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Research article

Assessing effectiveness of air purifiers (HEPA) for controlling indoor particulate pollution

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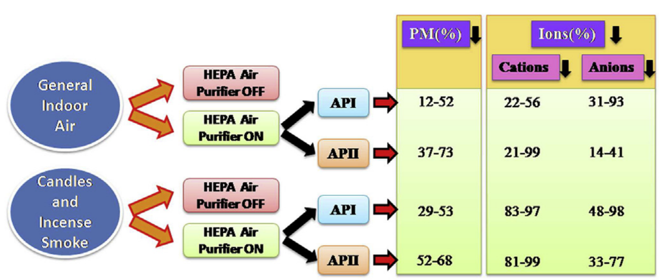
HIGHLIGHTS

- Efficiency of air purifier (AP) in removing indoor air pollutants was observed.
- AP was more effective on small-sized particles than large ones.
- AP of large Clean Air Delivery Rate removed particulate and ions more effectively.
- APs with mechanical filters must be employed instead of ions generators.

GRAPHICAL ABSTRACT



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ABSTRACT

The present study deals with an evaluation of the air purifier's effectiveness in reducing the concentration of different sized particulate matter (PM) and ions in the real-world indoor environment. Two types of air purifiers (API and APII) mainly equipped with High-Efficiency Particulate Air (HEPA) filters that differed in other specifications were employed in general indoor air and the presence of an external source (candles and incense). The gravimetric sampling of PM was carried out by SKC Cascade Impactor and further samples were analyzed for determining ions' concentration while real-time monitoring of different sized PM was done through Grimm Aerosol Spectrometer (1.109). The result showed that API reduced PM levels of different sizes ranged from 12-52% and 29–53% in general indoor air and presence of external source respectively. Concerning the APII, a higher decrease percent in PM level was explored in presence of an external source (52–68%) as compared to scenarios of general indoor air (37–64%). The concentrations of the ions were noticed to be decreased in all three size fractions but surprisingly some ions' (not specific) concentrations increased on the operation of both types of air purifiers. Overall, the study recommends the use of air purifiers with mechanical filters (HEPA) instead of those which release ions for air purification.

1. Introduction

Concerning the fact of expenditure of 80–90% of people's time in the indoor environment (Nazaroff and Goldstein, 2015), the problem of Indoor Air Pollution (IAP) depends on multiple factors (viz. indoor emission sources, outdoor concentration, airflow and other) has gain enormous expansion of research in past years. In indoors, people get exposed to number of indoor and outdoor pollutants which ultimately prompt different acute and severe diseases (Maji et al., 2017). According to State of Global Air (2019) report, about 846 million people in India

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(60% of the population) were exposed to IAP and the pollution has contributed to 1.6 million deaths worldwide in 2017 (SOGA, 2019). It has been mentioned in World Health Organization (WHO, 2018) report that IAP may results in ~3.8 million premature deaths annually which include diseases like chronic obstructive pulmonary diseases, lung cancer, ischemic heart diseases, and stroke. As per State of Global Air (SOGA, 2019) report, India recorded the second-highest number of deaths of children (below 5 years) due to the exposure of indoor air pollution in 2016, and 98% of them were exposed to $PM_{2.5}$. Owing to its very small size, chemical composition, and a significant risk factor for adverse human health outcomes; Particulate Matter (PM) (a key indicator of air pollution and also a major determinant of indoor air quality) has gathered attention among various pollutants. Based on their size (diameter of PM), the U.S. Environmental Protection Agency (USEPA) has differentiated PM into three categories i.e. coarse particles, PM_{10} (PM<10 μm in diameter); fine particles, $PM_{2.5}$ (PM<2.5 μm in diameter) and ultrafine particles, $PM_{1.0}$ (PM<0.1μm in diameter). The size of PM is directly proportional to penetration power into the lungs' bloodstreams and leads to cardiovascular and respiratory diseases (Karimi and Samadi, 2019). Apart from size, chemicals bound to PM greatly determine the toxic and carcinogenetic character of PM. Along with carbonaceous fraction, inorganic components especially water-soluble ions (i.e. cations e.g. NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}, and anions e.g. NO_3^-, SO_4^{2-}, Cl^-, F^-, NO_2^-, Br^-) bound to airborne PM (Xiang et al., 2017; Yang et al., 2018) play a significant role in controlling the mass concentration of PM and constitute 35–60% of PM mass (Saxena et al., 2017). Moreover, the extent of acidity and toxicity of PM is governed by secondary inorganic ions (as SO_4^{2-}, NO_3^- and NH_4^+) which may lead to adverse health outcomes (Cao et al., 2017).

The critical effects of PM and ions on human health arise dire need to lower indoor pollutants concentration by adopting effective measures. Strategies (source control, increase in ventilation, and adjustment in humidity level) opted for dilution of pollutants can naturally reduce IAP (in terms of PM) to some extent still they are not as effective as pollution control equipments because filtration is a potentially effective intervention to reduce PM level. Among various interventions and tools (as gravity settling chamber, mechanical collectors, wet scrubber, electrostatic precipitator, fabric filters, etc.); air purifiers (APs) are sought as the best solution to improve indoor air quality and are commonly employed in homes, hospitals, offices, and other working places. The commercialization of air purifiers is increasing with great pace as in 2016; the online sale of air purifiers registered a seven-fold increase in India (https://www.borgenmagazine.com/air-purifiers-in-india/) which may be attributed to an increase in the number of middle-class families and awareness of indoor air quality among people. Air purifiers equipped with a High-Efficiency Particulate Air (HEPA) filter which is known to remove 99.97% of particles (≥0.3μm in diameter) seem to be an effective technology in improving indoor air quality (IAQ) and widely adopted by urban Indian residences. These air purifiers employ HEPA filter through which air is passed and particles are captured physically by employing four mechanisms viz. interception, inertial impaction, diffusion, and sieving. The smallest particles are removed by diffusion whilst the rest three mechanisms work more effectively on large particles (Yang, 2012). The volume of filtered air delivered by an air cleaner or filtering efficiency of HEPA air purifiers is delineated by a figure of merit known as Clean Air Delivery Rate (CADR). The filtering efficacy of air purifiers is directly proportional to CADR value, the more the CADR value higher the filtering efficiency of HEPA air purifiers. Ample of international studies linked the use of HEPA air purifiers in indoor spaces to substantial reduction (varied percent) in the concentration of TVOC, CO_2, and CO (Xu et al., 2010); fungi spores (Hashimoto and Kawakami, 2018); airborne allergy particles (Punsmann et al., 2019); PM (Lowther et al., 2020; Kelly and Fussell, 2019; Barn et al., 2018; Ward et al., 2017), influenza virus particles (Zuraimi et al., 2011) as well as induce some health benefits including a decrease in systematic inflammation, coagulation, vasoconstriction, systolic and diastolic blood pressure and improved lung function (Chen et al., 2015; Kelly and Fussell, 2019). In contrast, study like Karottki et al. (2013) found no difference in micro vascular and lung function after usage of air purifiers in old age homes. In the national context single study (Vyas et al., 2016) conducted with HEPA air purifiers noticed a significant reduction in PM level after deployment of HEPA air purifiers. After deployment of air purifier, varied reduction percentage in PM concentration was reported in the literature, studies like Batterman et al. (2012) and Karottki et al. (2013) have reported 50%, while Du et al. (2011) and Henderson et al. (2005) have mentioned 69–80% and 63–88% respectively. Although literature deficit with the studies that consider the efficacy of air purifiers in terms of specific particle cut points (mostly focused on Environmental Tobacco Smoke (ETS), Total Suspended Particles (TSP), PM_{10}, and $PM_{2.5}$), few studies like Hart et al. (2011) focused on particle count concentration of size (0.3, 0.5, 1, 2.5, 5 and 10μm) but none of them talks about chemical constituents of PM. So, the present study was designed to fill the gap by assessing the effectiveness of air purifiers in terms of mass concentration of different sized PMs and also chemical composition.

