbon fibers, which provides high local electric field strength. This allows for efficient production of negative oxygen ions at low operating voltages without generating ozone. Experiments demonstrated that the device can efficiently generate negative oxygen ions at a working voltage as low as 2.16 kV, 28% lower than the lowest voltage reported in similar studies. The purification device manufactured in this study had a total decay constant for $PM_{2.5}$ purification of 0.8967 min^{-1} within five minutes, compared to a natural decay constant of only 0.0438 min^{-1}, resulting in a calculated Clean Air Delivery Rate (CADR) of 0.1535 m^3/min. Within half an hour, concentrations of $PM_{2.5}$, PM_1, PM_{10}, formaldehyde, and TVOC were reduced by 99.09%, 99.40%, 99.37%, 94.39%, and 99.35%, respectively, demonstrating good decay constants and CADR. These findings confirm its effectiveness in improving indoor air quality, highlighting its significant application value in air purification.

Keywords: negative oxygen ions; air purification; $PM_{2.5}$; formaldehyde; TVOC

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1. Introduction

In the current societal context, air quality has become a crucial factor affecting public health [1,2]. Good air quality is not only essential for maintaining respiratory and cardiovascular health but also effectively reduces the risk of respiratory and cardiovascular diseases. Fine particles in the air, such as PM_1, $PM_{2.5}$, and PM_{10}, can remain suspended in the air for a long time due to their tiny size and are easily inhaled by humans [3]. These particles can cause lung inflammation, impair lung function, and even lead to permanent health issues such as lung cancer. Due to their light weight, these particles do not easily settle naturally, can travel long distances, and carry harmful substances that invade the human body, posing serious health risks [4]. With the worsening smog problem, the threat posed by these fine particles to health has become a major concern for the public and research institutions [5,6]. Similarly, indoor air pollution, particularly the presence of formaldehyde and total volatile organic compounds (TVOCs), also poses a significant threat to human health [7]. Formaldehyde, a highly irritating gas, can cause respiratory irritation and skin allergic reactions, and long-term exposure may lead to severe lung disease and cancer [8]. Prolonged exposure to various organic compounds in TVOCs can cause symptoms such as headaches, fatigue, and lack of concentration, and high concentrations can damage the nervous system and liver [9]. Therefore, effectively removing particles, formaldehyde, and TVOCs from indoor air is crucial for protecting public health [10,11].

For TVOCs, different organizations have different definitions. According to the Chinese national standard GB/T 18883-2002 [12] and the International Organization for Standardization ISO 16000-6:2021 [13], TVOC refers to volatile organic compounds that have a retention time between hexane and hexadecane, sampled using TenaxGC or TenaxTA, and analyzed through a non-polar chromatographic column (with a polarity index of less than 10). According to this definition, formaldehyde is not considered part of TVOCs. In addition, formaldehyde itself has significant harmful effects in indoor air pollution. Therefore, in this study, its removal effectiveness was specifically reported as an important purification parameter to provide a clearer and more detailed assessment of air purification effectiveness.

Among the many air purification technologies, the negative oxygen ion air purification method stands out due to its unique advantages. Generating large amounts of negative oxygen ions in indoor environments can efficiently purify the air and significantly reduce the concentration of suspended particles [14]. These negative oxygen ions effectively aggregate and settle dust and bacteria in the air, and they can also positively affect human health. Thus, the concentration of negative oxygen ions has become an important indicator for assessing environmental quality, sports facilities, and tourist attractions' air quality [15,16]. However, traditional negative oxygen ion devices often generate ozone due to high operating voltages, negatively affecting the air environment [17].

There are various methods to generate negative oxygen ions, including ultraviolet irradiation, thermal ionization, radioactive material radiation, charge transfer, high-pressure water jets, and corona discharge. Each method has unique advantages and limitations, making them suitable for different practical applications. Among these methods, the corona discharge method has become the mainstream technology for generating negative oxygen ions in many air purification devices due to its simplicity and high efficiency [18,19]. It typically operates at voltages between 3 kV and 10 kV, where the high-voltage electric field and current work together to ionize oxygen molecules in the air, producing negative oxygen ions.

Carbon fiber, as an excellent conductive material, can efficiently generate negative oxygen ions during corona discharge [20–22]. The large surface curvature of the carbon fiber electrodes in the negative oxygen ion device and the strong local electric field during corona discharge help reduce the operating voltage, thereby lowering the likelihood of ozone generation.

Based on this, this study utilizes negative oxygen ions generated by nanometer-tip carbon fibers as a novel air purification technology to reduce the levels of $PM_{2.5}$ and other harmful substances. This method effectively avoids ozone generation by operating at low voltage. The efficiency of this technology in generating negative oxygen ions and its contribution to air purification effects were thoroughly tested and analyzed. The study results not only reveal the great potential of negative oxygen ions in improving indoor air quality but also confirm the efficiency of carbon fibers in generating negative oxygen ions. This provides important scientific evidence and practical value for the future development of air purification technologies.

2. Materials and Methods

2.1. Principle of Using Negative Oxygen Ions as an Air Purification Method

Negative oxygen ions are highly effective in purifying air due to their ability to neutralize and remove various pollutants.

The mechanism of negative oxygen ions in air particulate purification involves three main steps: charge transfer, particle aggregation, and final deposition. Suspended particles in the atmosphere, such as $PM_{2.5}$, mainly consist of inorganic compounds like silicates and aluminosilicates. Their surfaces become positively charged due to friction with the air. When negative oxygen ions come into contact with these particles, the attraction generated by their electronegativity neutralizes the charges, changing the charge state of the $PM_{2.5}$ particles. Once neutralized, the $PM_{2.5}$ particles begin to aggregate due to the attraction between charges, forming larger particle clusters. As the aggregation process continues, the particle clusters become increasingly unstable due to gravity, reducing their suspension ability, and eventually settle to the ground or other surfaces, effectively removing them from the air. This process significantly reduces the concentration of $PM_{2.5}$ and other particulate matter in the air, achieving the goal of air purification [23].

Additionally, negative oxygen ions possess significant oxidizing properties, enabling them to effectively decompose organic pollutants in the air, such as formaldehyde and TVOCs. For example, free radicals generated by negative oxygen ions react with TVOC molecules, causing their structural decomposition. From the perspective of deposition, because negative oxygen ions carry a negative charge, they can effectively capture organic molecules in the air and react with them. The products of these reactions form larger particles and precipitate. This process not only involves directly decomposing harmful substances through chemical reactions but also includes physical adsorption, which causes these pollutants to aggregate in the air. Ultimately, these pollutants are effectively removed through filtration systems or natural sedimentation, thereby achieving the goal of air purification.

In addition to purifying particulate matter like $PM_{2.5}$, formaldehyde, and TVOCs as discussed in this study, the negative oxygen ion generator can also impact other indoor pollutants. It can reduce bacteria and viruses by damaging their cell structures, inhibit the growth of mold and mold spores, adsorb odor molecules such as those from secondhand smoke to eliminate unpleasant smells, and adsorb pollen and allergens to alleviate allergic reactions. Furthermore, it can oxidize and decompose harmful gases such as carbon monoxide (CO), ammonia (NH_3), and hydrogen sulfide (H_2S), thereby enhancing overall indoor air quality.

2.2. Negative Oxygen Ion Generation Methods—Corona Discharge

Among the diverse technologies for generating negative oxygen ions, corona discharge technology has become a favored method due to its wide application prospects, simple equipment requirements, and convenient operation process. The core of this technology lies in using the non-uniform electric field formed around sharp electrodes to produce air ions. Such devices mainly include metal needle generators and carbon fiber brush ion generators.

