Original Article

Personal exposures to particulate matter <2.5 μm in mass median aerodynamic diameter ($PM_{2.5}$) pollution during the burning of six most commonly used firecrackers in India

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ABSTRACT

Introduction: Diwali or the festival of lights is the most popular festival celebrated in India when firecrackers are burnt by almost every household for 3 days. Levels of ambient air pollution are reported to be very high during the Diwali festival in India. In this study, we aimed to measure and compare the personal exposure levels to particulate matter <2.5 μm in mass median aerodynamic diameter ($PM_{2.5}$) during burning of six of the most commonly used firecracker types in India. **Methods:** Sparklers, ground spinners, flower pots, pulpuls, a garland of 1000 sounding crackers, and snake tablets were burnt outdoors in an open area during the late evening hours. Minute by minute $PM_{2.5}$ levels were measured at a distance and height from where they are normally burnt using Thermo pDR 1200, USA, and a set of five such experiments were conducted to examine the variability between the firecrackers. **Results:** When measured at a distance and height from where they are normally burnt, the burning of snake tablets produced the highest peak level of $PM_{2.5}$ (64,500 mcg/m^3), followed by a garland of 1000 sounding crackers (38,540 mcg/m^3), pulpuls (28,950 mcg/m^3), sparklers (10,390 mcg/m^3), ground spinners (9490 mcg/m^3) and flower pots (4860 mcg/m^3). **Conclusion:** Burning of firecrackers produce extremely high levels of personal exposure to $PM_{2.5}$ levels that are likely to have significant short-term and long-term adverse health effects. The initiative taken by the Supreme Court of India in 2017 to ban the sale of firecrackers seems to be a step in the right direction to reduce the adverse health impacts in the community.

KEY WORDS: Air pollution, firecrackers, particulate matter, particulate matter <2.5 μm in mass median aerodynamic diameter, public health

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INTRODUCTION

Diwali, the festival of lights, is one of the most celebrated festivals in India. The return of Ram, Sita, and Laxman to Ayodhya after defeating Ravana is considered to be an auspicious time to celebrate the victory of good over evil. During this festival, which falls during the beginning of winter session, almost all households in India burn lamps, distribute sweets, perform pooja, and burn firecrackers every day in the evening for a period of 3 days. All firecrackers emit bright lights of different colors and/or produce sound and invariably produce smoke containing both gaseous and particulate matter (PM) air pollution.

All firecrackers are composed of two basic chemical components, viz., (a) a base used for burning such as

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charcoal, sulfur, potassium nitrate, chlorate, perchlorate, and manganese,[1] and (b) metal salts added to produce a variety of different colors, for example, strontium carbonate and lithium carbonate to produce red color, calcium chloride for orange, sodium chloride for yellow, barium compounds for green, copper compounds for blue, and a mixture of strontium and copper compounds for purple color. In addition, burning of iron produces a golden color, whereas burning of magnesium or aluminum barium oxide produces white light. Silver color is produced by burning aluminum, titanium, or magnesium powder.[2,3]

Burning firecrackers release a range of particles of various sizes, including PM with a mass median aerodynamic diameter (MMAD) of <10 μ (PM_{10}), fine particles (PM <2.5 μm in MMAD [$PM_{2.5}$]), ultrafine particles (MMAD ≤100 nm), and nanoparticles (MMAD ≤50 nm).[4] $PM_{2.5}$ particles are responsible for various short-term and long-term respiratory health hazards. $PM_{2.5}$ particles also have a relatively larger surface-to-volume ratio, have a longer residence time in the atmosphere, and carry a persistently high proportion of organic compounds than larger particles such as $PM_{10.}$ They also have the ability to reach the distal portions of the lung and produce relatively more reactive oxygen species than PM_{10} and are therefore more harmful.[5] The Central Pollution Control Board of India has laid down the 24 h average National Ambient Air Quality Standards for PM_{10} as 100 μg/m^3 and $PM_{2.5}$ as 60 μg/m^3.[6] Increased levels of $PM_{2.5}$ are reported to have pronounced impacts not only on health but also on visibility and direct as well as indirect effects on the ecosystem.[7] Chronic exposures to PM are reported to cause chronic respiratory and cardiovascular diseases, alter host defense, lead to premature death, and also cause lung cancer.[8] Further, recent studies have also established a relationship between the harmful effects of increased atmospheric particulates on human health and mortality with increased concentration of atmospheric particulates.[9]

