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# Removal of incense smoke and corollary particulate matter using a portable bipolar air ionizer in an unventilated setup

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**Introduction:** Indoor air pollution-associated health risk is substantially higher than outdoor. Incense smoke represents a group of multiple hazardous air pollutants including particulate matter. Bipolar air ionizers have been one of the most escalated indoor air cleaning options in recent years. Albeit, removal efficiency against incense smoke and potential byproduct ozone have been little understood due to limited studies.

**Method:** The present study assessed a portable needlepoint technology-based bipolar air ionizer's removal efficacy against incense smoke in unventilated glass boxes (size 0.16 m<sup>3</sup>). A series of experiments were performed in order to estimate the average efficiency. The total removal efficacy of bipolar air ionizer (BAI *eff.*) was estimated by using empirical equations of the particulate matter PM<sub>2.5</sub> (BAI *eff.* pm<sub>2.5</sub>) and PM<sub>10</sub> removal (BAI *eff.* pm<sub>10</sub>). Particulate matter was used as the marker of incense smoke in this study. The concentration of particulate matter, potential byproduct ozone, relative humidity, and the temperature was monitored by a customized sensor-based air quality monitor.

**Results:** The tested bipolar air ionizer showed a significant decline in incense smoke. The average reduction in PM<sub>2.5</sub> and PM<sub>10</sub> concentration was observed by 74%–75%. The overall efficacy (BAI *eff.*) against incense smoke particulate proportion was 90% ± 10% compared to the control. Byproduct ozone was not exceeded abnormally. However, the marginal elevation in temperature and humidity (up to 5°C or 21%) and humidity (1.8%) were observed when the bipolar air ionizer was conducted.

**Discussion:** Incense smoke consists of multiple hazardous air pollutants including volatile organic compounds and carcinogens. Incense smoke may be the major source of household pollution. A portable bipolar air ionizer could be an auxiliary air cleaning option where incense burning practices are common.

## KEYWORDS

bipolar ionizer, indoor air cleaning, incense smoke, particulate matter, ozone emission

## 1 Introduction

Clean air is essential for overall health (Rai and Tripathi, 2022). Howbeit, rampant air pollution, and associated repercussion have increased for the past few years, almost 99% of the world's population, particularly in countries with low or middle incomes, is routinely exposed to polluted air (IQ Air, 2022). Studies indicated indoor air pollution could be more harmful due to the high exposure as people spend more than 65% of their time in indoor activities (Yadav et al., 2022b). It is important to understand and manage indoor air quality to prevent airborne health risks (Cooper et al., 2021; Nair et al., 2022). There is a great chance of indoor air is prone to be polluted with several combustible sources, responsible for substantial respiratory morbidity and ailments burden (Rice et al., 2020). Indoor smoke is one of the main indoor air pollution concerns. The indoor smoke source can be secondhand smoke, incense burning, and biomass smoke (Pathak et al., 2020; Yeh et al., 2022). Recent experiments showed incense sticks tend to generate persistent aerosol containing a greater amount of particulate matter. Incense sticks can be a hazardous combustible source of indoor pollution, mainly particulate matter (PM<sub>2.5</sub>, PM<sub>10</sub>), HCHO, CO<sub>2</sub>, and volatile organic compounds (VOCs) (Yadav et al., 2020a; Yadav et al., 2020b; Yadav et al., 2021; Yadav et al., 2022a). A single incense stick burning may generate 45 mg/g of average particulate matter, more than a cigarette, which is 10 mg/g (Rauniyar et al., 2020; Thuy et al., 2022).

Such indoor smoke particles including secondhand smoke can accumulate in an indoor environment, mix with indoor dust, and be embedded in building materials, furniture, carpet, and upholstery, these deposited harmful residues are also known as thirdhand smoke (Matt et al., 2019; Matt et al., 2020). Therefore, incense smoke is a great source of indoor particulate matter, especially fine PM<sub>2.5</sub> is one of the most hazardous air pollutants and is associated with major cases of mortality and aggravating COVID-19 cases globally (Yadav et al., 2022b). In recent years, indoor air quality awareness has led to a surge of air cleaning products such as portable high-efficiency particulate air (HEPA) air filters, which are able to reduce residential PM<sub>2.5</sub> concentrations by 52%–67% (Wheeler et al., 2021). But despite effectiveness, HEPA-based multilayer filtration may be prohibitively expensive for some families due to the high maintenance cost (Allen and Barn, 2020). Low and middle-income countries, where novel technologies are limited, more effective and alternative high-performance household air cleaning options, may provide low-cost health hazard protection (Jumlongkul, 2022).

Bipolar air ionizers seem low-maintenance air cleaning options that draw considerable attention and interest during the COVID-19 pandemic. Bipolar ionizer devices can produce both positive and negative ions in a special ratio, negative ions composition usually high. Bipolar air ionization air cleaning potential is reported against a variety of air pollutants such as particulate matter, and airborne pathogens including viruses compare to unipolar (Jiang et al., 2018; Curtis, 2021). The evidence of bipolar air ionizers against particulate matter, i.e., PM<sub>2.5</sub> and PM<sub>10</sub> is also growing, a recent comparative analysis of several bipolar air ionizers showed, bipolar air ionizers can reduce particulate matter effectively in controlled laboratory conditions. Bipolar air ionizers are simple electrical

TABLE 1 Bipolar air ionizer specification.