Under normal conditions, the air does not carry a charge. However, when a high voltage is applied near sharp electrodes, a strong electric field is formed, promoting the ionization process of the air. In this process, the strong electric field around the sharp electrode releases high-energy electrons, which then generate activated air molecules or primary positive ions. These generated ions subsequently recombine with electrons, releasing photons and forming an ionization region or corona zone. In the corona zone, the free ions produced by ionization diffuse towards or neutralize at the collecting electrode, completing the ionization process. The generation of corona discharge relies on creating a non-uniform electric field, which requires the ratio of the electrode spacing to the curvature radius of the electrode tip to exceed a specific threshold to ensure the stability of the discharge process. During the discharge, consistent self-sustaining discharge occurs only in the electrode tip region, while the rest of the area remains insulated, ensuring the stability of the entire discharge process.

The reason why a very high startup voltage is required to generate negative oxygen ions is to provide sufficient energy for the emission of electrons from the electrode surface, allowing them to collide with oxygen molecules in the air and form negative oxygen ions. Additionally, the strong electric field created by the high voltage is crucial for both electron emission and the generation of negative oxygen ions.

2.3. Advantages of Using Carbon Fiber as Electrode Material

For corona discharge-based negative oxygen ion generators, traditional metal needle generators tend to use corrosion-resistant precious metals to ensure long-term reliable operation. In contrast, carbon fiber generators provide a more cost-effective solution. Due to their excellent corrosion resistance and chemical stability, carbon fibers are suitable materials for designing negative oxygen ion generation devices.

The carbon fiber negative oxygen ion generator manufactured in this study efficiently generates consistent negative oxygen ions by ionizing air through fine carbon fiber tips. Although carbon fibers are not as sharp as metal needles, their finer diameter and high curvature radius can produce a higher local electric field strength under the same voltage, leading to a more significant corona discharge phenomenon. As shown in Figure 1, the generator is designed with a large number of closely arranged carbon fiber bundles, which spread out at the ends to prevent mutual influence and shielding of the generated electric fields. Additionally, this study utilized a pre-treatment step where carbon source gas decomposes and deposits on the carbon fiber substrate surface, forming nano-carbon tips with high curvature radii. This pre-treatment significantly increases the electrode's surface area and electric field strength, enhancing the electrode's electron emission efficiency and boosting negative oxygen ion generation [24]. The formation of nano-carbon tips also helps to lower the operating voltage and avoid ozone production, thus improving air purification effectiveness and overall device performance [25].

Figure 1. Nanometer-tip carbon fiber electrode.

During the operation of the negative oxygen ion device, high-energy electrons are emitted from the electrode surface. These electrons are captured by oxygen molecules in the air and react as follows:

$$O_2 + e^- \rightarrow O_2^- \tag{1}$$

The larger surface curvature of the carbon fiber electrodes in the negative oxygen ion device and the stronger local electric field during corona discharge help reduce the operating voltage, thereby decreasing the likelihood of ozone generation. This is because an increase in voltage leads to more electron collisions and excitations, accelerating the dissociation and recombination of oxygen molecules, thus increasing ozone generation. During the corona discharge process, an increase in voltage results in increased energy, making oxygen molecules more easily excited to produce reactive oxygen atoms, which then combine with other oxygen molecules to form ozone.

Specifically, oxygen molecules are dissociated into oxygen atoms and low-energy electrons after being struck by high-energy electrons:

$$O_2 + e^- \rightarrow O + O + e^- \tag{2}$$

Oxygen atoms combine with oxygen molecules in the presence of a third body M to form ozone, releasing heat:

$$O + O_2 + M \rightarrow O_3 + M + heat \tag{3}$$

In this equation, M represents other gas molecules in the environment [26]. This process not only generates ozone but is also an exothermic reaction. The negative oxygen ion device used in this study can effectively produce negative oxygen ions at low voltage without generating ozone. During the operation of the negative oxygen ion device designed in this study, ozone was not detected using an ozone detection device with a range of 0–10.00 ppm, a resolution of 0.01 ppm, and an accuracy of ±6% FS (@5 ppm, 25 °C, 50% RH).

Besides ozone, nitrogen oxides are also a concern during the operation of the negative oxygen ion device. Nitrogen (N_2) and oxygen (O_2) in the air can dissociate and react under the influence of electrons, forming various nitrogen oxides such as nitric oxide (NO) and nitrogen dioxide (NO_2). Specifically:

$$N_2 + 2O \rightarrow 2NO \tag{4}$$

$$NO + O \rightarrow NO_2 \tag{5}$$

$$NO_2 + O^- \rightarrow NO_3^- \tag{6}$$

Nitrogen oxides are harmful to human health and can cause respiratory problems and other health issues. The formation mechanism of nitrogen oxides is very similar to that of ozone; theoretically, reducing the corona discharge voltage can reduce their generation. This study mainly focuses on eliminating the possibility of ozone production, and the risk analysis of nitrogen oxides will be an important research direction in the future. Currently, using an industrial nitric oxide detector with a measurement range of 0–100 ppm, a resolution of 0.01 ppm, an accuracy of ±1% FS, and a linear error of ±1%, no related gases were detected.

Compared to traditional metal needle-type negative oxygen ion generators, the nanometer-tip carbon fiber low-voltage negative oxygen ion generator has the following advantages:

1. The excellent conductivity and chemical stability of carbon fiber allow it to continuously and stably produce negative oxygen ions under an electric field, ensuring long-term performance stability.
2. The relatively low manufacturing cost and simplified production process of carbon fiber make it suitable for large-scale production, meeting industrial demands.
3. The structural stability of carbon fiber and its high resistance to external environmental factors ensure that it can effectively generate negative oxygen ions under various environmental conditions, demonstrating good adaptability and stability.
4. The negative oxygen ions produced by the nanometer-tip carbon fiber electrode not only have a high concentration and strong activity but can also effectively react with fine particles like $PM_{2.5}$ and pollutants such as formaldehyde in the air, causing them to settle or decompose, achieving efficient air purification.
5. Due to the high conductivity and high curvature radius of the nanometer-tip carbon fiber electrode, the negative oxygen ion generation equipment can operate stably at lower working voltages, effectively avoiding ozone generation and making the air purification process safer and more environmentally friendly.