The foremost objective of the study is to gain in-depth knowledge of the usage of air purifiers in general indoor air and with an external source (candles and incense smoke) and to assess the efficiency of the air purifiers in terms of reducing PMs (or particles), cations and anions'. The specific objectives are (i) to provide quantified information on the concentration levels of particulate matter during filtering and non-filtering period in a room chamber. (ii) to assess the ions concentration in different sizes of PMs collected in filtering and non-filtering periods.

2. Materials and methods

2.1. Study area

Agra (27́10′ and 78́2′ E) is the city of imitable Taj founded by Sikandar Lodi (ruler of Lodi Dynasty) is located in the north-central part of India and is situated on the bank of the river Yamuna. It is 200 km south of the national capital New Delhi and 363 km west of the state capital Lucknow. It is one of the prominent destinations on the world tourism map with three heritage monuments- Taj Mahal, Red Fort, and Fatehpur Sikri. Along with industrialization and urbanization, Agra also faces a high transportation load (due to major tourist spots in India and 3 major National Highways) which leads to deterioration of outdoor air quality and in turn affects the air quality of indoor spaces.

2.2. Study design

Sampling was undergone in a room chamber (length = 6.3m, breadth = 3.2m, and height = 3.5m with effective volume) located in the Department of Chemistry at Khandari campus, Agra during May and June 2018. To maintain the thermal comfort of residents in summers (due to the flow of summer winds locally called loo), the window was kept closed and ventilation was through the door during sampling to observe the effectiveness of air purifiers in real-world indoor environments.

2.3. Indoor residential air pollution measurements

Gravimetric PM sampling in three size fractions i.e. 2.5–1.0 μm, 1.0–0.5 μm, and 0.5–0.25μm was done using Leland Legacy pump (SKC Inc. Eighty-Four PA USA) in combination with a five-stage, Sioutas Cascade Impactor and the instrument's calibration was performed using a Drycal DC-2 calibrator (Bios International Corporation, NJ USA). In this study, PM samples were collected on 25 mm PTFE (Poly Tetra Fluor Ethylene) filters with pore size 0.5 μm with a pump operation rate of 9 l/min. The PM samples collected through SKC Cascade Impactor were then analyzed for the determination of ions' concentration. Real-time monitoring of PM per minute was done by Grimm Portable Aerosol Spectrometer (1.109), a portable environment dust monitor (which measure PM with a diameter range from 0.22 to 32 μm) in general indoor air and during (candles and incense smoke) events, with and without operation of air purifier. As per the constraint of working time of the Leland Legacy pump, sampling was carried out for 6 h in each sampling scenario. Candles and incense (Dhoopbatti) opted as sources as they are most commonly used in buildings (homes and worship places) and are also one of the prominent sources of indoor pollutants. Burning of candles produce $PM_{2.5}$ (1,200 μg/m^3), PM_{10} (200 μg/m^3) (Chuang et al., 2012) with emission factor (5–56 mg/g) for $PM_{2.5}$ (Jetter et al., 2002) and trace amounts of organic chemicals (C_2H_4O, CH_2O, C_3H_4O, and $C_{10}H_8$) (Lau et al., 1997), while incense burning generates large quantities of PM (0.24 < median diameter <0.40 μm) (Mannix et al., 1996). Chuang et al. (2012) reported the mass concentration of PM_{10} and $PM_{2.5}$ as 91.6μg/$m^3$and 38.9 μg/m^3 respectively, when the burning of candles and incense was impaired.

2.4. Air purifier's selection

In the present study, two types of air purifiers with different CADR and other specifications were employed. The first air purifier (API) comprised of an anti-dust filter, activated carbon filter, active HEPA filter, electrostatic filter, vita ions, cold catalyst filter with programmable control panel, sleep mode, timer function, and independent air ducts, while the second air purifier (APII) was equipped with six sense technology, humidifier, filter replacement indicator along with filters viz. pre-dust filter, activated carbon filter, HEPA filter, nanocaptur filter; UV lamps and also ionizer function. This was done to measure the effectiveness of air purifiers that are commonly used. Along with the different types of filters used in air purifiers, they also have different specifications the details of which have been provided below in Table 1.

Table 1. Specifications of both air purifiers.

Specifications	Air Purifier I (AP I)	Air Purifier II (AP II)
Dimensions (mm)	18 × 18×50	28 × 54×30
Weight	3.2 kg	5.7 kg
Wattage	16 Watts	30 Watts
Noise level	40 dB	22–45 dB
Coverage Area	19 m^2	35 m^2
CADR	120 m^3/h	150 m^3/h
Power Requirement	AC 220V/50 Hz	AC 110–120 V/50 Hz

The purifier was placed at a height of 1.5m from the ground (average inhalation height), while candles and incense were placed at a distance of 1m from the air purifier in both cases. The overall methodology adopted in the study is depicted in Figure 1.