During the Diwali festival in India, 30%–40% increase in the cases of wheezing, respiratory infections, exacerbation of bronchial asthma, and chronic obstructive pulmonary disease (COPD) have been reported.[10] Respiratory hospitalization post-Diwali has been reported to be significantly more compared to pre-Diwali from both rural and urban locations.[11] Children are the most vulnerable population to the harmful effects of firecrackers air pollution since their lungs are growing and guided by a complex and precise time sequence of chemical messages. Many of these air pollutants interfere with this pathway making them vulnerable to develop infections, asthma, and overall poor lung development.[12] Furthermore, their airway epithelium is more permeable to air pollutants, has a poor defense against PM as compared to adults, and has differential ability to metabolize and detoxify environmental agents.[13] The harmful effects of the pollutants emitted from firecrackers are not just restricted to respiratory illnesses but also have a significant effect on cardiovascular health as well.[14,15]

During the Diwali festival, various types of firecrackers are burnt. The snake tablets, sparklers (fuljhadi), and pulpuls are burnt from very short distances (often <1 feet away), while the laad, fountains (anar), and ground spinners (chakri) are burnt at a distance of 4–6 feet away. Different firecrackers produce different levels of air pollutants. While several studies have reported the ambient level of $PM_{2.5}$ during the Diwali festival in India,[16-19] in this study, we aimed to measure the level of $PM_{2.5}$ produced during the burning of different type of firecrackers from a distance that simulates real-life exposure to get an insight into the personal exposure to $PM_{2.5}$.

MATERIALS AND METHODS

Study site

The study was carried out in a real-life, quiet residential area with an open ground with natural wind flow, around 300 m from the main road.

Selection of crackers

A short survey was conducted among children in the city of Pune to understand which were the most common firecrackers that they burnt. We selected six of these most widely used firecrackers and these included flower pots (anar), sparklers (fuljhadi), ground spinners (chakri), snake tablets (naag goli), pulpuls (string), and garlands of 1000 sounding crackers (laad of 1000). The most commonly used brands of five of these firecrackers were purchased from the local market for the experiments. A pilot study was conducted to standardize the exposure protocol and ensure that the $PM_{2.5}$ monitor was capable of recording minute by minute levels of $PM_{2.5}$. The pilot study helped in fine-tuning the experiment in several ways such as measuring the exposures and calculating the required washout period to start the next set of experiments. Figure 1 shows the firecrackers selected for the study.

Measurement of particulate matter <2.5 μm in mass median aerodynamic diameter levels

A battery-operated, data-logging, real-time aerosol monitor (pDR-1200, Thermo Scientific, Franklin, MA, USA) equipped with a cyclone inlet was used to measure the concentrations of $PM_{2.5}$ on minute-to-minute basis at a flow rate of 4 L/min using a BGI 400S vacuum pump (BGI Inc., Waltham, MA, USA). The personalDataRAM™ (Personal Data-logging Real-time Aerosol Monitor) is a technologically advanced instrument designed to measure the concentration of airborne PM (liquid or solid), providing direct and continuous readout as well as an electronic recording of the information. Zeroing was accomplished by means of a hand-inflatable "zero air" pouch included with the model pDR-1000AN and by an inlet filter cartridge provided with the model pDR-1200. This instrument measured $PM_{2.5}$ at every 1-min interval. We started the machine 15 min before burning firecrackers and 15-min washout period was given between each experiment.