2.4. Relevant Parameters

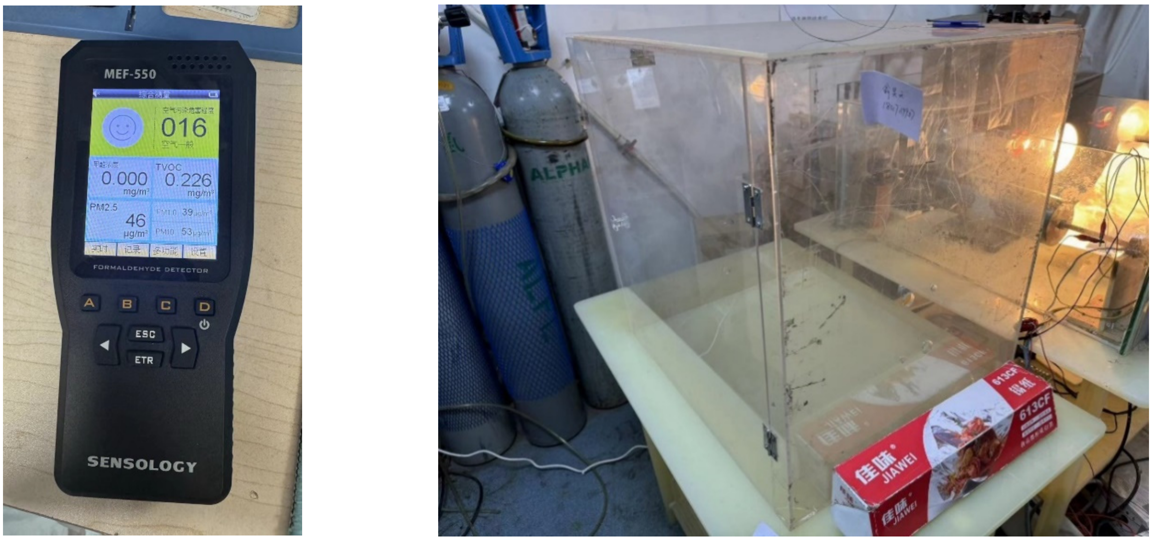
The concentration of negative oxygen ions in the air is an important parameter in this study. It is typically defined as the number of negative oxygen ions per unit volume of air, measured in ions per cubic centimeter (ions/cm^3).

In this research project, the input voltage of the negative oxygen ion generation equipment can be precisely controlled through an external transformer, with an adjustment range from 0 volts to 220 volts. When the input voltage is set to 220 volts, the device can produce an output working voltage of approximately 6.71 kilovolts.

The negative oxygen ion measurement equipment used is the WST-05A air negative oxygen ion detector, with a resolution of 10 ions/cm^3, a range of up to 5×10^6 ions/cm^3, and an error margin of ±5%.

To address common pollutants in the air, this study tested the purification capability of negative oxygen ions on $PM_{2.5}$, PM_1, PM_{10}, formaldehyde, and total volatile organic compounds (TVOCs).

As shown in Figure 2a, this study utilized the commercial air detector Sensology MEF-550 to test these pollutants. The device measures formaldehyde using an electrochemical sensor, with a range of 0–2.5 mg/m^3, a resolution of 0.01 mg/m^3, a measurement error of less than ±1%, and a repeat accuracy of less than 2%. TVOCs were detected using a WINSEN semiconductor sensor, with a range of 0–9.999 mg/m^3, a resolution of 0.01 mg/m^3, and a measurement error of less than ±1%. Particulates such as $PM_{2.5}$ were measured with a laser sensor, which has a range of 0–999 µg/m^3 and a resolution of 0.1 µg/m^3.



(**a**) (**b**)

Figure 2. (**a**) Air pollutant measurement instrument—Sensology 235 MEF; (**b**) inert glass experiment chamber (0.6 m × 0.6 m × 0.5 m).

As shown in Figure 2b, the testing environment was selected to be a sealed space measuring 0.6 m × 0.6 m × 0.5 m. The enclosed environment used in this experiment is made of glass, which will not react with air particles, formaldehyde, TVOCs, or the negative oxygen ions produced by the device.

2.5. Air Pollutant Measurement Methods

Before the experiment, a certain concentration of air pollutants should be established in the simulated environment chamber. In this study, particulate matter, formaldehyde, and total volatile organic compound (TVOC) pollutants were generated in the closed simulation chamber by burning cigarettes. By controlling the number and duration of cigarette burns, the required pollutant concentrations can be precisely generated under laboratory conditions, enabling a series of standardized tests. Then, the negative oxygen ion generator is activated to observe its effect on improving air quality. During the experiment, the air pollution detector is first activated to accurately record the initial concentrations of air pollutants. Then, at predetermined intervals, the changes in pollutant concentrations in the air are systematically monitored and recorded, ensuring that the collected data are comprehensive and accurate.

To more precisely evaluate the purification effect of negative oxygen ions, this study also designed a control experiment. In the same closed environment, an equal concentration of air pollutants is set, but the negative oxygen ion generator is not activated. By monitoring and recording the natural decay process of air pollutant concentrations, the actual impact of negative oxygen ions can be comparatively analyzed, further verifying their effectiveness and potential value in air purification.

For the measurement of pollutant concentrations, data are collected every minute for 30 min in both the experimental group with negative oxygen ions and the control group without negative oxygen ions. This process ensures the timeliness and accuracy of the data, allowing for a detailed depiction of changes in pollutant concentrations over time. Through this high-frequency data collection and recording, it is possible to observe the immediate impact of negative oxygen ions on air quality in the short term and to comprehensively evaluate their long-term purification effects. By comprehensively comparing the data trends between the experimental group and the control group and calculating the decay constants of the pollutants as well as the natural decay constants, the actual purification capability and potential application prospects of negative oxygen ions can be clearly determined.

In the evaluation of air purification equipment, the following indicators will be considered for calculation:

1. Decay constant (*k*): The decay constant is used to evaluate the rate at which the purifier removes pollutants. Its calculated value represents the slope of the regression line of particulate matter or gaseous pollutants decay in the experimental environment. A larger decay constant indicates a faster pollutant removal rate. Therefore, the decay constant plays a crucial role in guiding the optimization and application of air purification technologies. The calculation method for the decay constant (*k*) of pollutants is as follows:

$$C_t = C_0 e^{-kt} \tag{7}$$

where C_t is the pollutant concentration (mg/m^3 or ppm) at time t (min), C_0 is the initial pollutant concentration (mg/m^3 or ppm) at time 0, and k is the decay constant (min^{-1}).

Through linear regression analysis, the formula to calculate k is obtained as follows:

$$k = \frac{(\sum_1^n t_i lnC_{t_i}) - \frac{1}{n}(\sum_1^n t_i)(\sum_1^n lnC_{t_i})}{\sum_1^n {t_i}^2 - \frac{1}{n}\left(\sum_n^1 t_i\right)^2} \tag{8}$$

2. Clean Air Delivery Rate (CADR): CADR refers to the volume of air that an air purification device can clean per unit time. The calculation method is the following:

$$\text{CADR} = V \times (K_e - K_n) \tag{9}$$

where CADR is the Clean Air Delivery Rate (m^3/min), V is the volume of the experimental equipment (m^3), K_e is the total decay constant obtained from measurements (min^{-1}), and K_n is the natural decay constant (min^{-1}).

3. Purification Efficiency: Purification efficiency indicates the ability of the air purification device to remove specific pollutants. It can be calculated based on the pollutant concentrations before and after purification. The formula for calculating removal efficiency is the following:

$$\frac{C_1 - C_2}{C_1} \times 100\% \tag{10}$$

where C_1 is the pollutant concentration before using the purifier, and C_2 is the pollutant concentration after using the purifier.

3. Results and Discussion

3.1. Relationship between Voltage and Negative Oxygen Ion Concentration

When evaluating the air purification performance of the carbon fiber negative oxygen ion generator, voltage as an input parameter significantly impacts the concentration of negative oxygen ions. As shown in Figure 3, testing indicates that the device begins generating negative oxygen ions at an input voltage of 75 V, with a working voltage of 2.16 kV. This startup threshold voltage demonstrates the minimum energy requirement for the carbon fiber ion generator to start operating. Compared to traditional corona discharge-based negative oxygen ion devices, which generally operate at voltages between 3 kV and 10 kV [27–37], the working voltage of the carbon fiber negative oxygen ion generator developed in this study is significantly reduced, decreasing by at least 28% from the lowest recorded values. This is mainly due to the high curvature radius and high local electric field strength of the carbon fiber electrodes. As analyzed earlier, this characteristic more effectively prevents ozone generation. Table 1 compares the working voltages of similar negative oxygen ion devices in recent years.