2.5. Chemical analysis

The water extraction method was used for the determination of the concentration of ions using Ultrasonicator and the procedures followed for this were adopted from Satsangi et al. (2016). The exposed filter papers were cut into strips followed by digestion in a 50 ml prewashed Borosil beaker using double distilled water for 2 h. The solution was then filtered using prewashed Whatman filter paper followed by washing of beakers two to three times and then the solution was makeup with 25ml of double-distilled water. Finally, sample solutions were stored in polypropylene sample bottles in a refrigerator under 4°C until got analyzed with Ion chromatography (Dionex 1100). To maintain quality control in the work, precautions' regarding sample storage and glassware cleaning procedures were done according to Rohra et al. (2018).

2.6. Statistical analysis

Statistical Analysis was performed using MS Excel 2010 for Windows. Paired t-test was carried out to observe the difference in mass concentration of different sized PMs after the operation of the air purifier during each sampling scenario. Statistical significance was a 5% level ($p < 0.05$). The increase and decrease percentage in mass concentration of ions and decrease percentage in case of PM have been calculated by dividing the increased and decreased concentration by their initial concentration and further multiplying the resultant with 100.

2.7. Health risk assessment

The health risk posed by PM (via inhalation) before and after deployment of air purifier in general indoor air as well as candles and incense smoke was quantified. Non-carcinogenic risk (posed by PM_{10}) estimated by Hazard Quotient (HQ) and carcinogenic risk (posed by $PM_{2.5}$) by Excess Lifetime Cancer Risk (ELCR) was performed similarly to Morakinyo et al. (2017) and Kim et al. (2018) respectively.

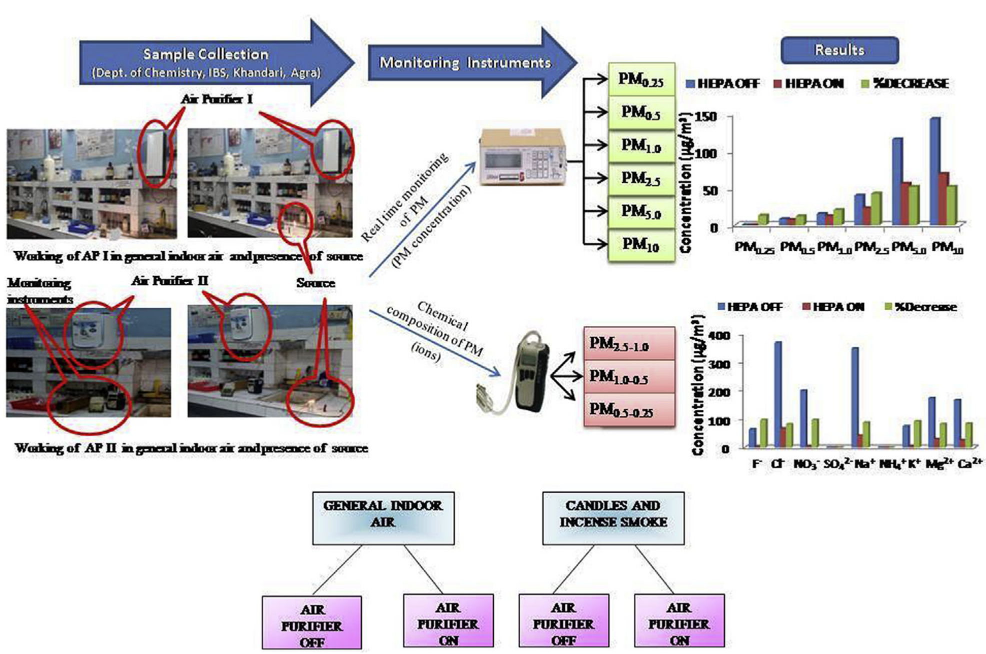

Figure 1. Summary of data collection.

HQ reflects the probability of an adverse health outcome occurring among healthy and/or sensitive individuals. Non-cancer risks were calculated for acute and chronic exposure scenarios as-

$$HQ = ADD/\ REL \text{ (chronic exposure) or} \tag{1}$$

$$HQ = AHD/\ REL \text{ (acute exposure)} \tag{2}$$

where REL (reference exposure level) refers to the dose at which significant detrimental health effects will occur in the exposed group. In this study, REL for PM_{10} was adopted from guidelines provided by CPCB according to which the mass concentration of PM_{10} must be 100 μg/m^3 for an exposure time of 24 h.

The value of HQ ≤ 1.0 and >1.0 indicate no adverse health risk and some risk to sensitive populations as a result of exposure respectively.

ELCR is defined as the incremental probability of an individual to develop cancer over a lifetime as a result of exposure to a potential carcinogen. Its reference value is 3.14×10^3, which pertains to one cancer incidence for every one million people. The equations for the calculation of ELCR are narrated in the supplementary file. The health risk (carcinogenic and non-carcinogenic) imposed by PM when exposed to such concentration was carried out for both adults and children by using exposure factors mentioned in USEPA, 2014.

3. Result

The overall scenario of the effectiveness of air purifier in terms of particulate exposure is discussed foremost followed by its efficacy on PM bounded ionic exposure. This is further presented in a way to portray particle size dynamics in conjugation with the presence and absence of an external source. The study attempts to make a comparison of PM levels with guidelines proposed by different national and international organizations in different sampling scenarios. At last, the upgrading in IAQ as exhibited by quantitative health risk after deployment of air purifiers is discussed.

3.1. Effectiveness of air purifiers on PM concentration

3.1.1. Air purifier removal efficacy on different sized PM in general indoor air

In the case of AP I, both PM_{10} and $PM_{5.0}$ showed a maximal decrease (52%) whilst decrease in mass concentration of $PM_{0.5}$ was least (12%) during the filtering vs non-filtering period. Significant ($p < 0.05$) and borderline significant ($p = 0.05$) difference in particle mass concentration between HEPA and non-HEPA conditions was observed at $PM_{1.0}$ and $PM_{2.5}$ respectively while the non-significant difference was observed at rest particle size. Except for $PM_{0.5}$, the trend ($PM_{10} \approx PM_{5.0} > PM_{2.5} > PM_{1.0} > PM_{0.25} > PM_{0.5}$) attained in reduction percentages (in mass concentrations of different sized PM) revealed that the HEPA filter was more effective in the case of larger particles (as PM_{10} and $PM_{5.0}$) as compared to PM with small size.