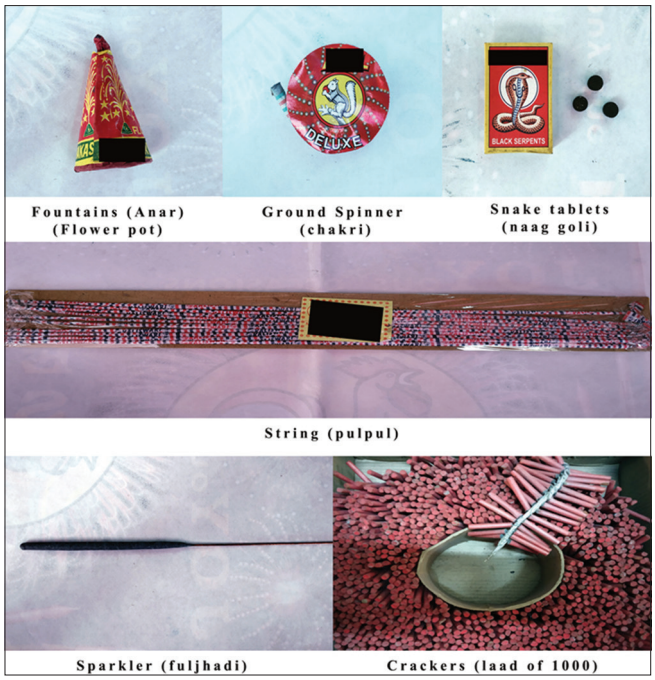

Figure 1: Six of these most widely used firecrackers selected for study

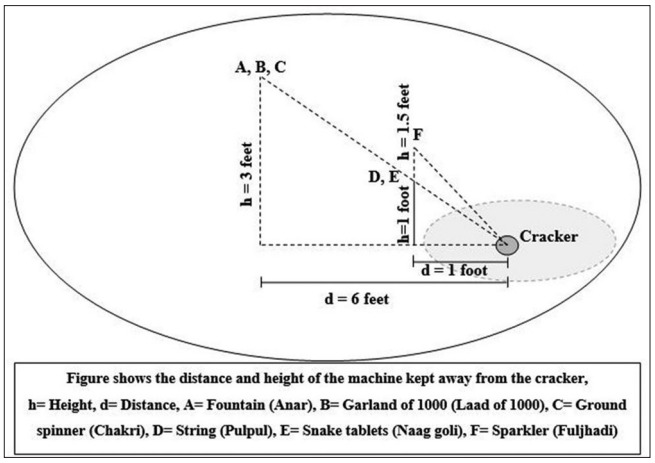

Figure 2: Exposure experiment: Position of the machine and the distance at which the crackers were burnt to see reallife scenario

Standardization during experiment

The height and distance of the inlet of the instrument used for measuring the exposures are illustrated in Figure 2. The height and distance between the instrument and the burning firecracker were kept separately for each firecracker to simulate real-life human exposures. A set of five experiments were conducted to study the variability between each experiment for each firecracker, and the mean (±standard deviation [SD]) and median (interquartile range) values were used to compare among different firecrackers. A washout period of at least 15 min was kept for all firecrackers between each experiment. The experiments were conducted over a period of 5 days from 8 p.m. to 10 p.m. (including time taken for logistics of filter cleaning, set up, and wash-off period between experiments), to simulate the real-life cracker-burning and celebrations hours of the day during Diwali.

The distance of instrument from each cracker

Flower pot, also called fountains or anar, forms a volcanic-shaped pattern. Starting slowly, they build up to quite magnificent plumes. To enumerate real-time situation, for measuring the exposure, the machine was kept 6 feet away and at a height of 3 feet from the flower pot (the height of 3 feet was chosen to simulate the height of an average child of 6–7 years).

Ground spinner or chakri is a type of firework consisting of a powder-filled spiral tube mounted with a pin through its center. When ignited, it rotates quickly, producing a display of sparks and colored flame. After igniting, a person tends to move at a safe distance to enumerate real-time situation; for measuring exposure, the machine was kept 6 feet away and at a height of 3 feet for measuring the exposure.