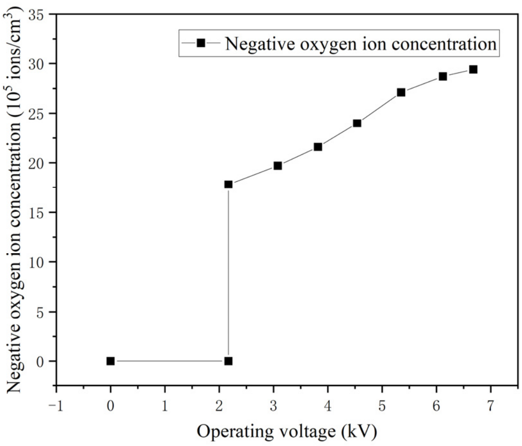


Figure 3. Relationship between voltage and negative oxygen ion concentration.

At lower working voltages, electrons only possess lower energy, so they cannot excite gas molecules to a sufficient energy level to form ions, which is insufficient to overcome the natural potential barrier in the air. This explains the existence of a startup voltage, making it almost impossible to produce negative oxygen ions below 2.16 kV. As the working voltage increases from 2.16 kV to 6.71 kV, the concentration of negative oxygen ions shows a linear growth trend. After exceeding the startup threshold, the increased voltage boosts electron energy, enhancing their collision energy. This allows the electrons to more effectively collide with gas molecules and transfer sufficient energy to them, thereby exciting or ionizing the gas molecules. Consequently, as the voltage increases, the concentration of negative oxygen ions also increases. Throughout the tested voltage range, no saturation was observed in the production of negative oxygen ions, indicating that the device has the potential to generate even more negative oxygen ions beyond this voltage limit.

Table 1. Operating voltages of negative ion devices in recent years.

Literature	Year	Minimum Working Voltage
This study	2024	2.16 kV
Wen Z. Preparation and air purification performance of carbon fiber-based central radial ion generator. Master, Donghua University, Shanghai, 2024 [27].	2024	10 kV
Jiaxue H; Bo L; Xunan H; et al. Quantum ozone emission effect in needle-to-plate negative ion generators. *Journal of Xidian University*, 2022, 49, pp. 238–244 [28].	2022	5 kV, at which point "ozone concentration significantly increases".
Renxiang Z; Tingjia Z. Correlation between Artificial Negative Oxygen Ions and Human Physiological Activities. In Proceedings of the China Hi-Tech Industrialization Research Conference, Dongyang, China, 2 February 2022 [29].	2022	3–6 kV
Korzec, D.; Neuwirth, D.; Nettesheim, S. Generation of Negative Air Ions by Use of Piezoelectric Cold Plasma Generator. *Plasma* 2021, 4, pp. 399–407 [30].	2021	10 kV
Johnson, M.; Go, D. Piezoelectric transformers for low-voltage generation of gas discharges and ionic winds in atmospheric air. *Journal of Applied Physics* 2015, 118, pp. 1–10 [31].	2015	5 kV
Yuexi C. Negative oxygen ions air purification device. CN201320474560.1, 2014 [32].	2014	8 kV
Sawant, V. Removal of Particulate Matter by Using Negative Electric Discharge. *International Journal of Engineering and Innovative Technology* 2013, 2, pp. 48–51 [33].	2013	8.5 kV
Sawant, V.; Meena, G.; Jadhav, D. Effect of Negative Air Ions on Fog and Smoke. *Aerosol and Air Quality Research* 2012, 12, pp. 1007–1015 [34].	2011	8.5 kV
Fletcher, L.; Gaunt, L.; Beggs, C. et al. Bactericidal action of positive and negative ions in air. *BMC Microbiology* 2007, 7, pp.1–9 [35].	2007	10 kV
Ping L, Jie L, Yan W, et al. Experimental study on optimum of low-ozone negative ion generator. In Proceedings of 5th International Conference on Applied Electrostatics, Shanghai, China, 2 November 2004 [36].	2004	9 kV
Wu, C.; Lee, G. Oxidation of volatile organic compounds by negative air ions. *Atmospheric Environment* 2004, 38, pp. 6287–6295 [37].	2004	15 kV

The minimum working voltage of the negative oxygen ion generator fabricated in this study is 2.16 kV, but the working current is extremely low, in the microampere range. Tests have shown that even direct contact with the electrodes during corona discharge does not cause harm to humans. This indicates that the electrical conditions of our device are safe for indoor environments and do not negatively impact the surrounding biological and environmental conditions.

During the operation of the negative oxygen ion device designed in this study, no ozone was detected by using an ozone detection device with a range of 0–10.00 ppm, a resolution of 0.01 ppm, and an accuracy of ±6% FS (@5 ppm, 25 °C, 50% RH).

3.2. Distribution of Negative Oxygen Ion Concentration in Open Environments

As shown in Figure 4, the concentration of negative oxygen ions significantly decreases with increasing distance from the generator. Within 5 to 15 cm of the generator, the concentration remains relatively high but begins to exhibit a nonlinear decay as the distance further increases. The experimental results indicate that the rate of decrease in negative oxygen ion concentration accelerates with increasing distance.

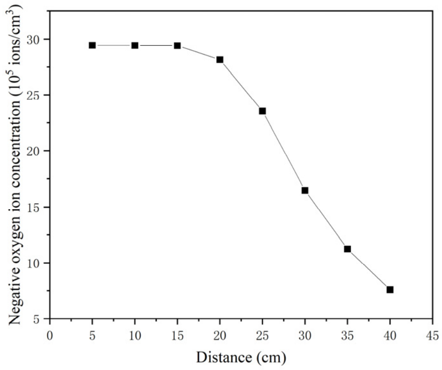


Figure 4. The relationship between linear distance and negative ion concentration.

Specifically, when the distance increases from 5 cm to 15 cm, the decrease in negative oxygen ion concentration is relatively gradual. However, once the distance exceeds 15 cm, the decay rate becomes faster, especially at distances of 20 cm and beyond, where the concentration drops rapidly. This suggests that the effective range of the negative oxygen ion device is limited at greater distances. This phenomenon is related to the interaction between negative oxygen ions and other molecules or particles in the air, such as binding with dust and water molecules leading to their settling, and diffusion caused by air movement, all contributing to the decrease in concentration. Additionally, the natural decay of negative oxygen ions is another factor contributing to the concentration reduction.

The spatial distribution of negative oxygen ions in open environments is also crucial for evaluating and optimizing air purification effects. As shown in the three-dimensional diagram in Figure 5, the concentration of negative oxygen ions varies along different linear distances and angles in an open space. This three-dimensional concentration distribution allows for an intuitive observation of the spatial variation trend and its non-uniformity.

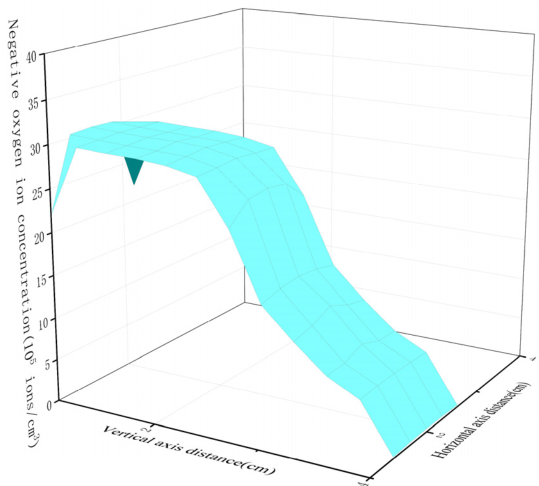


Figure 5. Three-dimensional diagram of negative ion concentration in an open environment.