| Specifications    | Range                                                         |
|-------------------|---------------------------------------------------------------|
| Dimensions (mm)   | 200W × 200D × 125H                                            |
| Positive Ions     | >2.9 million pcs/cc (200 mm away in the direction of airflow) |
| Negative Ions     | >3 million pcs/cc                                             |
| Temperature Range | Up to +60 °C                                                  |
| Power Supply      | 230 V, 50 Hz                                                  |
| CADR              | 154 m <sup>3</sup> /h or 90.6 CFM                             |

devices that produce electrically charged positive (H<sup>+</sup>) and negative (O<sub>2</sub><sup>-</sup>) ions into the air, water molecules present in air breakdown into positive and negative ions due to the exposure to high voltage discharge generated by bipolar air ionizers. Those highly reactive ions react with air pollutants and cause agglomeration which lead settlement of several air pollutants, in case of microbial airborne contaminants OH<sup>-</sup> ions attract H<sup>+</sup> from microbial cell to form a water molecule, which causes the inactivation of airborne pathogens (Gupta et al., 2023).

Techniques such as atmospheric-pressure non-thermal plasma (NTP), which can be two types: multipin corona discharge and a dielectric barrier discharge generator, used to create an electrical field by air ionization devices and produce ions and free radicals may react with atmospheric water molecules and form reactive oxygen species (ROS), hydroxyl radical (OH<sup>-</sup>), superoxides (O<sub>2</sub><sup>-</sup>) and singlet oxygen [(O<sub>2</sub> (1Dg)] and ozone (O<sub>3</sub>). The byproduct of ozone emission is mostly observed with negative ions production in unipolar ionizers (Hernández-Díaz et al., 2021). Incense smoke represents a group of indoor air pollutants including particulate matter, but portable bipolar air ionizers' effect on incense smoke is not fully evaluated and limited so far. In addition, byproduct ozone remained a serious concern associated with ionization air cleaning techniques. The main objective of this research work is to investigate a portable bipolar air ionizer's Incense smoke removal efficiency along with the potential byproduct (Ozone) in unventilated conditions.

## 2 Methodology

A concatenation of experiments conducted repeatedly up to 7 days, to examine the incense smoke (including particulate matter PM<sub>2.5</sub> and PM<sub>10</sub>) reduction capacity of a locally manufactured bipolar air ionizer. The experiment setup comprised two glass boxes (54.8 cm × 54.8 cm × 54.8 cm or 0.16 m<sup>3</sup> size each), incense sticks (16 cm long and 1.5 mm thick), 2 customized air quality monitors (Airveda, Model PM2510CVTH) 2 bipolar air ionizers (needlepoint, made by PetriMed CA, model AI 100), specification given in Table 1; air quality monitor and bipolar air ionizer were purchased from the manufacturer, specifications given in Table 1; concentration of negative and positive ions of bipolar air ionizer was measured before each test, by an air ion counter, model NKMH-103 [measurement range 10–19,990,000 (pcs/cc)], Figures 1.

Air quality monitor selection criteria certification and validation report of inbuilt sensors; particulate matter sensors working

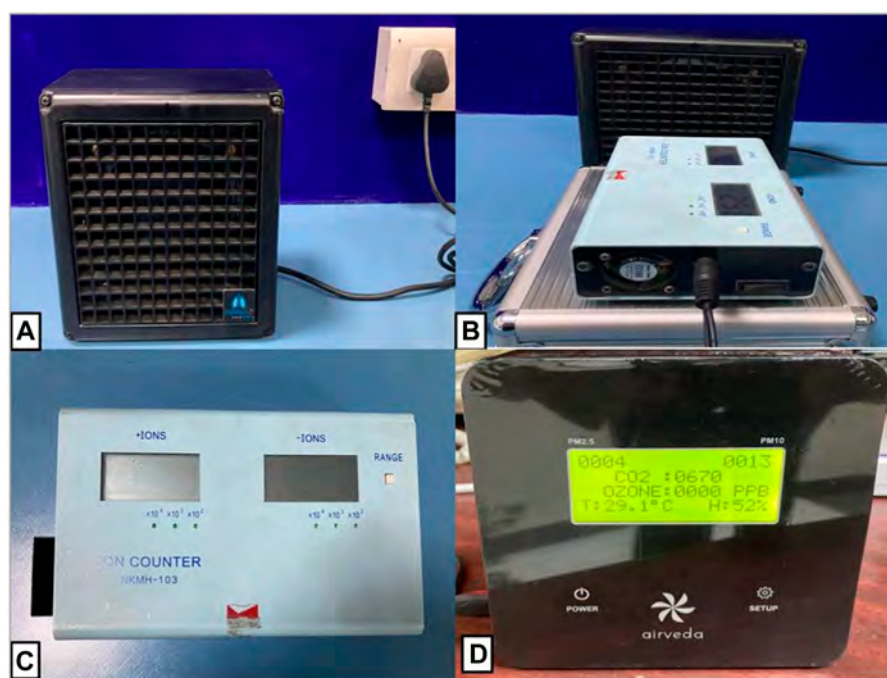


FIGURE 1

Used equipment: bipolar air ionizer (BAI) (A), BAI with ion counter (B), an ion counter (C), air quality monitor (C).