A sparkler or fuljhadi is a type of hand-held firework that burns slowly while emitting colored flames, sparks, and other effects. Since sparkler is held in the hand while lightened by a person, the machine was kept 1 foot away at a height of 1.5 feet for exposure experiment.

Similarly, a string or pulpul is hand-held cracker; therefore, the machine was kept 1 foot away and at a height of 1 foot to measure exposure.

Snake tablets or naag goli after being lit begins to spew out ash resembling a snake. Since it does not emit sparks, flares, any form of projectiles, or any sound, children tend to sit in proximity to this cracker. Hence, the machine was kept 1 foot away and at a height of 1 foot for exposure experiment.

Garland of 1000 sounding crackers or laad of 1000 is a small explosive device primarily designed to produce a large amount of noise, especially in the form of a loud bang. For crackers, exposure was measured by keeping the machine 6 feet away and at a height of 3 feet.

Data analysis

Data were collected for $PM_{2.5}$ levels for each firecracker accounting for five repeated measures. Descriptive statistics were used to compare the mean $PM_{2.5}$ values among different firecrackers. $PM_{2.5}$ data were recorded as mcg/m^3 and summarized as mean, SD, median, and minimum and maximum values for each type of firecracker and for each experiment. Box plot and bar chart were used to represent the results graphically. All the analyses were performed using Statistical Package for the Social Sciences (SPSS, IBM Corp., Version 22.0, Armonk, NY, USA).

RESULTS

Comparison of the peak level of $PM_{2.5}$ between different firecrackers and their burning duration time

Duration of exposure experiment and peak $PM_{2.5}$ levels

for each of the firecrackers are given in Figure 3. The results reveal that the peak levels of $PM_{2.5}$ were highest for snake tablet (64,500 mcg/m^3) followed by a garland of 1000 sounding crackers (38,540 mcg/m^3) and pulpul (28,950 mcg/m^3). Although the snake tablet burnt for only 0.2 min (9 s), it produced the highest levels of $PM_{2.5}$ which lasted for nearly 3 min. Garland of 1000 sounding crackers which burnt for 0.8 min produced high levels of $PM_{2.5}$ over 6 min. The flower pot produced the lowest $PM_{2.5}$ among the selected crackers (4860 mcg/m^3).

Comparison of Median $PM_{2.5}$ levels produced by the burning of different firecrackers

The highest median $PM_{2.5}$ level when snake tablet burnt was 39,630 mcg/m^3 (30,190–52,600) followed by the garland of 1000 sounding crackers being 21,660 mcg/m^3 (11,940–33,180), pulpul 12,120 mcg/m^3 (9030–22,960), sparklers 5230 mcg/m^3 (4460–6140), spinner 3029 mcg/m^3 (2868–3047), and flower pot 1866 mcg/m^3 (783–3306). Figure 4 shows the median $PM_{2.5}$ levels of different firecrackers.

DISCUSSION

Diwali or the festival of lights is the most celebrated festival in India during the beginning of winter season. Children, as well as adults from across the country, burn a variety of firecrackers during the late evening and at night (6 p.m. onward, but usually between 8 p.m. and 10 p.m.) for a period of 3 days. The most widely used firecrackers are the sparklers (fuljhadi), pulpuls, garlands (laad), fountain (anar), snake tablet (naag goli), and spinner (chakri), which are often burnt from a very short distance. Aerial firecrackers comprising rockets are also used, but by a limited number of people.