From Figure 5, it can be seen that the concentration of negative oxygen ions decreases with increasing linear distance from the generator to the surrounding space. Additionally, along directions at certain angles from the generator, the negative oxygen ion concentration exhibits different decay characteristics. In the direction directly in front of the generator, at a 0-degree angle, the concentration is higher due to the design of the carbon fiber electrodes, which focuses the emission of negative oxygen ions in this direction. In the lateral directions, the concentration gradually decreases with increasing angle, indicating that the propagation of negative oxygen ions in space is also affected by directionality.

The concentration variation surface in the three-dimensional diagram shows a distinct peak, indicating a maximum concentration region within a certain distance range. Beyond this region, the concentration of negative oxygen ions rapidly decreases, which is related to air movement and the inherent decay characteristics of the ions. Additionally, physical obstacles in the environment, air humidity, temperature, and other environmental factors may also affect the distribution of negative oxygen ions.

3.3. Distribution of Negative Oxygen Ion Concentration in the Pipeline and the Effect of Wind Flow on Concentration

To determine the distribution characteristics of negative oxygen ions in a limited-length pipeline environment, the concentration distribution was tested in a 25 cm long pipeline. As shown in Figure 6, the concentration of negative oxygen ions remains at a high level throughout the 25 cm pipeline. However, it drops sharply at the open end of the pipeline.

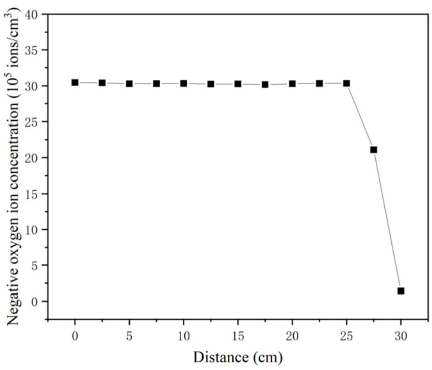


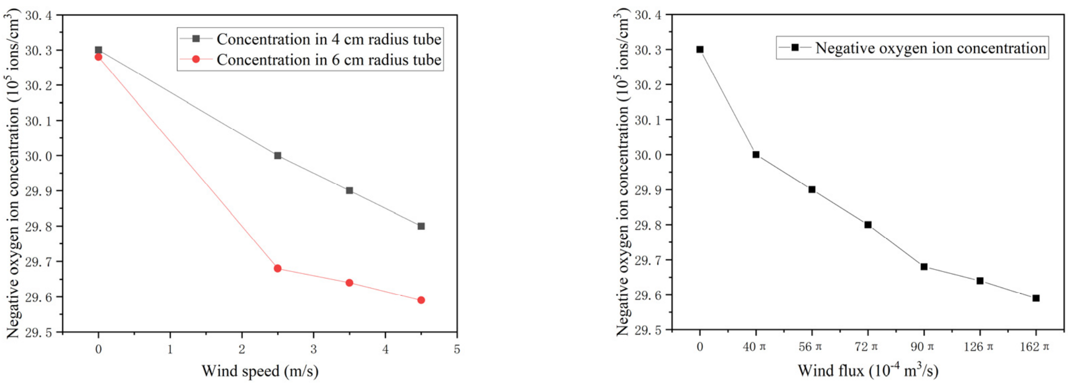
Figure 6. The relationship between distance and concentration within a pipeline environment.

Inside the pipeline, due to the enclosed space, negative oxygen ions can maintain a high concentration in the absence of external disturbances. This enclosed environment helps sustain a sufficient concentration of negative oxygen ions for effective air purification. However, at the pipeline opening, the increased air flow causes the negative oxygen ions to quickly disperse from the limited pipeline space into the larger open environment, resulting in a decrease in concentration. The reason for this phenomenon is that the outside of the pipeline is an open space, where the air flow rate is significantly higher compared to the enclosed environment inside the pipeline. This causes the negative oxygen ions to rapidly disperse and dilute after reaching the end of the pipeline.

The experimental results emphasize the importance of considering space enclosure and layout when deploying negative oxygen ion devices in different environments. Proper consideration of these factors is crucial for maximizing the concentration of negative oxygen ions. For example, in open spaces, the concentration of negative oxygen ions rapidly decreases with distance after exceeding a certain point, whereas in enclosed environments, high concentrations can be maintained over longer distances. Therefore, strategically placing negative oxygen ion devices to optimize coverage helps to increase the concentration, significantly enhancing air purification effectiveness.

Air flow is one of the key factors determining the concentration of negative oxygen ions inside a pipeline. By changing the wind speed within the pipeline, i.e., the wind flux, the change in the concentration of negative oxygen ions can be observed. As shown in Figure 7a, this experiment used two different pipeline radii, 4 cm and 6 cm, with varying wind speeds to measure the impact of wind flux on negative oxygen ion concentration.

According to the experimental data, the concentration of negative oxygen ions exhibits different trends as wind speed increases.



(**a**) (**b**)

Figure 7. The impact of air flow rate on negative ion concentration: (**a**) based on wind speed; (**b**) based on air flow rate.

The experimental data show that changes in wind speed and wind flux have a significant impact on the concentration of negative oxygen ions. With increased wind speed or flux, the concentration of negative oxygen ions shows a clear downward trend. As observed in Figure 7b, at higher wind fluxes, the decrease in negative oxygen ion concentration is very pronounced. This is because high wind flux increases the chances of collisions between negative oxygen ions and other substances in the air, accelerating their decay process. This also indicates that in high wind flux environments, the stability of negative oxygen ions decreases, affecting their efficiency in air purification.

3.4. Effect of Air Humidity on Negative Oxygen Ion Concentration

Air humidity is also a key environmental factor affecting the concentration of negative oxygen ions. This experiment aims to study the distribution of negative oxygen ions in the air under different humidity conditions. The experimental results show that changes in humidity have a significant impact on the concentration of negative oxygen ions.

As shown in Figure 8, at the same distance, the concentration of negative oxygen ions decreases as air humidity increases. In an environment with 40% relative humidity, the concentration of negative oxygen ions can remain relatively constant at a high level during the initial stage (5 to 15 cm). However, in environments with 50% and 60% humidity, the concentration of negative oxygen ions at the same distance does not reach the same level. Particularly at 60% humidity, the concentration of negative oxygen ions shows a significant downward trend. This is because in a humid environment, the higher content of water molecules in the air makes negative oxygen ions more likely to form larger ion clusters by adsorbing water molecules and settling, leading to a decrease in negative oxygen ions.

Additionally, higher humidity causes a more pronounced decay of negative oxygen ions over distance. Within the 20 to 30 cm range, the decay rate of negative oxygen ions at 60% humidity is significantly higher than in drier conditions. In a high-humidity environment, more water molecules cause negative oxygen ions to lose charge through collisions, reducing their stability and lifespan in the air and leading to their settling. This phenomenon needs to be considered in air purification applications, especially in environments sensitive to humidity.

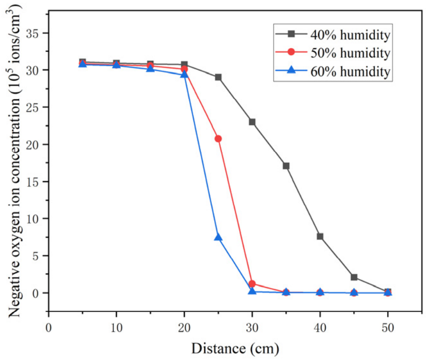


Figure 8. The relationship between distance and concentration within a pipeline environment.