TABLE 2 Air quality (variables) monitor specification.

| Monitoring Sensors | Measuring Range                                         | Relative error/Accuracy                      | Working Principle                                                                        | Calibrated Against                        |
|--------------------|---------------------------------------------------------|----------------------------------------------|------------------------------------------------------------------------------------------|-------------------------------------------|
| PM <sub>2.5</sub>  | Range of PM <sub>2.5</sub> :<br>0–999 µg/m <sup>3</sup> | Maximum of ±10%<br>and ±10 µg/m <sup>3</sup> | LASER scattering principle                                                               | Beta Attenuation Monitor                  |
| PM <sub>10</sub>   | 0–1999 µg/m <sup>3</sup>                                | Maximum of ±10%<br>and ±10 µg/m <sup>3</sup> | LASER scattering principle                                                               | Beta Attenuation Monitor                  |
| CO <sub>2</sub>    | 0–5000 ppm                                              | 50ppm 3% ± 3%                                | The CO <sub>2</sub> sensor is dual wavelength NDIR-based (Nondispersive infrared sensor) | Can be self-calibrated to 400ppm outdoors |
| O <sub>3</sub>     | 0–10ppm                                                 | ± 10% and 10 ppb                             | Electrochemical                                                                          | Can be self-calibrated                    |
| Temperature        | 10 to 60°C                                              | Accuracy: ±1°C<br>Resolution: 1°C            | CMOS sensor                                                                              | Master traceable to NABL                  |
| RH                 | 0%–90%                                                  | Accuracy: 3%<br>Resolution: 1%               | Capacitive sensor                                                                        | Master traceable to NABL                  |

principle is LASER scattering which is validated/calibrated by widely accepted Beta Attenuation Monitor (BAM) method, specification and details of other sensors given in Table 2. The calibration report was provided by the manufacturer and can be accessed online (<https://www.airveda.com/>).

The air quality monitor is rechargeable and can transfer real-time data by Wireless Fidelity (WiFi) to the laboratory computer. The air quality monitor is customized with the required sensors (PM<sub>2.5</sub>, PM<sub>10</sub>, CO<sub>2</sub>, O<sub>3</sub>, Temp., RH) which have been employed in our previous study (Gupta et al., 2023). The experiment was conducted at River Engineering Private

Limited's research and development laboratory in Greater Noida, India, near the national capital Delhi (28.4744° N, 77.5040° E).

During experiments, ambient Particulate matter (PM) concentration in the study area was derived from the nearby regional air quality monitoring station (Knowledge Park—V, Greater Noida-UPPCB) operated by the central pollution control board of India ([https://app.cpcbcr.com/AQI\\_India/](https://app.cpcbcr.com/AQI_India/)).

Experiment boxes A (with BAI ON) and B (BAI Off) assembled with bipolar air ionizers, air quality monitor, and incense sticks as represented in Figure 2. Burning incense sticks

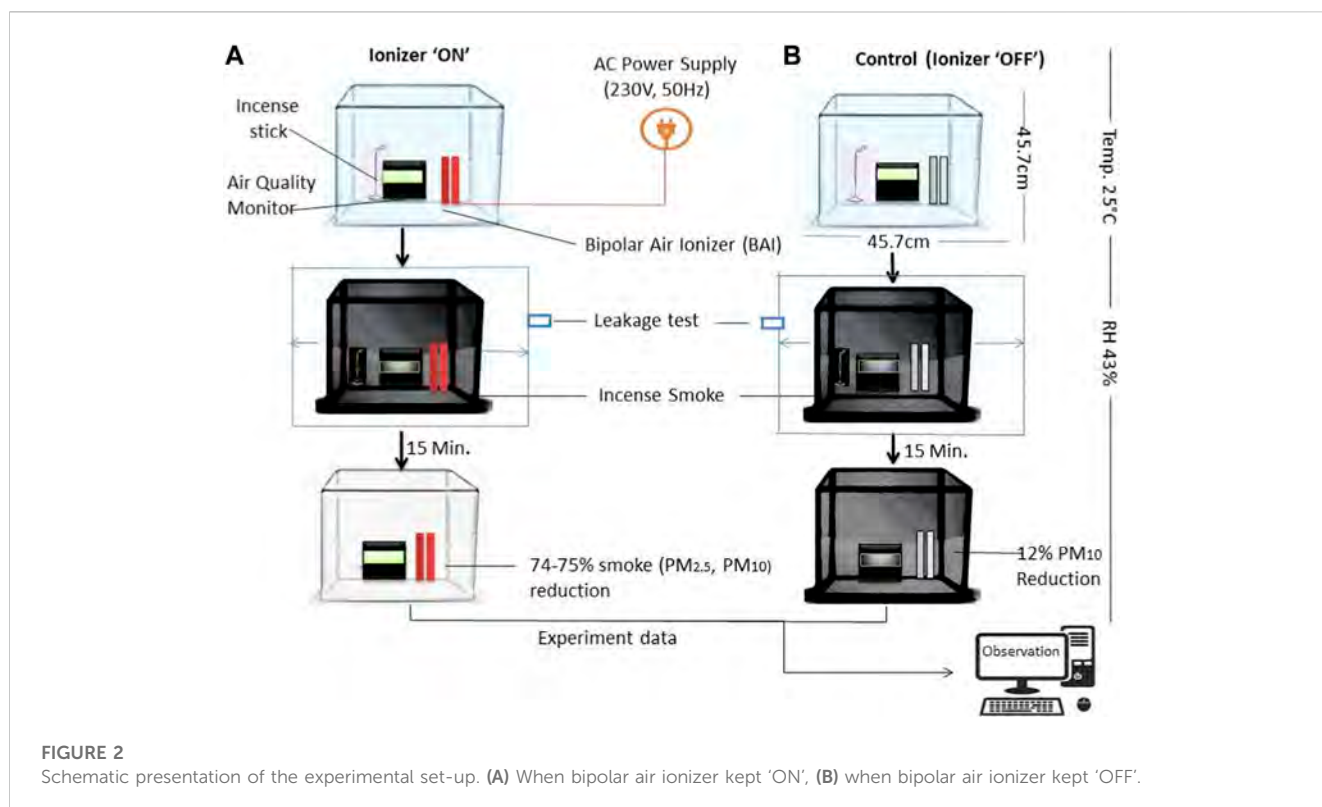


FIGURE 2

Schematic presentation of the experimental set-up. (A) When bipolar air ionizer kept 'ON', (B) when bipolar air ionizer kept 'OFF'.

