Quantifying indoor $PM_{2.5}$ reduction through control measures

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This study aims to compare 10 indoor air pollution sources for their $PM_{2.5}$ emissions and quantify the indoor $PM_{2.5}$ reduction through control measures. $PM_{2.5}$ emission rates were evaluated with experiments in a testing unit. A chemical mass balance equation was used to predict the control scenario. Two $PM_{2.5}$ emission scenarios were generated, viz. emissions from a single source and a combination of two sources. The incense stick and dhoop combination showed the highest $PM_{2.5}$ concentration among the six tested combinations. The emission rate reduction by 50% and doubling the room volume resulted in 75.2–79.1% and 49–50% reduction in the predicted indoor $PM_{2.5}$ concentration respectively, when a combination of incense stick and dhoop was considered. The reduction in emission rate significantly reduces the predicted controlled $PM_{2.5}$ concentration compared to the increase in room volume; hence control of pollution at the source is recommended.

Keywords: Chemical mass balance equation, control measures, incense stick, indoor air pollution, $PM_{2.5}$ concentration.

INDOOR air pollution persists as a significant global health threat. The use of solid fuels for cooking generates particulates, gases and numerous other pollutants which adversely affect human health. According to the World Health Organization (WHO), household air pollution from solid fuels and kerosene used for cooking resulted in 3.8 million premature deaths[1]. According to the National Family Health Survey, Government of India (GoI), there is an increase in the total number of households using clean fuel for cooking from 43.85% (2015–16) to 58.6% (2019–21)[2]. Among them, 89.7% of the urban households and 43.2% of the rural households use clean fuels like LPG/gobar gas as cooking fuel[2]. However, 41.4% of the households still rely on polluting fuels for cooking[2]. Ambient particulate matter (PM) pollution was responsible for 0·67 million deaths and household air pollution for 0·48 million deaths in 2017 (ref. 3). It has been reported that polluting cooking fuels like cow dung cakes, agricultural waste and wood are responsible for the increased asthma cases[4]. PM emitted from any source is measured as PM_{10} (PM size less than or equal to 10 μm) and $PM_{2.5}$ (PM size less than or equal to 2.5 μm). The Central Pollution Control Board (CPCB), GoI, has specified ambient air quality standards for both. Household cooking using solid fuels in India accounted for 27% of the total annual $PM_{2.5}$ emissions generated due to various humanmade activities[5]. Hence, it is clear that PM pollution from the combustion of solid fuels for cooking is a point of concern. Various measures are being taken to mitigate indoor air pollution from solid cooking fuels. Some models have estimated that after the introduction of 150 million low-emission cookstoves in India, there will be a saving of 12,500 disability-adjusted life years (DALYs)[6].

Apart from solid fuels used for cooking or heating, there are other sources of indoor air pollution in Indian and South Asian households, like incense sticks, dhoop (a thick form of incense), mosquito coils, etc. Incense sticks are fragrant sticks prepared with various herbal materials, aromatic wood and oil coated over a thin bamboo stick. Dhoop is another aromatic material thicker than incense, prepared using various herbs, cascalia powder, oil, charcoal powder, resins, etc.[7]. It has no bamboo stick. Cigarette smoke is also emitted in certain households, and the health hazards because of exposure to cigarettes are well known. The consumption pattern of these sources is reported in the literature[8]. Use of incense sticks during certain festivals/celebrations results in increased indoor $PM_{2.5}$ and Polycyclic Aromatic Hydrocarbon (PAH) concentration, which can pose cancer risk to the exposed population[9]. Burning three incense sticks twice daily in a less ventilated room may adversely affect the exposed population[10]. The use of mosquito coils is widely practised in India. These coils are designed in such a manner that they will be in smouldering condition for long hours after the initial ignition. It is reported that burning mosquito coils resulted in very high concentrations of $PM_{2.5}$ and carbon monoxide (CO) in an unventilated room[8,11].