3.5. Effect of Negative Oxygen Ions on the Removal of Particulate Matter (PM_1, $PM_{2.5}$, PM_{10})

Conducted in a closed simulated chamber, the experimental results of the purification effect of negative oxygen ions on particulate matter are shown in Figure 9.

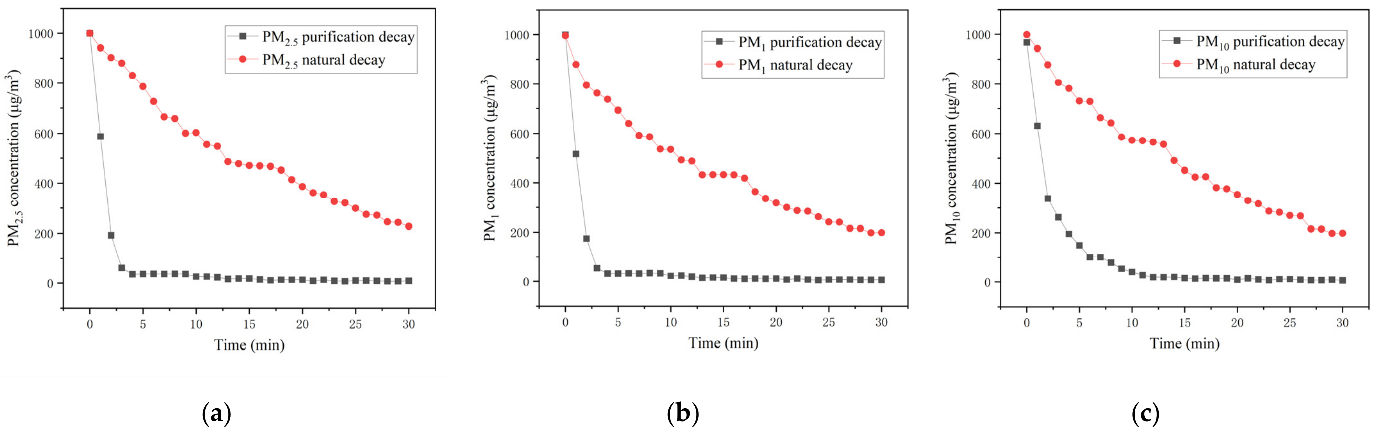


Figure 9. The cleaning effect of negative ions on particulate matter: (**a**) $PM_{2.5}$; (**b**) PM_1; (**c**) PM_{10}.

The results of the experiments show that negative oxygen ions have a significant effect on reducing the concentration of particulate matter in the air.

For $PM_{2.5}$ particles: In a simulated environment, the concentration of $PM_{2.5}$ particles rapidly decreases after the negative oxygen ion generator is turned on, approaching zero within a short time. This demonstrates the effective removal capability of negative oxygen ions for very fine particles. The decay constant within five minutes reached 0.8967 min^{-1}, compared to the natural decay constant of only 0.0438 min^{-1}. The CADR was 0.1535 m^3/min, with a removal rate of 96.50% within five minutes, reaching 99.09% after thirty minutes.

For PM_1 particles: Negative oxygen ions also showed strong removal effects, with the particle concentration rapidly decreasing at the initial stage of the experiment and then continuing to decrease at a slower rate. The decay constant within five minutes reached 0.9221 min^{-1}, compared to the natural decay constant of only 0.0739 min^{-1}. The CADR was 0.1527 m^3/min, with a removal rate of 96.90% within five minutes, reaching 99.40% after thirty minutes.

For PM_{10} particles: Although the removal efficiency is slightly lower compared to PM_1 and $PM_{2.5}$, negative oxygen ions can still significantly reduce the concentration of PM_{10} particles, proving their applicability for larger particle sizes in air purification. The decay constant within five minutes reached 0.4081 min^{-1}, compared to the natural decay constant of only 0.0645 min^{-1}. The CADR was 0.0618 m^3/min, with a removal rate of 79.83% within five minutes, reaching 99.37% after thirty minutes.

Control experiments showed that, without the use of the negative oxygen ion generator, the particle concentration only slowly decayed naturally, confirming the experimental conclusion of the effectiveness of negative oxygen ions in removing particulate matter. The purification-related data from the experiment are shown in Table 2.

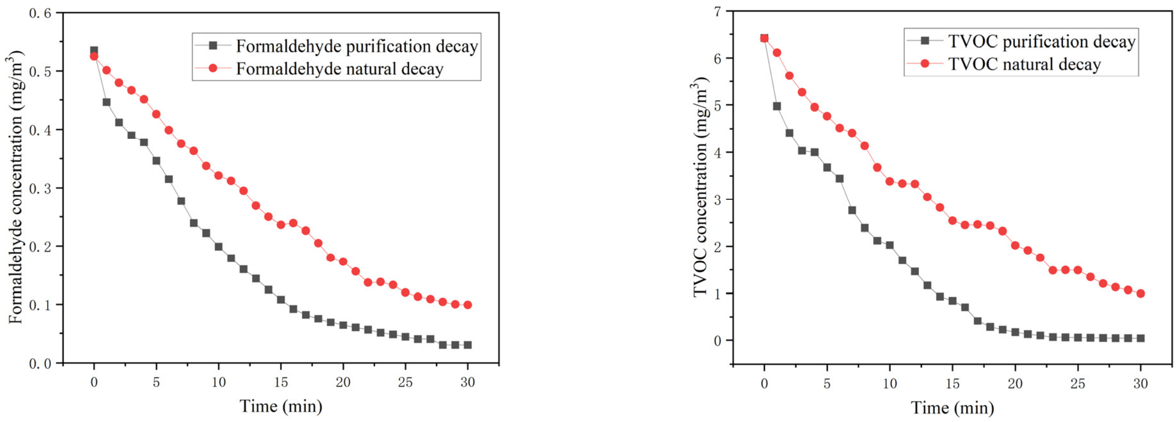
Table 2. Negative ion purification effect data on particulate matter.

Purification Parameters	$PM_{2.5}$	PM_1	PM_{10}
Decay constant within 5 min (min^{-1})	0.8967	0.9221	0.4081
Natural decay constant within 5 min (min^{-1})	0.0438	0.0739	0.0645
CADR within 5 min (m^3/min)	0.1535	0.1527	0.0618
Removal rate within 5 min	96.50%	96.90%	79.83%
Removal rate within 30 min	99.09%	99.40%	99.37%

Based on the above experimental results, it can be concluded that negative oxygen ions can effectively remove PM_1, $PM_{2.5}$, and PM_{10} particles from the environment. In the design and practical application of air purification technology, negative oxygen ions generally exhibit excellent removal efficiency for particles of different sizes. This conclusion provides a scientific basis for the application of negative oxygen ion technology in the field of air purification and supports the optimization of future air purification devices.

3.6. Effect of Negative Oxygen Ions on the Removal of Formaldehyde and TVOCs

Conducted in a closed simulated chamber, the experimental results of the purification effect of negative oxygen ions on formaldehyde and TVOCs are shown in Figure 10 and Table 3.



(**a**) (**b**)

Figure 10. The cleaning effect of negative ions on (**a**) formaldehyde and (**b**) TVOCs.

Table 3. Negative ion purification effect data on particulate matter.