In contrast to the above findings no specific trend (in reduction %) ($PM_{0.5} > PM_{0.25} > PM_{1.0} > PM_{10} > PM_{5.0} > PM_{2.5}$) was obtained after the deployment of AP II. The effectiveness of AP II in general indoor air was found maximal (73%) for $PM_{0.5}$ and minimal (37%) for $PM_{2.5}$. All PMs showed non-significant ($p>0.05$) difference except $PM_{5.0}$ which showed a significant difference ($p<0.05$) in its mass concentration under HEPA and non-HEPA periods. Table 2 depicts the filtration efficacy of AP I and AP II in general indoor air.

3.1.2. Air purifier removal efficacy on different sized PM in external source event

In the presence of external source (candles and incense smoke event), AP I showed the highest effectiveness on $PM_{0.25}$ (53%) and least on PM_{10} (29%) and also a reverse trend ($PM_{0.25} > PM_{0.5} > PM_{1.0} > PM_{2.5} > PM_{5.0} > PM_{10}$) in mean reduction percentage was observed as compared to general indoor air. During HEPA OFF and HEPA ON periods, for $PM_{0.25}$ and $PM_{0.5}$ a significant difference ($p < 0.05$) in mass concentration was noticed whereas a non-significant ($p > 0.05$) difference was observed for rest particle sizes. The mass concentration of small-sized PM showed a maximal reduction with the deployment of AP I while the large-sized PM was reduced the least in terms of concentration.

In contrast with the findings of AP I, APII depicted the following trend ($PM_{2.5} > PM_{1.0} > PM_{5.0} > PM_{10} > PM_{0.5} > PM_{0.25}$) after the removal of particles associated with candles and incense burning. The mass concentration of $PM_{2.5}$ was reduced the most (68%) while $PM_{0.25}$ was reduced the least (52%) after air filtration. During HEPA OFF and HEPA ON periods, a non-significant difference ($p > 0.05$) in the mass concentration of $PM_{1.0}$, $PM_{2.5}$, and $PM_{5.0}$ was observed. On the other hand, a significant difference ($p < 0.05$) in case of $PM_{0.25}$ and $PM_{0.5}$ while borderline significant difference ($p = 0.05$) in case of PM_{10} was observed under HEPA and non-HEPA conditions. The efficiency of both air purifiers in candles and incense smoke events is given in Table 3.

An ample of studies had been conducted to evaluate the effectiveness of air purifiers in terms of PM and showed significant and varied reduction percentage in the mass concentration of different sized PM. Table 4 gives a global scenario in terms of reduction in PM level by HEPA filters employed in current and previous studies.

3.2. Effectiveness of air purifiers on ions concentration (in different size fractions)

Ions were grouped into six classes viz. moderate decrease (reduction<50%), significant decrease (reduction 50–100%), high decrease (reduction >100%), moderate increase (increase<50%), significant increase (increase 50–100%) and high increase (increase >100%) based upon ions efficacy of purifiers' (% decrease as well as an increase of ions concentration) in general indoor air as well as candles and incense smoke event. In some sampling scenarios, values that define the mass concentration of ions were found below the detectable limit (shown by zero in graphs), hence increase and decrease percentages are excluded in that case.

Table 2. Mean and 95% confidence interval of PM in general indoor air according to filtration scenario by API and APII.

PM/Cases	Air purifier I				Air purifier II			
	HEPA purifier OFF *Mean (95% CI)*	HEPA purifier ON *Mean (95% CI)*	% Decrease	P value	HEPA purifier ON *Mean (95% CI)*	HEPA purifier OFF *Mean (95% CI)*	% Decrease	P Value
$PM_{0.25}$	0.06 (0.05–0.07)	0.05 (0.04–0.06)	13	0.07	0.07 (0.06–0.08)	0.03 (0.01–0.04)	64	0.14
$PM_{0.5}$	8.33 (7.86–8.79)	7.33 (7.01–7.64)	12	0.09	19.24 (18.65–19.83)	5.10 (4.83–5.38)	73	0.29
$PM_{1.0}$	15.35 (14.72–15.97)	12.18 (11.77–12.59)	21	0.04	25.50 (24.52–26.48)	10.08 (9.32–10.83)	60	0.11
$PM_{2.5}$	40.08 (38.80–41.35)	22.98 (22.27–23.69)	43	0.05	40.42 (35.37–45.47)	25.27 (24.23–26.31)	37	0.08
$PM_{5.0}$	116.07 (110.55–121.60)	56.02 (53.51–58.53)	52	0.19	119.75 (81.99–157.51)	63.45 (61.30–65.60)	47	0.02
PM_{10}	143.35 (135.56–151.15)	69.11 (65.11–73.12)	52	0.24	165.97 (103.62–228.33)	76.78 (74.08–79.49)	54	0.07

*Statistical significance was a 5% level ($p < 0.05$).

Table 3. Mean and 95% confidence interval of PM in candles and incense according to filtration scenario by API and APII.

PM/Cases	Air purifier I				Air purifier II			
	HEPA purifier OFF *Mean (95% CI)*	HEPA purifier ON *Mean (95% CI)*	% Decrease	P value	HEPA purifier ON *Mean (95% CI)*	HEPA purifier OFF *Mean (95% CI)*	% Decrease	P Value
$PM_{0.25}$	0.39(0.36–0.42)	0.18 (0.16–0.21)	53	0.03	0.41 (0.39–0.42)	0.19 (0.17–0.22)	52	0.03
$PM_{0.5}$	193.54 (175.06–212.02)	96.74 (81.77–111.72)	50	0.001	196.89 (187.16–206.62)	79.29 (68.94–89.65)	60	0.04
$PM_{1.0}$	480.06 (428.99–531.13)	288.43 (238.56–338.29)	40	0.06	504.82 (470.50–539.15)	165.87 (138.92–192.81)	67	0.86
$PM_{2.5}$	561.80 (502.91–620.70)	370.09 (306.34–433.83)	34	0.12	605.77 (564.04–647.50)	191.60 (160.33–222.87)	68	0.83
$PM_{5.0}$	612.28 (552.59–671.96)	423.99 (356.09–491.89)	31	0.93	644.22 (602.52–685.92)	213.94 (182.49–245.39)	67	0.76
PM_{10}	626.07 (566.25–685.90)	443.62 (373.85–513.40)	29	0.6	657.81 (616.26–699.36)	223.72 (192.19–255.24)	66	0.51

*Statistical significance was a 5% level ($p < 0.05$).