Numerous studies have been conducted on monitoring indoor air pollution and associated health risks. The effect of infrastructure development projects on reducing vehicular air pollution has also been studied[12]. The effect of natural ventilation on indoor $PM_{2.5}$ and CO concentrations has been reported when mosquito coil is the source[11]. However, only a few studies have focused on quantifying the mitigation of indoor air pollution with different control

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strategies and predicting the controlled concentration with a single or a combination of two active sources. The present study aimed to estimate the reduction in concentration of indoor $PM_{2.5}$ emitted from 10 indoor air-pollution sources through control measures. The sources used were incense sticks, dhoop, mosquito coil, cigarettes, coal and wood. Emission rates of $PM_{2.5}$ were evaluated by indoor air quality monitoring experiments carried out in a controlled environment with standard methodology[8]. The reduction in indoor $PM_{2.5}$ concentration will result in the control of indoor air pollution and improvement in the indoor air quality. Hence, this can be called as a control scenario and is predicted here. This reduction in indoor $PM_{2.5}$ concentration was estimated for two different emission scenarios, viz. $PM_{2.5}$ emitted individually from specific sources and $PM_{2.5}$ emitted simultaneously from a combination of sources. Two control measures were considered for reducing the indoor $PM_{2.5}$ concentration, viz. reducing the $PM_{2.5}$ emission rates and increasing the room volume.

Materials and methodology

The sources tested in this study were three different types of incense sticks (IS1, IS2 and IS3), two different types of dhoop (DH1 and DH2), one mosquito coil (M1), two different types of cigarettes (CG1 and CG2), one coal (C1) and one wood (W1). Fine particulate samplers (Envirotech make, Model APM 550EL, APM 550 and BGI make, Model PQ200) were operated at 16.67 lpm flow for collecting samples on Whatman make 47 mm dia PTFE filters, according to US EPA[8,13]. The sources were tested in an Indoor Air Testing Unit (IATU) of 2.3 × 2.4 m area and 3.0 m height. Other details and the experimental conditions have been described in an earlier study[8]. It was ensured that outside pollutants did not penetrate inside the IATU.

Mass balance equation

The indoor concentration of any pollutant is dependent on the number of active sources, the emission rate of each source, duration of the emission-generating activity, dispersion and dilution of the pollutants, penetration of outdoor pollutants, ventilation, efficiency of the air pollution control device, if any, and other pollutant removal processes/mechanisms such as deposition/adsorption/exhaust. The control scenario of the indoor environment was predicted using the mass balance equation. For a pollutant i emitted in the indoor environment, the mass balance equation is represented as[14].

$$\frac{\mathrm{d}C_i}{\mathrm{d}t} = -\lambda C_i + \frac{\varepsilon_i}{V} - \frac{\eta_i Q_C C_i}{V} - v_{\mathrm{d}i}\frac{A}{V}C_i, \quad (1)$$

where λ is the air exchange rate, C_i the concentration of pollutant i, V the room volume, ε_i the emission rate of pollutant i, A the surface area of the testing unit, η_i the fraction of mass removed from pollutant i with a control device, Q_c the airflow rate of the control device and $v_{\mathrm{d}i}$ is the deposition velocity of pollutant i.

The air exchange rate denotes the number of times indoor air is replaced in a single time unit. The IATU was in a controlled environment set-up, wherein penetration of outdoor air pollutants indoors and air exchange were not permitted. Hence, the term λC_i in eq. (1) will be zero.

Control scenario

The indoor $PM_{2.5}$ concentration needs to be below the permissible air quality standards. Indoor air quality (IAQ) standards are specified in developed countries like the UK, USA, Germany, China and Singapore. WHO has prescribed IAQ guidelines for selected air pollutants like CO, benzene, formaldehyde, naphthalene, nitrogen dioxide, polycyclic aromatic hydrocarbons (especially benzo[a]-pyrene; BaP), radon, trichloroethylene and tetrachloroethylene[15]. India is yet to regulate the IAQ standards. CPCB has specified ambient air quality standards for 12 air pollutants, including two particulate fractions, viz. PM_{10} and $PM_{2.5}$ (ref. 16). The others are six gaseous air pollutants, three particulate-bound trace metals, and a PAH, i.e. BaP (ref. 13). Hence, this CPCB standard is considered for comparison in the control scenario. The control scenario prediction aims to reduce the existing $PM_{2.5}$ concentration below the CPCB standard.