were placed in each box and then the boxes were sealed. The authors have observed that a single incense stick (16 cm long and 1.5 mm thick) decayed in about 15 min and was able to increase particulate matter and CO<sub>2</sub> concentration up to the highest limit given in the air quality monitor, increased concentration persisted for several hours in unventilated test boxes (PM<sub>2.5</sub> 999 µg/m<sup>3</sup>, PM<sub>10</sub> 1999 µg/m<sup>3</sup>, CO<sub>2</sub> 1967 ppm). The airtightness of the boxes has been tested using a tracer gas technique, and the test indicated that air leakage is negligible. A run of tests with the above setup was conducted each day (up to 190 min, as the variables graph flattened in <120 min) with box A and box B. The same test was repeated for up to 7 days to get the average values of cumulative results. Laboratory temperature and relative humidity (RH) were maintained during the experiment. Temperature and RH were measured by an additional air quality monitor kept in the laboratory. CMOS sensor with an accuracy of 1°C and RH capacitive sensor with an accuracy of 3% were used. The sensors were calibrated as per master traceable to National Accreditation Board for Testing and Calibration Laboratories, India (NABL).

## 2.1 Variables analysis and data processing

Each experiment run's data (both A and B) was transferred to the laboratory computer. Cumulative variables were further calculated by using the arithmetic mean.

Consecutive daily arithmetic means of the received variables of PMs, CO<sub>2</sub>, O<sub>3</sub>, temperatures, and humidity were calculated by the following formula:

$$A = \frac{1}{n \sum_{i=1}^n a_i} = \frac{a_1 + a_2 + a_3 \dots a_n}{n} \quad (1)$$

Where A is the arithmetic mean (average) of variables for runs/day when the bipolar ionizer is ON.  $n$  is the number of variables values.  $a_i$  is the different variable values for runs/day when the bipolar ionizer is ON. Similarly, when the bipolar air ionizer is kept Off, the natural decay of variables is calculated with:

$$B = \frac{1}{n \sum_{i=1}^n b_i} = \frac{b_1 + b_2 + b_3 \dots b_n}{n} \quad (2)$$

Where B arithmetic mean (average) of variables for runs/day when bipolar ionizer OFF.  $n$  is the number of variables values.  $b_i$  is the different variable values for runs/day when the bipolar ionizer is OFF. The obtained average values of the concerned variables were further processed and interpreted.

Whilst, incense smoke removal efficacy of tested bipolar air ionizer (BAI<sub>eff.</sub>) in test boxes was calculated by the total particulate matter removal efficacy of BAI, i.e., total PM<sub>10</sub> removal efficacy of BAI (BAI<sub>eff.</sub> PM<sub>10</sub>) followed by total PM<sub>2.5</sub> removal efficacy of BAI (BAI<sub>eff.</sub> PM<sub>2.5</sub>).

Procured average values of PM<sub>10</sub> and PM<sub>2.5</sub> reduction from Eqs 1, 2 were added in Eqs 3, 4, and finally, Eq. 5 was used to get the total incense smoke removal efficacy.

$$BAI_{eff. PM10} = 1 - \frac{B(PM10)}{A(PM10)} \times 100 \quad (3)$$

$$BAI_{eff. PM2.5} = 1 - \frac{B(PM2.5)}{A(PM2.5)} \times 100 \quad (4)$$

$$BAI_{eff.} = \frac{BAI_{eff. PM10} + BAI_{eff. PM2.5}}{2} \pm RE \quad (5)$$

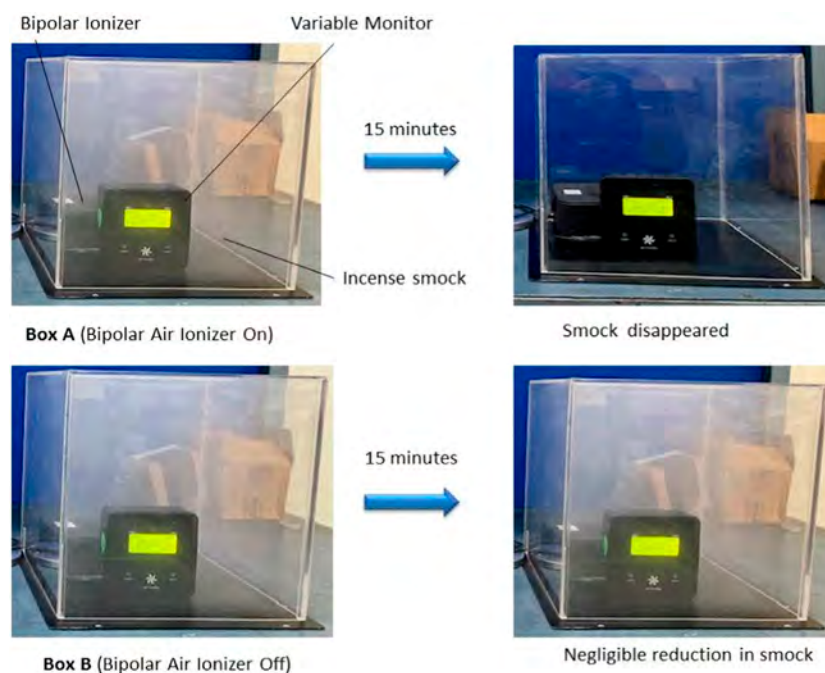


FIGURE 3

Bipolar ionization effect on incense: Box "A" when the bipolar air ionizer kept on, and box "B" smoke when the bipolar air ionizer kept off.