Table 4. Comparison of reduction percentage in PM with different studies.

Study	Year	Region	Source	Type of Filter	Reduction in PM Level
Batterman et al.	2005	Michigan	Cigarette Smoke	HEPA	30–70%
Myatt et al.	2008	US	Environmental Tobacco Smoke	HEPA	70–80%
Du et al.	2011	Michigan	General indoor air	HEPA	69–80%
Batterman et al.	2012	Michigan	General indoor air	HEPA	50%
Present Study	2018	India	Candles and incense	HEPA(AP I) HEPA(AP II)	29–53% 52–68%
			General indoor air	HEPA (AP I) HEPA(AP II)	12–52% 37–64%

3.2.1. Air purifier's removal efficacy on ions (in different size fractions) in general indoor air

The efficacy of AP I in terms of anions followed the trend as $Cl^- > F^-$ in $PM_{2.5\text{-}1.0}$ and reverse for $PM_{1.0\text{-}0.5}$. In terms of anions, the mass concentration of F^- significantly reduced in all three size fractions (Figure 2a). Cl^- ion was significantly (82%) and moderately (31%) decreased in $PM_{2.5\text{-}1.0}$ and $PM_{1.0\text{-}0.5}$ respectively except for $PM_{0.5\text{-}0.25}$ for which the mass concentration increased significantly (52%) after air filtration. A similar trend of increased mass concentration of NO_3^- was observed in all three size fractions in such a way that mass concentration significantly increased in $PM_{2.5\text{-}1.0}$, $PM_{1.0\text{-}0.5}$, and highly increased in $PM_{0.5\text{-}0.25}$. No effect of air purifier on mass concentration of cations in $PM_{2.5\text{-}1.0}$ was observed, while in $PM_{1.0\text{-}0.5}$ reduction in the mass concentrations of cations followed the order: $K^+ > Ca^{2+} > Na^+ > Mg^{2+}$ in such

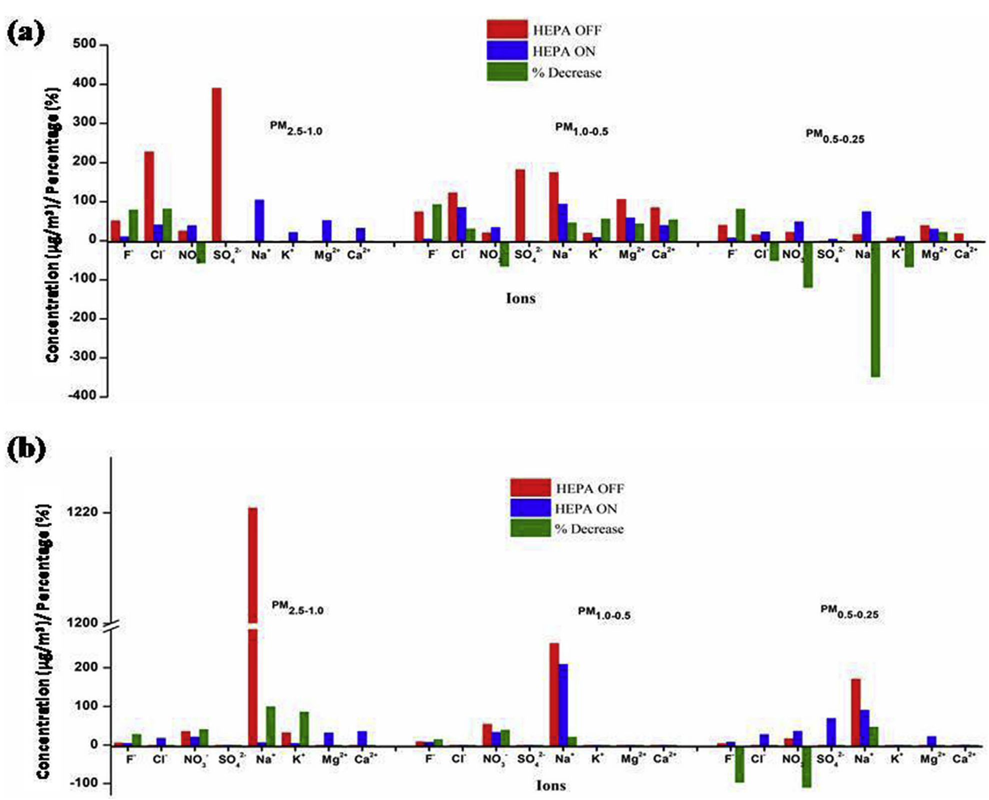

Figure 2. (a) Mass concentration of ions (in $PM_{2.5\text{-}1.0}$, $PM_{1.0\text{–}0.5}$ and $PM_{0.5\text{-}0.25}$) in general indoor air during API OFF and ON scenario (b) Mass concentration of ions (in $PM_{2.5\text{-}1.0}$, $PM_{1.0\text{–}0.5}$ and $PM_{0.5\text{-}0.25}$) in general indoor air during APII OFF and ON scenario.

a way that K^+ was reduced significantly (56%) and Mg^{2+} was moderately decreased (44%). In $PM_{0.5\text{-}0.25}$, Mg^{2+} showed a moderate decrease (22%) in its mass concentration whereas the concentration of Na^+ was highly increased (349%) followed by K^+ (significant increase i.e. 68%) on the operation of air purifier.

The effectiveness of AP II on anions concentration was observed in the manner that NO_3^- showed more reduction in its mass concentration followed by F^- ion ($NO_3^- > F^-$) and both ions reduced moderately in $PM_{2.5\text{-}1.0}$ and $PM_{1.0\text{-}0.5}$. Whereas in $PM_{0.5\text{-}0.25}$, surprisingly both ions concentration was found to be increased in the same trend (same to reduction %) as NO_3^- was highly (110%) and F^- was significantly increased (97%). Moreover, in case of cations, both Na^+ and K^+ were significantly reduced ($Na^+ > K^+$) in $PM_{2.5\text{-}1.0}$ while K^+ was moderately reduced in the rest two size fractions. Na^+ concentration was most reduced among all cations in all size fractions (Figure 2b).