The quantification of concentration reduction using two control measures was carried out. The control measures are emission rate reduction by 50% and an increase in room volume by 100%. All the other conditions were maintained the same. Emission rate is a quantity (expressed in units of weight) of any air pollutant released from any source per unit time. The quantification of pollutant emission per unit activity or per unit of fuel burnt or per unit time of the activity is known as the emission factor, e.g. grams of particulate matter ($PM_{2.5}$) emitted per gram of coal burnt. The emission rate in this study was measured as the amount of pollutant emitted per minute of burning activity. The emission factor and emission rate are useful in quantifying air-pollutant emissions due to various air-pollution sources. This approach helps in preparing an emission inventory of a particular area/indoor environment.

The indoor environment (residential/places of worship) may have a single active source or more than one active source at a particular time. Majority of Indian households use incense sticks and dhoop simultaneously during prayers in the morning or evening. The $PM_{2.5}$ concentration was predicted assuming two scenarios. Scenario 1 was generated based on the assumption that only one source emitted $PM_{2.5}$ at a particular time. Whereas scenario 2 was generated based on the assumption that two sources simultaneously emitted $PM_{2.5}$ at a particular time. Further, two control measures were considered for predicting indoor $PM_{2.5}$ concentration from a single or a combination of two active sources at a time. The emission rate reduction highlights pollution control at the source concept, whereas room volume increase indicates the availability of higher air volume for proper dispersion and dilution of the emitted air pollutants. The final aim of both these control measures is a reduction in the indoor $PM_{2.5}$ concentration.

Result and discussion

Emission rate

The average $PM_{2.5}$ emission rate (µg/min) was calculated based on the total $PM_{2.5}$ absorbed by the sampler over the total sampling time. This value was calculated for every source using the experimental data (Figure 1). The source dhoop (DH2) was observed to have the highest emission rate of 188 µg/min followed by wood (W1), dhoop (DH1), incense stick (IS1), mosquito coil (M1), coal (C1), incense stick (IS2), cigarette (CG2), cigarette (CG1), while the lowest emission rate of 1.97 µg/min was observed for incense stick (IS3).

Hence, if DH2, DH1 and IS1 burn for 30 min in a non-ventilated room, it will lead to the generation of 5665, 1071 and 668 µg of $PM_{2.5}$ respectively. These values are 94, 18 and 11 times higher respectively, than the CPCB standard of 60 µg/m^3. Similarly, if a mosquito coil burns for 1 hour at night in a non-ventilated room, it will generate 877 µg of $PM_{2.5}$, which is 15 times higher than the CPCB standard. Sometimes, during winter months, a small stove (commonly called sigdi in India) with coal or wood as fuel for burning is used for room heating during the evening and night at various places in India. This will generate 599 and 8065 µg of $PM_{2.5}$ from coal and wood respectively, for a burning duration of just 1 h. These values are 10 and 134 times higher respectively, than the CPCB standard. The occupants of the room will be in contact with the mosquito coil, coal and wood emissions for a longer sleep-time duration of 7–8 hours at night. Emissions of PM from any combustion source result from incomplete combustion, which will result in the emission of other air pollutants like $PM_{2.5}$, CO, sulphur dioxide (depending on the sulphur content of the fuel), nitrogen dioxide, etc. This will make the occupants of the room more vulnerable to respiratory/lung-related adverse health effects arising from inhalation of these air pollutants.

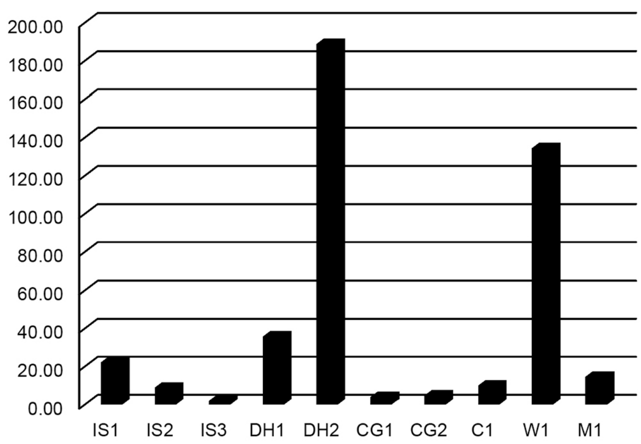

Figure 1. Average $PM_{2.5}$ emission rates (µg/min) for individual sources.