Purification Parameters	Formaldehyde	TVOCs
Decay constant within 30 min (min^{-1})	0.1006	0.1925
Natural decay constant within 30 min (min^{-1})	0.0600	0.0609
CADR within 30 min (m^3/min)	0.0073	0.0237
Removal rate within 30 min	94.39%	99.35%

In the formaldehyde removal experiment, it was observed that the formaldehyde concentration decreased noticeably within the first few minutes after the device was turned on, followed by a slower decline, but overall showed a continuous downward trend. Under the influence of negative oxygen ions, the decay constant reached 0.1006 min^{-1} within 30 min, the CADR reached 0.0073 m^3/min, and the formaldehyde concentration decreased by nearly 95%. This result confirms the effectiveness of negative oxygen ion technology in eliminating indoor formaldehyde pollution. Negative oxygen ions can decompose formaldehyde molecules through their strong oxidizing properties, while also physically aggregating formaldehyde molecules and reaction products, promoting their deposition, thus effectively reducing the formaldehyde content in the air.

Total volatile organic compounds (TVOCs) refer to organic compounds that exist in the air in a gaseous form at standard room temperature, with boiling points between 50 and 260 degrees Celsius. These substances are of concern due to their high vapor pressure or significant volatility at specific temperatures. TVOCs include various compound categories, such as oxygen-containing organics, nitrogen-containing, and sulfur-containing organic compounds, which can participate in atmospheric chemical reactions, adversely affecting regional air quality and human health. Additionally, formaldehyde, under the influence of high-energy electrons or ultraviolet light, can react with oxygen to form hydrogen peroxide (H_2O_2) and other peroxides. These peroxides pose potential health risks, particularly hydrogen peroxide, which has strong oxidizing properties and can cause respiratory and other health issues. They are also included in the measurement of total volatile organic compounds (TVOCs). Therefore, reducing the concentration of TVOCs in the air is a crucial aspect of air purification technology.

Similar to formaldehyde, negative oxygen ions effectively remove TVOCs as well. As shown in Figure 10, the operation of the negative oxygen ion generator causes the TVOC concentration to decrease noticeably. The largest reduction in TVOC concentration occurred within the first 10 min of the experiment, after which the decline curve stabilized. Within 30 min, the decay constant reached 0.1925 min^{-1}, the CADR reached 0.0237 m^3/min, and the removal rate reached 99.35%, demonstrating the effective ability of negative oxygen ions to reduce indoor TVOC concentrations. Negative oxygen ions remove TVOCs by neutralizing compound charges, promoting the aggregation of TVOC molecules to accelerate deposition, and leveraging their strong oxidizing properties.

The purification effect of negative oxygen ions on formaldehyde and TVOCs is not as effective as on $PM_{2.5}$ and other particulate matter. This is mainly reflected in the comparison of the decay constant with the natural decay constant, as well as the CADR. Therefore, the negative oxygen ion air purification device manufactured in this study primarily targets the purification of particulate matter, with a supplementary effect on the purification of formaldehyde and TVOCs.

4. Conclusions

This study designed and manufactured a low operating voltage negative oxygen ion generator based on nanometer-tip carbon fiber electrodes and experimentally confirmed that the generator effectively removes harmful substances such as particulate matter (PM_1, $PM_{2.5}$, PM_{10}), formaldehyde, and TVOCs from the air.

Using nanometer-tip carbon fiber electrodes with a high curvature radius, the ionization voltage required for corona discharge was reduced to 2.16 kV, which is 28% lower than the lowest recorded in similar studies. This effectively generated a large amount of negative oxygen ions, addressing the key application issue of ozone toxicity associated with traditional devices requiring high operating voltages.

Performance tests showed a linear relationship between operating voltage and negative oxygen ion concentration: the higher the voltage, the more ions are produced. In open environments, ion concentration decreases with distance, while in enclosed spaces, high ion concentrations can be maintained over longer distances. High wind speeds and high humidity also affect ion concentration, with both causing accelerated ion decay.

In the evaluation of pollutant removal performance, the negative oxygen ion air purification device manufactured in this study demonstrated significant ability to remove harmful substances such as fine particulate matter, formaldehyde, and TVOCs from indoor air. Experimental data showed that negative oxygen ions could significantly reduce $PM_{2.5}$, PM_1, and PM_{10} concentrations in enclosed spaces within half an hour, achieving purification rates of 99.09%, 99.40%, and 99.37%, respectively. The removal efficiency for formaldehyde and TVOCs was 94.39% and 99.35%, respectively. The removal effectiveness for all these pollutants demonstrated favorable decay constants and Clean Air Delivery Rate (CADR) data. These results further demonstrate its application value in the field of air purification.

This study conducted innovative research on the key structural issues of devices used in negative oxygen ion air purification technology. By using nanometer-tip carbon fiber electrodes, the required operating voltage for generating negative oxygen ions through corona discharge was effectively reduced, addressing the key issue of ozone toxicity associated with traditional devices and effectively purifying the air environment. This not only provides a new solution for improving living environments and protecting public health but also opens up new application potential for negative oxygen ion technology in environmental protection.

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References

1. Urrutia, A.R.; Schlener, S.D.; Sherrine, E.; Bock, K.A.; Worrilow, K.C. The Effects of an Advanced Air Purification Technology on Environmental and Clinical Outcomes in a Long-Term Care Facility. *J. Gerontol. Ser. A* **2023**, *12*, 2325–2332. [CrossRef]
2. Pope, C.A., III; Arden, C. Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution. *JAMA* **2002**, *287*, 1132–1141. [CrossRef]
3. Dominici, F.; Peng, R.D.; Bell, M.L.; Pham, L.; McDermott, A.; Zeger, S.L.; Samet, J.M. Fine Particulate Air Pollution and Hospital Admission for Cardiovascular and Respiratory Diseases. *JAMA* **2006**, *295*, 1127–1134. [CrossRef]
4. Putaud, J.P.; Raes, F.; Van Dingenen, R.; Brüggemann, E.; Facchini, M.C.; Decesari, S.; Fuzzi, S.; Gehrig, R.; Hüglin, C.; Laj, P.; et al. A European Aerosol Phenomenology—1: Physical Characteristics of Particulate Matter at Kerbside, Urban, Rural and Background Sites in Europe. *Atmos. Environ.* **2004**, *38*, 2561–2577. [CrossRef]
5. Lanphear, B.P.; Hornung, R.W.; Khoury, J.; Yolton, K.; Lierl, M.; Kalkbrenner, A. Effects of HEPA Air Cleaners on Unscheduled Asthma Visits and Asthma Symptoms for Children Exposed to Secondhand Tobacco Smoke. *Pediatrics* **2011**, *127*, 93–101. [CrossRef] [PubMed]
6. Lyu, J.; Zhu, L.; Burda, C. Optimizing Nanoscale TiO_2 for Adsorption-Enhanced Photocatalytic Degradation of Low-Concentration Air Pollutants. *ChemCatChem* **2013**, *5*, 3114–3123. [CrossRef]
7. Gilbert, N.L.; Guay, M.; Gauvin, D.; Dietz, R.N.; Chan, C.C.; Lévesque, B. Air Change Rate and Concentration of Formaldehyde in Residential Indoor Air. *Atmos. Environ.* **2008**, *42*, 2424–2428. [CrossRef]
8. Largiuni, O.; Giacomelli, M.C.; Piccardi, G. Concentration of Peroxides and Formaldehyde in Air and Rain and Gas-Rain Partitioning. *J. Atmos. Chem.* **2002**, *41*, 1–20. [CrossRef]
9. Molhave, L.; Nielsen, G.D. Interpretation and Limitations of the Concept "Total Volatile Organic Compounds" (TVOC) as an Indicator of Human Responses to Exposures of Volatile Organic Compounds (VOC) in Indoor Air. *Indoor Air* **2010**, *2*, 65–77. [CrossRef]
10. An, J.Y.; Kim, S.; Kim, H.J.; Seo, J. Emission Behavior of Formaldehyde and TVOC from Engineered Flooring in Under Heating and Air Circulation Systems. *Build. Environ.* **2010**, *45*, 1826–1833. [CrossRef]
11. Parhizkar, H.; Elzeyadi, I. Investigating the Impact of Plant Phytoremediation on Indoor Air Quality in Work Environments: A Meta-Analysis. *ASHRAE Trans.* **2020**, *126 Pt 1*, 109–119.