Where  $BAI_{eff\ pm10}$  represents the total  $PM_{10}$  removal efficacy of BAI,  $BAI_{eff\ pm2.5}$  represents the total  $PM_{2.5}$  removal efficacy of BAI, and  $BAI_{eff}$  represents the overall particulate matter removal efficiency of BAI. "B" average values of particulate matter when the bipolar ionizer OFF, and "A" average particulate matter values when the bipolar ionizer is ON,  $\pm RE$  represents relative error, associated with the particulate matter specific sensor.

### 3 Results and discussion

#### 3.1 Concentration of ambient particulate matter and other laboratory variables

Air Quality Index reports from the local air quality monitoring station showed fluctuating trends of ambient particulate matter in the study area, concentration ranges  $PM_{2.5}$  78–165;  $PM_{10}$  85–201  $\mu g/m^3$  observed during the experiment. Other variables concentration including particulate matter inside the laboratory was observed as  $PM_{2.5}$   $69 \pm 10 \mu g/m^3$ ,  $PM_{10}$   $80 \pm 10 \mu g/m^3$ ,  $CO_2$   $650 \pm 3$  ppm,  $O_3$   $49 \pm 10$  ppb, air change rate was  $\sim 1.2$ – $1.6$  per hour (1/h), temperature  $25^\circ C \pm 1^\circ C$ , and relative humidity  $43\% \pm 1\%$

#### 3.2 Average effect on particulate matter, background temp. RH and $O_3$ when bipolar ionizer "ON" box A

Daily and cumulative average variables data showed a noticeable reduction in incense smoke including  $PM_{2.5}$  and  $PM_{10}$

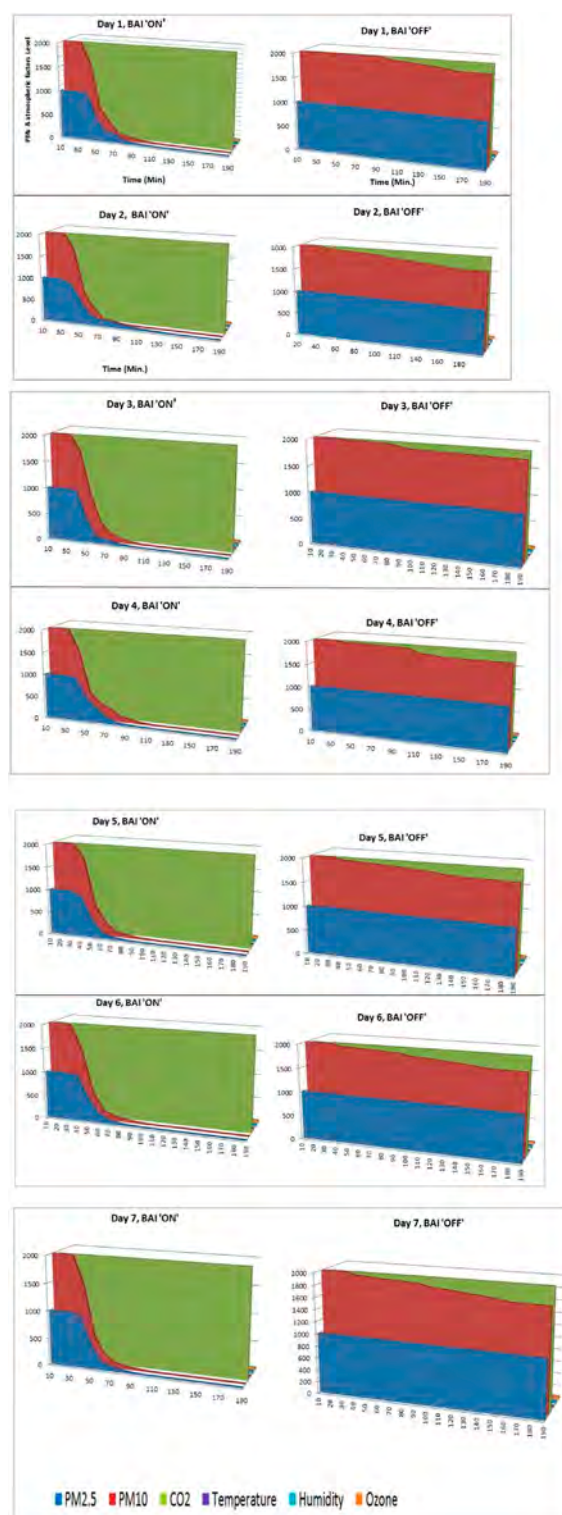
concentration. Incense smoke was reduced after 15–20 min of BAI operation, and box "A" was turned transparent from opaque haze Figure 3.