Effect of control measures on $PM_{2.5}$ concentration

(i) Scenario 1: single active source

This scenario depicts that only one source is active at a particular time. The initial $PM_{2.5}$ concentration without any control measures was determined using the experiments. Then $PM_{2.5}$ concentration using the control measures was predicted.

Emission rate reduction: The initial $PM_{2.5}$ concentration without any control measures for all the sources ranged from 18 (IS3) to 1753 (DH2) µg/m^3. Figures 2 and 3 show the initial and predicted $PM_{2.5}$ concentration for various sources using control measures. Dhoop (DH2) was found to be responsible for the highest $PM_{2.5}$ concentration, followed by wood (W1) and dhoop (DH1). The sources IS1, IS2, DH1, DH2, C1, W1 and M1 showed initial concentration exceeding the CPCB standard. A 50% reduction in the emission rate resulted in a 77.3% (for IS3) to 78.2% (for CG2) reduction in the predicted $PM_{2.5}$ concentration from all the sources. The estimated controlled concentration of all the sources was below the CPCB standard except for DH1, DH2 and W1.

Increased room volume: Doubling the room volume (100% increase in room volume) resulted in a 46.7% (CG1) to 51% (C1) reduction in the predicted $PM_{2.5}$ concentration from all the sources. The controlled concentration of all

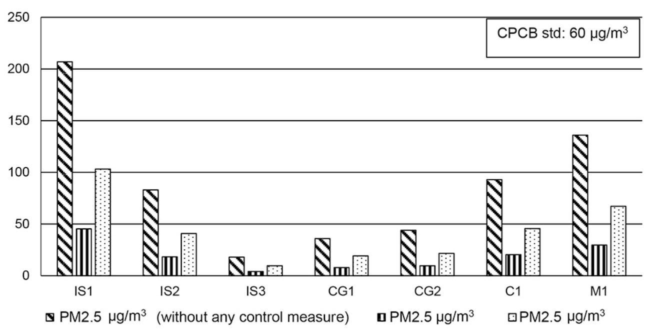

Figure 2. Initial and predicted $PM_{2.5}$ concentration for the sources IS1, IS2, IS3, CG1, CG2, C1 and M1.

the sources was found to be below the CPCB standard, except for IS1, DH1, DH2, W1 and M1.

(ii) Scenario 2: two active sources

Many of the Indian households use both incense sticks and dhoop during prayers. Scenario 2 is based on the assumption that one incense stick and one dhoop are simultaneously burning and emitting $PM_{2.5}$ indoors. The combination of all three incense sticks with both types of dhoop was considered. Hence, a total of six combinations were evaluated. Figure 4 shows the initial $PM_{2.5}$ concentration without any control measures and the estimated concentration using control measures. The initial $PM_{2.5}$ concentration without any control measures ranged from 277 to 2948 μg/m^3 for the combination IS2 + DH1 and IS1 + DH2 respectively. These were found to exceed the CPCB standard. Since DH2 had a higher emission rate, the combinations where it was present showed higher initial concentration than the other combinations.

Emission rate reduction: The 50% reduction in the emission rate resulted in 75.2% (for IS3 + DH2) to 79.1% (for IS1 + DH2) reduction in the predicted $PM_{2.5}$ concentration from all the sources. The controlled concentration of all the combinations of sources exceeded the CPCB standard except IS2 + DH1.

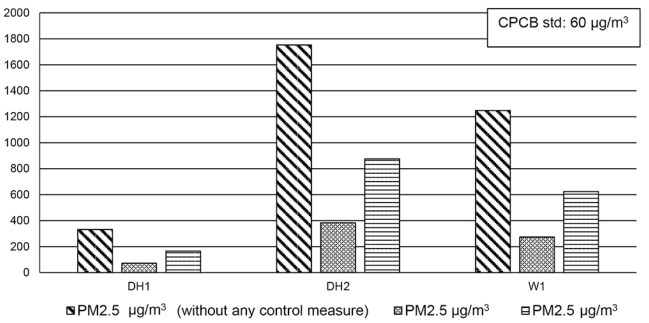

Figure 3. Initial and predicted $PM_{2.5}$ concentration for the sources DH1, DH2 and W1.