12. *GB/T 18883-2002*; Indoor Air Quality Standard. General Administration of Quality Supervision. Inspection and Quarantine of the People's Republic of China: Beijing, China; Standardization Administration of China: Beijing, China, 2002.
13. *ISO 16000-6:2021*; Indoor Air—Part 6: Determination of Volatile Organic Compounds in Indoor and Test Chamber Air by Active Sampling on Tenax TA® Sorbent, Thermal Desorption and Gas Chromatography Using MS or MS-FID. International Organization for Standardization: Geneva, Switzerland, 2021.
14. Wen, M.L. Design of Automatic Air Purification Device. *Appl. Mech. Mater.* **2014**, *644*, 158–161. [CrossRef]
15. Li, W.; Wang, W.; Sun, R.; Li, M.; Liu, H.; Shi, Y.; Zhu, D.; Li, J.; Ma, L.; Fu, S. Influence of Nitrogen Addition on the Functional Diversity and Biomass of Fine Roots in Warm-temperate and Subtropical Forests. *For. Ecol. Manag.* **2023**, *545*, 121309. [CrossRef]
16. Tian, H.; Huang, N.; Niu, Z.; Qin, Y.; Pei, J.; Wang, J. Mapping Winter Crops in China with Multi-Source Satellite Imagery and Phenology-Based Algorithm. *Remote Sens.* **2019**, *11*, 820. [CrossRef]
17. Fan, L.; Song, J.; Hildebrand, P.D.; Forney, C.F. Interaction of Ozone and Negative Air Ions to Control Micro-organisms. *J. Appl. Microbiol.* **2002**, *93*, 144–148. [CrossRef]
18. Liu, L.; Wang, Y. Negative Ion Purifier Effects on Indoor Particulate Dosage to Small Airways. *Int. J. Environ. Res. Public Health* **2021**, *19*, 264. [CrossRef]
19. Cao, J.J.; Huang, Y.; Zhang, Q. Ambient Air Purification by Nanotechnologies: From Theory to Application. *Catalysts* **2021**, *11*, 1276. [CrossRef]
20. Thostenson, E.T.; Li, W.Z.; Wang, D.Z.; Ren, Z.F.; Chou, T.W. Carbon Nanotube/Carbon Fiber Hybrid Multiscale Composites. *J. Appl. Phys.* **2002**, *91*, 6034–6037. [CrossRef]
21. Fathi, B.; Esfandeh, M.; Soltani, A.K.; Taghavian, H. Effect of Corona Discharge Treatment on Dynamic Mechanical Properties of Unsaturated Polyester/Carbon Fiber Pultruded Composites. *Polym.-Plast. Technol. Eng.* **2014**, *53*, 162–166. [CrossRef]
22. Chen, F.; Huang, C.; Sun, Y. Study on Dust-removing Characteristic of Carbon Fiber Membrane in Electrostatic Precipitator. In *Advanced Materials Research*; Trans Tech Publications, Ltd.: Zurich, Switzerland, 2014. [CrossRef]
23. Wang, Y.; Zhuang, G.; Tang, A.; Yuan, H.; Sun, Y.; Chen, S.; Zheng, A. The Ion Chemistry and the Source of PM2.5 Aerosol in Beijing. *Atmos. Environ.* **2005**, *39*, 3771–3784. [CrossRef]
24. Brook, R.D.; Brook, J.R.; Urch, B.; Vincent, R.; Rajagopalan, S.; Silverman, F. Inhalation of Fine Particulate Air Pollution and Ozone Causes Acute Arterial Vasoconstriction in Healthy Adults. *ACC Curr. J. Rev.* **2002**, *11*, 32–40. [CrossRef]
25. Mendes, M.A.; Moraes, L.A.B.; Sparrapan, R.; Eberlin, M.N.; Kostiainen, R.; Kotiaho, T. Oxygen Atom Transfer to Positive Ions: A Novel Reaction of Ozone in the Gas Phase. *J. Am. Chem. Soc.* **1998**, *120*, 7869–7874. [CrossRef]
26. Hackam, R.; Aklyama, H. Air Pollution Control by Electrical Discharges. *IEEE Trans. Dielectr. Electr. Insul.* **2000**, *7*, 654–683. [CrossRef]
27. Wen, Z. Preparation and Air Purification Performance of Carbon Fiber Based Central Radial Ion Generator. Master's Thesis, Donghua University, Shanghai, China, 2024. [CrossRef]
28. Hao, J.; Liu, B.; Huang, X.; Xu, W.; Zhang, H.; Wang, G.; Miao, Q.; Li, T.; Jia, G. Quantum ozone emission effect in needle-to-plate negative ion generators. *J. Xidian Univ.* **2022**, *49*, 238–244. [CrossRef]
29. Renxiang, Z.; Tingjia, Z. Correlation between Artificial Negative Oxygen Ions and Human Physiological Activities. In Proceedings of the China Hi-Tech Industrialization Research Conference, Dongyang, China, 2 February 2022. [CrossRef]
30. Korzec, D.; Neuwirth, D.; Nettesheim, S. Generation of Negative Air Ions by Use of Piezoelectric Cold Plasma Generator. *Plasma* **2021**, *4*, 399–407. [CrossRef]
31. Johnson, M.; Go, D. Piezoelectric transformers for low-voltage generation of gas discharges and ionic winds in atmospheric air. *J. Appl. Phys.* **2015**, *118*, 243304. [CrossRef]
32. Cao, Y. Negative Oxygen Ions Air Purification Device. CN201320474560.1, 19 February 2014.
33. Sawant, V. Removal of Particulate Matter by Using Negative Electric Discharge. *Int. J. Eng. Innov. Technol.* **2013**, *2*, 48–51.
34. Sawant, V.; Meena, G.; Jadhav, D. Effect of Negative Air Ions on Fog and Smoke. *Aerosol Air Qual. Res.* **2012**, *12*, 1007–1015. [CrossRef]
35. Fletcher, L.; Gaunt, L.; Beggs, C.; Shepherd, S.J.; Sleigh, P.A.; Noakes, C.J.; Kerr, K.G. Bactericidal action of positive and negative ions in air. *BMC Microbiol* **2007**, *7*, 32. [CrossRef]
36. Liang, P.; Li, J.; Wu, Y.; Lv, B.; Xu, M. Experimental study on optimum of low-ozone negative ion generator. In Proceedings of the 5th International Conference on Applied Electrostatics, Shanghai, China, 2–5 November 2004. [CrossRef]
37. Wu, C.; Lee, G. Oxidation of volatile organic compounds by negative air ions. *Atmos. Environ.* **2004**, *38*, 6287–6295. [CrossRef]