Air quality monitor showed  $PM_{2.5}$  and  $PM_{10}$  proportion of incense smoke took an average of 120 min to reduce maximum particulate matter concentration (up to  $8$ – $10 \mu g/m^3$ ) from the initial exceeded level:  $PM_{2.5}$   $999 \mu g/m^3$ ,  $PM_{10}$   $1999 \mu g/m^3$ . A minor elevation of up to 1% was observed in ozone concentration on the first day of the experiment, though did not notice in rest consecutive series of experiments. The  $CO_2$  level inside the box remained almost unaffected, Figures 4, 5.

Daily average values of variables are delineated in Figure 4. Different colors indicate a range of changes in concentration when a bipolar air ionizer is operated. Eq. 1, estimated 7 days average reduction (A) of  $PM_{10}$  levels was 75% and  $PM_{2.5}$  by 74%. The average elevation in background RH and the temperature was observed as 1.8% and 21% respectively compared to negligible  $CO_2$  (0.15%) and  $O_3$  (0.10%).

#### 3.3 Average effect on particulate matter, background temp., RH and $O_3$ when bipolar ionizer "off" box B

Procured average data showed, the particulate matter concentration reduction rate was significantly less and slow when BAI off Figures 4, 5. Incense smoke remained entrapped for more than 2 h, (Figure 3, box B). The average reduction in particulate matter concentration was observed as  $PM_{10}$  12% and  $PM_{2.5}$  2%, Eq. 2. The average value of  $CO_2$  0.15% was similar to "A". Minor elevation average values of relative



**FIGURE 4**  
Daily comparative performance of bipolar air ionizer, from box A (bipolar air ionizer "ON") and box B (bipolar air ionizer "OFF") against incense smoke, and its corollary  $PM_{2.5}$ ,  $PM_{10}$ ,  $CO_2$  and another variable, i.e., temp, RH, and byproduct  $O_3$ .

humidity (4.9%), temperature (4%), and  $O_3$  (1.02%) were observed, [Table 3](#).

An experiment has indicated a positive correlation between atmospheric temperature with particulate matter and  $O_3$  concentration ([Adhikari et al., 2006](#)). In the present study, even a slight elevation of ozone was observed during some runs when BAI was off. Besides byproduct  $O_3$  emission, there is limited experimental data to show the other potential factors responsible for  $O_3$  elevation, especially during bipolar ionization air cleaning. Though it has been well-documented that ozone production is highly sensitive to temperature and water vapor ([Kavassalis and Murphy, 2017](#)).

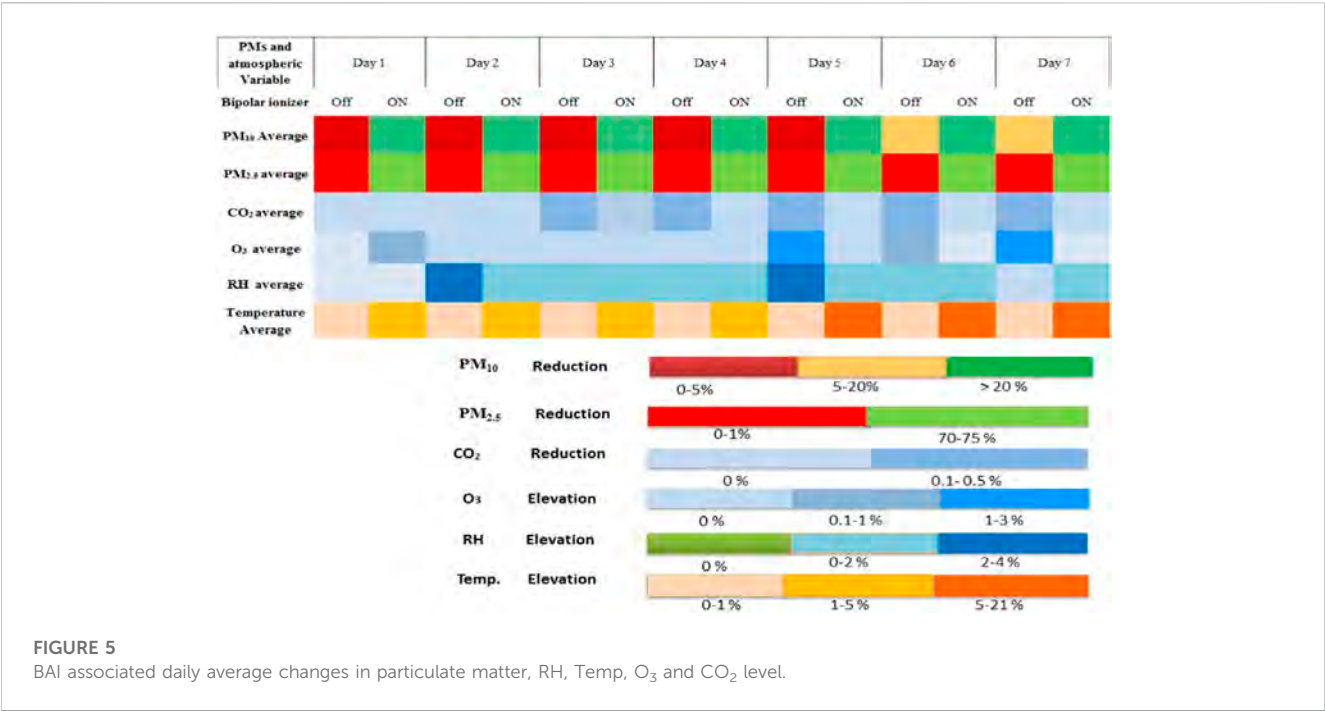
### 3.4 Overall particulate matter removal efficacy of tested BAI

The overall efficacy (BAI *eff*, Eq. 5), of the tested bipolar air ionizer against incense smoke was evaluated on the basis of corollary  $PM_{2.5}$  and  $PM_{10}$  removal efficacy of BAI, Eqs 3, 4, which is obtained from the Eqs 1, 2 daily average reduction. The average  $PM_{10}$  removal efficacy (BAI *eff*. $pm_{10}$ ) was observed  $84\% \pm 10\%$  and  $PM_{2.5}$  removal efficacy (BAI *eff*. $pm_{2.5}$ ) was  $97\% \pm 10\%$ .