3.2.2. Air purifier's removal efficacy on ions (in different size fractions) in external source event

In candles and incense smoke event, the efficacy of AP I revealed that anions mass concentration was reduced in trend as $F^- \sim NO_3^- > Cl^-$, $Cl^- > F^- > NO_3^-$ and $NO_3^- > F^-$ in $PM_{2.5\text{-}1.0}$, $PM_{1.0\text{-}0.5}$ and $PM_{0.5\text{-}0.25}$ respectively. Except for NO_3^- which was moderately reduced (48%) in $PM_{1.0\text{-}0.5}$, all other anions showed a significant decrease (66–92%) in their mass concentration. In the case of cations, the trend in reduction percentage was found as $K^+ > Na^+ > Ca^{2+} > Mg^{2+}$ in $PM_{2.5\text{-}1.0}$. In $PM_{1.0\text{-}0.5}$, except for Na^+ and K^+ ($Na^+ > K^+$) decrease in the mass concentration of cations followed a similar trend as in $PM_{2.5\text{-}1.0}$, while in $PM_{0.5\text{-}0.25}$ the trend obtained was as $Mg^{2+} > Ca^{2+} > K^+$. In all size fractions, cations described above significantly reduced (83–99%) and ions showed no increase in their mass concentration after turning on the air purifier depicted in Figure 3a.

In the case of AP II, the mass concentration of F^- ion was significantly reduced (77%) in $PM_{2.5\text{-}1.0}$, while it was highly increased viz. 429% and 596% in $PM_{1.0\text{-}0.5}$ and $PM_{0.5\text{-}0.25}$ respectively (Figure 3b). Contrary to a slight increment (2%) in the mass concentration of NO_3^- in $PM_{2.5\text{-}1.0}$, a moderate reduction in rest size fractions ($PM_{1.0\text{-}0.5}$ and $PM_{0.5\text{-}0.25}$) was observed. The percent decrease in mass concentration of cations was found in the order as $Na^+ > K^+ > Mg^{2+}$ for $PM_{2.5\text{-}1.0}$ with an exception for Mg^{2+} and Ca^{2+} (highly increased) that depicted a similar trend in $PM_{1.0\text{-}0.5}$. In case of $PM_{0.5\text{-}0.25}$, after the purification of incense and candle

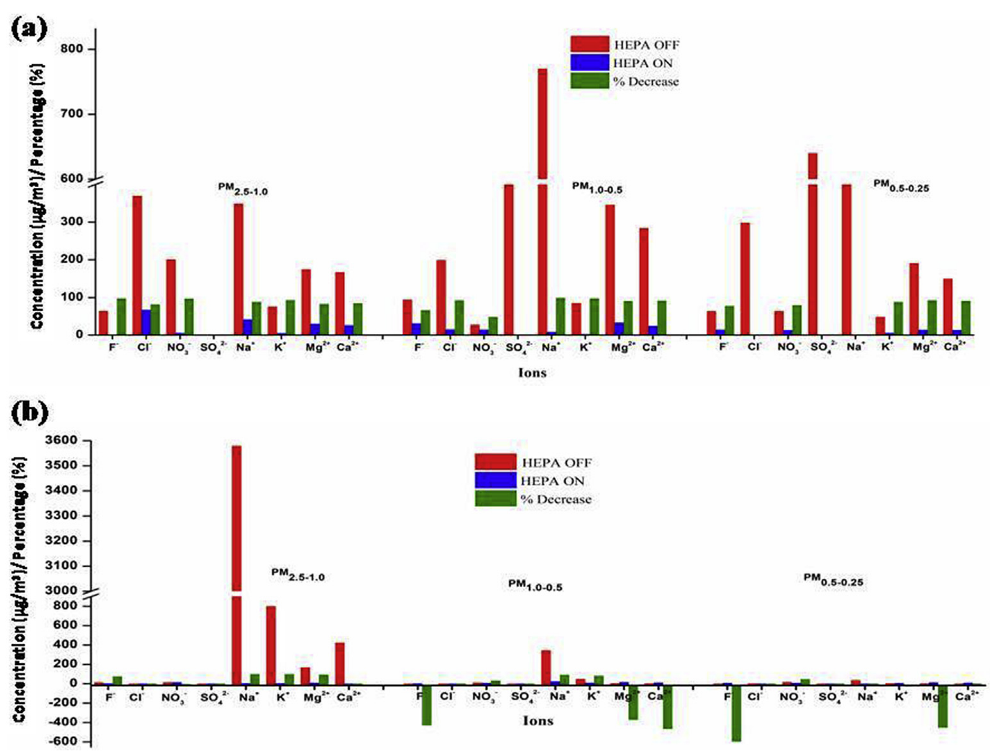

Figure 3. (a) Mass concentration of ions (in $PM_{2.5\text{-}1.0}$, $PM_{1.0\text{–}0.5}$ and $PM_{0.5\text{-}0.25}$) in candles and incense smoke during API OFF and ON scenario (b)Mass concentration of ions (in $PM_{2.5\text{-}1.0}$, $PM_{1.0\text{–}0.5}$ and $PM_{0.5\text{-}0.25}$) in candles and incense smoke during APII OFF and ON scenario.

Table 5. Comparison of effectiveness of both air purifiers in terms of reducing PM and ions.

	Reduction of PM (%)						Reduction of Anions (%)			Reduction of Cations (%)		
	$PM_{0.25}$	$PM_{0.5}$	$PM_{1.0}$	$PM_{2.5}$	$PM_{5.0}$	PM_{10}	$PM_{2.5\text{-}1.0}$	$PM_{1.0\text{-}0.5}$	$PM_{0.5\text{-}0.25}$	$PM_{2.5\text{-}1.0}$	$PM_{1.0\text{-}0.5}$	$PM_{0.5\text{-}0.25}$
AP I												
General Indoor Air	13	12	21	43	52	52	~80	30–93	81	ND	43–56	21
Candles and Incense Smoke	53	50	40	34	31	29	81–97	48–92	77–79	82–92	90–97	88–92
AP II												
General Indoor Air	64	73	60	37	47	54	27–40	14–38	ND	85–99	20	47
Candles and Incense Smoke	52	60	67	68	67	66	76	33	47	93–99	81–93	149

smoke by AP II, an increase in the mass concentration of cations were found in the order (Mg^{2+}>K^{+}); Mg^{2+} was highly increased (454%) followed by K^{+} which was increased moderately (27%).