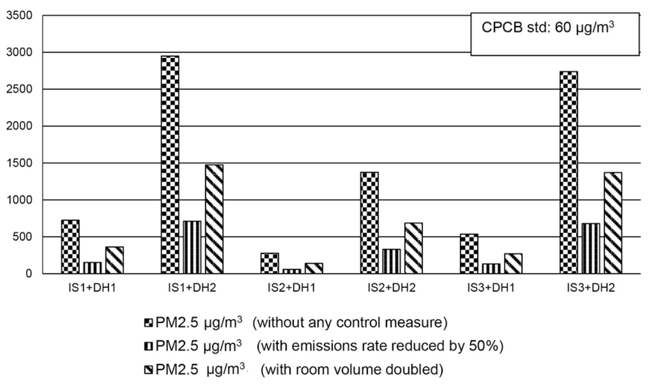

Figure 4. Initial and predicted $PM_{2.5}$ concentrations for a combination of sources.

Increased room volume: The effect of doubling the room volume (100% increase in room volume) resulted in 49.8% (IS3 + DH2) to 50.1% (IS2 + DH2) reduction in the predicted $PM_{2.5}$ concentration from all the combinations of sources. This indicates that small rooms or small closed environments with such active sources can be risky in terms of pollutant exposure to the occupants, especially Asthma patients, children and the aged population.

Mitigation approaches: The reduction in emission rate resulted in more than 75% reduction in $PM_{2.5}$ emissions, consequently leading to a similar reduction in $PM_{2.5}$ concentrations in the indoor environment. The emission rate can be reduced in humanmade sources by reducing the combustible area per unit time, which can be easily achieved by altering their sizes. For sources like incense stick, dhoop, mosquito coil and cigarette, this can be done by decreasing their diameter. Further, decreasing the height of these sources will also reduce their combustible mass during combustion, thereby reducing the overall $PM_{2.5}$ emissions from the sources and consequently reducing the indoor $PM_{2.5}$ concentration. However, such size alteration may not be feasible for cooking fuels like coal and wood, as the amount of wood and coal required for cooking cannot be changed. The other emission control options, like using clean fuels for residential cooking and heating, low-smoke stoves and proper exhaust, either by natural ventilation or using exhaust fans for emissions will help maintain proper indoor air quality in these situations.

Conclusion

Using incense sticks and dhoop during prayers/rituals releases aromatic compounds that create a pleasant fragrance. However, care should be taken while using them so that they do not cause any health problems. The notable variation in $PM_{2.5}$ concentration emitted from the three tested incense sticks indicates that users should select good ones for everyday use. Some preliminary screening, like the diameter and height of the incense sticks can help minimise indoor PM emissions. The smaller the diameter and height of the incense sticks and dhoop, the lower the emissions. The reduction in emission rate significantly reduces the predicted controlled $PM_{2.5}$ concentration compared to the increase in room volume. This highlights that the concept of control of pollution at source is more effective than any other control measure. In the case of a combination of sources, the emission rate must be reduced by more than 50% to achieve the controlled $PM_{2.5}$ concentration below the CPCB standard. Indoor environments where room volume cannot be increased, like low- and middle-income homes, should ensure that emissions from indoor sources are lower. Further, prayer rooms must be designed in such a way that they have sufficient air volume and proper ventilation. The use of mosquito coils in small rooms at night must be limited to less time and good ventilation must be ensured. This will help maintain good indoor air quality and minimise exposure to air pollutants. This applies even to places of worship with a closed environment with less ventilation, and one or two sources are simultaneously active inside for a significant amount of time. Hence, it can be concluded that controlling indoor air pollution is best achieved by reducing emissions at the source.

Conflict of interest: The authors declare that they have no conflict of interest.

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