The overall efficacy of tested BAI (BAI *eff*) against incense smoke was  $90\% \pm 10\%$  in  $0.16\text{ m}^3$  box, [Figure 6](#).

Present data provides significant outcomes against incense smoke and particulate matter removal efficacy of BAI. Since, incense smoke is known to have substantial harmful compounds (formaldehyde, particulate pollutants, and 12 types of volatile organic compounds) and carcinogens, despite the risk of health hazards, and major sources of household pollution, it is a common and prominent practice associated with Asian and Middle Eastern culture ([Dalibalta et al., 2015](#); [Zhang et al., 2015](#); [Al-Khlaiwi et al., 2022](#); [Jana et al., 2022](#)).

Various important experiments have been conducted to decrease the incense smoke's constituents such as electrostatic precipitators for  $NO_x$  and  $SO_2$  removal and nanofiber filter media and high relative humidity for  $PM_{2.5}$  removal ([Kawada et al., 2002](#); [Ryu et al., 2019](#); [Xia and Chen, 2020](#)). Though the bipolar air ionizer effect against incense smoke is in its infancy since hundreds of air pollutants make incense smoke a complex mixture of pollutants. The present study demonstrated a promising removal effect of BAI against only particulate matter, which is one of the major constituents of incense smoke. Harmful byproducts emission with BAI operation such as ozone, has been the most serious concern associated with ionization air cleaning. Albeit, there is no abnormal ozone emission observed in this study. Similarly, in our previous study, comparative results from several bipolar ionizers showed up to 80% particulate matter removal efficiency of tested bipolar air ionizers and negligible ozone ([Gupta et al., 2023](#)). Current and previous study data indicates ozone emission is not always linked with bipolar air ionizers air cleaning. But



**TABLE 3** Average data of variables, average PM<sub>2.5</sub>, PM<sub>10</sub> reduction, and overall particulate removal efficiency of tested BAI.

| BAI                       | Off (B)                | ON (A)                | Off (B) | ON (A) | BAI eff.pm10 (%) | BAI eff.pm2.5 (%) | BAI eff   |
|---------------------------|------------------------|-----------------------|---------|--------|------------------|-------------------|-----------|
| PM <sub>10</sub> Average  | 1877 µg/m <sup>3</sup> | 466 µg/m <sup>3</sup> | 12%↓    | 75%↓   | 84               | 97                | 90% ± 10% |
| PM <sub>2.5</sub> average | 980 µg/m <sup>3</sup>  | 256 µg/m <sup>3</sup> | 2%↓     | 74%↓   |                  |                   |           |
| CO <sub>2</sub> average   | 1965 ppm               | 1966 ppm              | 0.15%↓  | 0.15%↓ |                  |                   |           |
| O <sub>3</sub> average    | 48 ppb                 | 48 ppb                | 1.02%↑  | 0.10%↑ |                  |                   |           |
| Average RH                | 49%                    | 49%                   | 4.90%↑  | 1.80%↑ |                  |                   |           |
| Temperature Average (°C)  | 25°C                   | 30°C                  | 4%↑     | 21%↑   |                  |                   |           |

Without BAI, intervention, marginal changes in PM<sub>10</sub>, ozone, temp, and RH, may result from complex inter-reaction of these factors.

more experimental data and BAI models, especially those that used different methods to generate ions over the needlepoint bipolar ionization, are needed to understand.

Studies indicated the byproduct O<sub>3</sub> may be associated with specific ion-generating technology, such as the corona discharge method (Zou et al., 2016), while with needlepoint method may be less associated with O<sub>3</sub> emission (Zeng et al., 2021). Observed slight elevation of ozone, even when BAI off, was negligible, but indicates other possible events role. For instance, burning incense sticks can produce a variety of pollutants such as CO, CO<sub>2</sub>, NO<sub>2</sub>, SO<sub>2</sub>, and polycyclic aromatic hydrocarbons (Lin et al., 2008). According to the EPA, the presence of heat and light can generate ozone from oxides of nitrogen (NOx) and volatile organic compounds (VOC) (EPA, 2022).

Marginal temperature and RH fluctuated level association with BAI smoke removal, Figure 7.

Indicates the potential role of background RH and temperature during smoke cleaning. Hitherto, there is no evidence that bipolar air ionizers can influence temperature and RH. But studies suggest that temperature and RH impact could be associated with air pollution in different ways (Fischer et al., 2008; Ding et al., 2021). A recent comprehensive study in one of the most polluted cities, Ulaanbaatar, Mongolia showed HEPA-based air cleaner could be effective to reduce indoor PM<sub>2.5</sub> and secondhand smock by 29% in highly polluted regions. Though, a large portion of outdoor PM<sub>2.5</sub> in highly polluted areas can occur indoors, where HEPA-based air cleaners' effectiveness can reduce by > 50% within 5 months of use (Barn et al., 2018). In such a polluted scenario, where incense burning is also common practice and indoor-outdoor particulate matter concentration is high, a bipolar air ionizer could be an additional low-maintenance indoor smoke-reducing option (Zeng et al., 2021).