3.3. Comparative study of the effectiveness of air purifiers in terms of PM and ions

Both air purifiers with different specifications and Clean Air Delivery Rate (CADR) employed in the present study showed distinct efficacy in terms of decrease in the concentration of different sized PM and ions. The varied reduction percentages in the mass concentration of different sized PM and ions are summarized in Table 5. The range of reduction percentage reported in Table 5 is based on the lowest to highest reduction percentage in the case of cations and anions. In some sampling cases, a similar reduction percentage was observed which is presented as a single reduction percentage while all the increased values have not been included.

The result infers that the effectiveness of both air purifiers (in terms of reduction of PM levels) was enhanced in case of external source event (29–53% (API) and 52–68% (APII)) than general indoor air (12–52% (API) and 37–73% (APII)). Also, the PM reduction percentage did not follow any fixed trend in terms of size for the APII operational scenario for both sampling events whereas the AP I operational phase depicted enhanced reduction for PMs with larger diameters in general indoor air events with an inverse trend for external source event.

Also, both the air purifiers reduced ions concentration significantly while the concentration of some of the ions increased after the application of the air purifier. AP I reduced the ions concentration (in three different size fractions of PM) such that cations were reduced by 21–56% and 82–97% while anions by 30–93% and 48–97% in general indoor air and presence of source (candles and incense smoke) respectively. The reduction in the mass concentration of ions was also significant in the case of AP II i.e. for cations the decrease percentage (%) lies in the range 20–99% while it was 14–40% for anions in general indoor air. In presence of candles and incense smoke, the reduction percentage in cations concentrations ranged from 81-149%, and in the case of anions, it was 33–76%. It was observed that a higher reduction in the mass concentration of ions takes place after deployment of air purifier in presence of sources like candles and incense in comparison to its absence.

3.4. Effect of air purifier on health risk

In the case of adults, the health risk posed in terms of acute and chronic exposure significantly reduces with the employment of air purifiers. However, no health risk due to PM_{10} ($HQ \leq 1.0$) was observed in general indoor air as well as in presence of candles and incense smoke Table 6.

In general indoor air, all the values of HQ were found to be less than 1.0 which indicate the negligible risk posed by PM_{10}, while in presence of candles and incense smoke it was found to be greater than 1.0 (pose threat to human health) which was significantly reduced to a large extent by both air purifiers. The HQ (risk posed to adults and children) in case of acute and chronic exposure was reduced by 2.07 times and 1.41 times when air purifier I was operated in general indoor air and presence of external source (incense and candles smoke) respectively, while air purifier II reduced the risk by 2.16 times and 2.94 times in a similar sampling case.

The value of ELCR for both child and adult was also reduced significantly (Table S1) and almost similar to that of HQ after the application of air purifier in general indoor air as well as candles and incense smoke.

4. Discussion

The indoor level of different sized PM characteristics and ions (associated with PMs) under HEPA and non HEPA conditions in two different sampling scenarios viz. general indoor air and external source

Table 6. Health Quotient value for adult and child during different sampling scenario.

Adult

Cases	Air purifier I				Air purifier II			
	Acute		Chronic		Acute		Chronic	
	HEPA OFF	HEPA ON	HEPA OFF	HEPA ON	HEPA OFF	HEPA ON	HEPA OFF	HEPA ON
General Indoor Air	0.24	0.11	0.23	0.11	0.28	0.13	0.26	0.12
Candles and incense smoke event	1.04	0.74	1.00	0.71	1.09	0.37	1.05	0.36

Child

Cases	Air purifier I				Air purifier II			
	Acute		Chronic		Acute		Chronic	
	HEPA OFF	HEPA ON	HEPA OFF	HEPA ON	HEPA OFF	HEPA ON	HEPA OFF	HEPA ON
General Indoor air	1.29	0.62	1.24	0.60	1.49	0.69	1.43	0.66
Candles and incense smoke event	5.63	3.99	5.40	3.83	5.92	2.01	5.68	1.93

(candles and incense smoke) was assessed. After the API employment in general indoor air, the reduction of larger PMs was more obvious than the reduction of the smaller ones, which is in conjugation with a former study of the Department of Energy, USA (DOE, 2005). The obtained trend can be attributed to the fact that larger particles (more inertia) are found in higher concentration in general indoor air (as a result of mechanical (human) activities as walking, sweeping and vacuuming) as compared to smaller ones that travel in airstream direction to get through cross-hatching of fiber and are intercepted by fiber (Wallace, 2008). Shiue et al. (2011) had reported a similar reduction percentage in the mass concentration of $PM_{0.5}$ and $PM_{0.25}$, whereas reduction percentage in the mass concentration of $PM_{2.5}$ resembles with results in studies by Scheepers et al. (2015), Cheng et al. (2016), and Park et al. (2017).

After deployment of AP II in the same sampling conditions, no such similar trend in reduction percentage (in the mass concentration of PMs) was noticed in the case of API . AP II showed the lowest efficacy on $PM_{2.5}$ as its mass concentration was only reduced by 37% (from 40.42 μg/m^3 to 25.27 μg/m^3). A similar mean reduction percentage in the mass concentration of $PM_{2.5}$ was reported by Cheng et al. (2016), Scheepers et al. (2015), and Chuang et al. (2017), while Brauner et al. (2008) mentioned a remarkable reduction of 63% in $PM_{2.5}$ after the installation of HEPA air purifier. In the case of PM_{10}, the obtained reduction percentage (54%) in mass concentration was comparable to the estimate provided by Brauner et al. (2008) in which air purifier was operated in homes located proximity to roads, while Xu et al. (2010) has reported most notable decrease percentage (72%).

The efficacy of AP I in presence of candles and incense smoke was found as: small-sized PMs reduced more as compared to large-sized PM. This can be attributed to the fact that small-sized particles travel farther and faster due to less inertia and are more likely to be hit and trapped by fiber on the filter (Wallace, 2008). The reduction percentage in the mass concentration of PM_{10} associated with incense and candle smoke after the deployment of AP I was 29.14. This is incomparable to the study by Butz et al. (2011) in which HEPA air purifier was operated in presence of ETS. No as such trend in reduction percentage (in mass concentrations of PMs) after deployment of AP II in candles and incense smoke was observed as obtained in AP I. Mean mass concentration of $PM_{2.5}$ was reduced by 69% (from 605.77 μg/m^3 to 191.60 μg/m^3) which was highest among other sized PMs. The acquired reduction percentage in the mean concentration of $PM_{2.5}$ is consistent with the findings reported by Henderson et al. (2005) and Barn et al. (2008) that evaluated HEPA filter effectiveness in the appearance of wildfires and prescribed burns and residential wood smoke respectively. This is analogous to the studies by Allen et al. (2011) and Butz et al. (2011) when the same type of air purifier was operated in presence of wood smoke and ETS respectively.