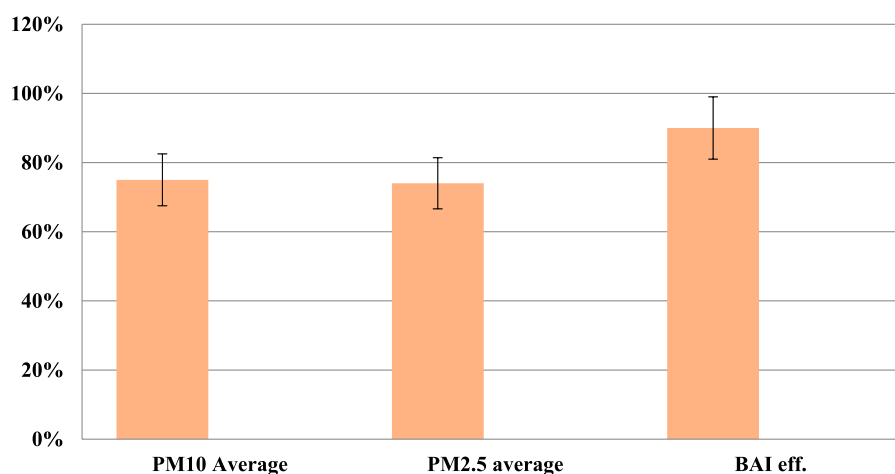


FIGURE 6

The average reduction rate of PM<sub>10</sub>, PM<sub>2.5</sub>, and overall particulate matter removal efficacy of tested BAI.

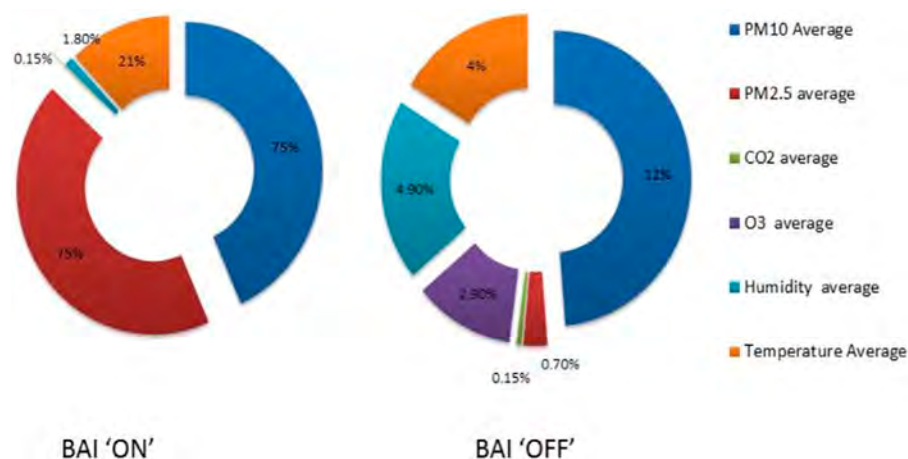


FIGURE 7

RH and temperature fluctuation proportion in Box A and Box B.

## 4 Limitations and prospects

There are certain limitations of our study such as controlled temperature and humidity settings in the laboratory, authors did not access different temperatures, and RH settings, which could be useful to elaborate correlation with bipolar air ionization. The authors have assessed only the main particulate matter proportion of incense smoke, over the other many air pollutants. The study is confined to a small unventilated experimental box, which could be limited to predicting bipolar ionizer smoke removal efficacy in a full-size room; the test bipolar ionizer claimed Clean Air Delivery Rate (CADR) range was 154 m<sup>3</sup>/h which may show the results according to small boxes size 0.16 m<sup>3</sup>. Despite, no significant byproduct of ozone emission in our study, the current data is insufficient to predict biopolar air

ionizers associated safety concerns. More trials and studies in larger cabins or buildings and other indoor places with occupants may be helpful to understand bipolar reliability and efficacy against other indoor air pollutants such as bioaerosol, allergens, and TVOC.

## 5 Conclusion

The present study contributes to understanding the bipolar air ionizer removal efficacy against the particulate proportion of incense smoke. Bipolar air ionizer-associated average reduction of PM<sub>2.5</sub> and PM<sub>10</sub> concentration was observed by 74%–75%. While compared to control, individual PM<sub>10</sub> removal efficacy (BAI *eff*.pm10) was observed 84% and

PM<sub>2.5</sub> removal efficacy (BAI *eff.* pm 2.5) was 97%. The overall efficacy of tested BAI (BAI *eff.*) against incense smoke was 90% ± 10% in 0.16 m<sup>3</sup> boxes. Byproduct ozone abnormal elevation was devoid. Tested bipolar air ionizers showed substantial incense smoke removal efficacy under limited experimental settings, which could be helpful to understand bipolar ionizers' role against indoor smoke and particulate matter. However, other potential byproducts and background temperatures relative humidity correlation, and occupants' presence relation with bipolar air ionizers requires larger cabin based investigations and trials.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

## Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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## Conflict of interest

Authors NG, AA, RS and SJ was employed by the company River Engineering Pvt. Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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