The comparison of PM concentration in different sampling scenarios with guidelines proposed by national and international organizations depicted that in the case of both air purifiers, the concentration of PM_{10} and $PM_{2.5}$ was very high as compared to the prescribed limit for 24-hour exposure concentration (μg/m^3) by WHO, USEPA, and Central Pollution Control Board (CPCB) and remained very high even after the filtration of candles and incense smoke. In the case of general indoor air, both air purifiers reduced the concentration of PM_{10} in manner that the resultant concentration lied under the prescribed limit of USEPA and National Ambient Air Quality Standards (NAAQS) but remained higher than the limits prescribed by WHO. Moreover, the concentration of $PM_{2.5}$ in general indoor air which was lower than the prescribed limit of USEPA and NAAQS and higher than that of WHO before filtration reduced to the prescribed limit of WHO and lower than that of NAAQS and USEPA limits after purification of air by both air purifiers is depicted by Figure 4.

Along with a significant decrease, results from the study also revealed an increase in the mass concentration of ions (not specific) after the operation of air purifiers. Studies like Nishikawa and Nojima (2001), Nojima and Nishikawa (2002), Nishikawa (2006), Kawamoto et al. (2006) confirm the release of both negative and positive ions from air purifiers (by the electric discharge) into the air to make it free from bacteria, mold and other allergens by deteriorating and making them inactive. The increase in the mass concentration of ions after the application of the air purifier may be due to the reason that air purifiers release ions continuously to purify the air and the release of ions continued even after the purification of air which results in increased concentration of ions. However, there was no such specific ion whose mass concentration was increased in presence of air purifiers and neither has it been provided in the literature.

4.1. Limitations and future studies

Along with important findings, the study has few limitations such that the effectiveness of air purifiers was observed for a short period and in the case of PM and ions only. As the toxicity of other chemical constituents of PM (such as metals) and other toxic gaseous pollutants are well known which is not encompasses in the study. The study also lacks in

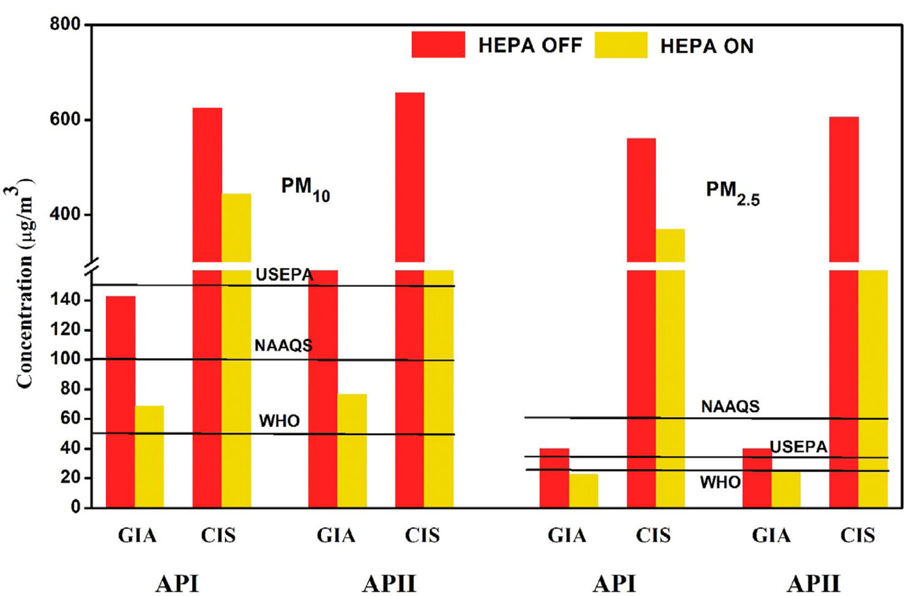

Figure 4. Comparison of PM_{10} and $PM_{2.5}$ concentration with proposed guidelines in different sampling scenario. *GIA = General Indoor Air, CIS = Candles and Incense Smoke.

terms of observation of the effectiveness of air purifiers in different seasons.

The study that dealt with an observation of the effectiveness of air purifiers on different chemical species associated with PM in different seasons and microenvironments can be carried out in the future which provides a clear picture regarding improvement of indoor air quality on the application of different types of purifiers. The dispersion and decay rate of PM in different indoor spaces can also be carried out.

5. Conclusion

Air cleaners (with HEPA filters) placed in the room chamber effectively reduced the PM concentration to a large extent whereas the concentrations of ions fluctuated. The purifying efficacy of both air purifiers was enhanced in the presence of candles and incense smoke and smaller particles were removed more efficiently as compared to larger ones. Still, PM concentrations were much higher than standards prescribed by national and international agencies that advocate the fact that source control is the best solution to deal with the problem of IAP rather than air purification. On a comparison basis, air purifier with greater CADR and coverage area was more effective on particulate pollution in general indoor air as well as candles and incense smoke support the fact of adoption of air purifier with higher coverage area (or CADR) for air filtration. However, the mass concentration of ions increased in some of the sampling cases which did not seem to be a good one. Though it is a short-term study, it doesn't fully adhere specificity of ions in presence of an air purifier. So, long-term studies are needed to be conducted to clarify the specificity of ions release from air purifiers. For the sake of health safety, air purifiers with mechanical filters (as HEPA) must be used instead of that which releases ions for air purification.

Also, as literature lacks a study that observes the effectiveness of air purifiers in terms of different sized PM and chemical constituents (ions), the study fills the gap. With the dramatic reduction in PM concentration and associated health risk under HEPA periods, the present study suggests (favors) that air purifiers are effective mitigation measures and can be employed in indoor environments but the air purification methods adopted by air purifiers cannot be disregarded. Moreover, such a kind of study will help the policymakers and implementing agencies to formulate such benchmark limits vital for a healthy environment perspective. Additionally, information from this study will provide crucial information to consumers regarding the selection of air purifiers. The findings of the study concerning the infiltration and effectiveness of air purifiers definitely have predominant policy implications.

Declarations

Author contribution statement

Stuti Dubey: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Himanshi Rohra: Analyzed and interpreted the data; Wrote the paper.

Ajay Taneja: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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