India is the most polluted country in the world with regard to air quality.[20] Against this background, a further increase in air pollution during the Diwali season due to the burning of firecrackers has been a matter of serious concern for the community at large and policymakers. Ambient levels of PM_{10} have been shown to increase by 3–10-fold in Central India, 5-fold in Kolkota, 2–3-fold in Northwest India, and 35-fold in Vadodara.[21-25] Even in Delhi, the National Capital of India which already has very high levels of air pollution at baseline, burning of firecrackers during Diwali has been shown to increase the levels of PM pollution even further.[26] Apart from burn injuries[27] and noise pollution,[28] air pollution due to the burning of firecrackers has been shown to cause respiratory tract infections, worsening of asthma, COPD, cardiovascular diseases, and even premature deaths.[29-33] Taking cognizance of the concerns of the ambient air pollution catastrophe during the Diwali festival, the Supreme Court of India banned the sales of firecrackers in 2017.

Most of the concerns of air pollution during the Diwali festival have been mainly focused on ambient air pollution; however, because of proximity during the burning of firecrackers, the personal exposure levels to air pollutants are likely to be very high. Children in particular burn the sparklers and pulpuls while holding the firecracker in the hand, barely a foot away from the breathing zone. The naag-goli is also burnt within a couple of feet from the source. Chakri, anar, and the laad are often burnt from a distance of a few feet. To the best of our knowledge, this is the first study that measured and compared the personal exposure levels of $PM_{2.5}$ during the burning of different types of individual firecrackers in a real-world setting using multiple sets of experiments.

The levels of $PM_{2.5}$ measured at the breathing zone that simulates real-life personal exposure levels during the burning of firecrackers were found to be extremely high. Although burning of most of these firecrackers lasted for around a minute or so only, the peak exposure levels were extremely high, varying from 4860 mcg/m^3 to 64,500 mcg/m^3, while the median levels varied between 1866 and 39,630 mcg/m^3.

The snake tablet burnt for only 9 s but produced peak $PM_{2.5}$ levels of 64,500 mcg/m^3 that lasted for 3 min at the breathing zone distance. Snake tablets are quite popular

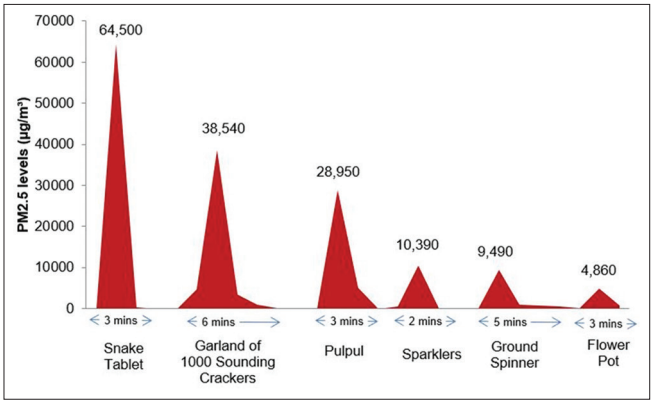

Figure 3: Duration of exposure and peak particulate matter <2.5 μm in mass mean aerodynamic diameter levels for each of the firecrackers

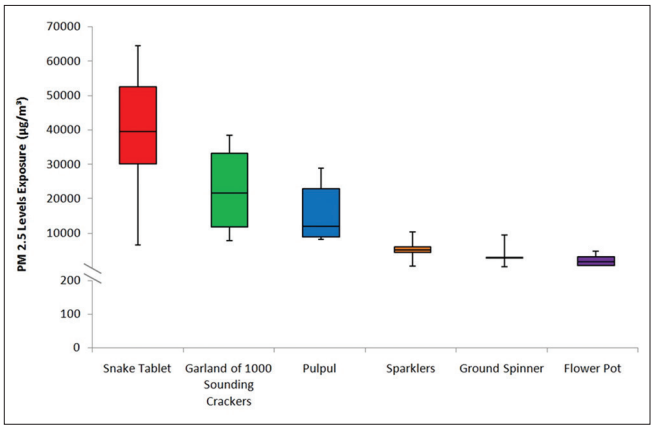

Figure 4: Box–Whisker plot showing summary statistics of peak exposure experiment for different types of crackers (maximum exposure for each of five repetitive experiments)

among children as they are very cheap, but they produce a thick black smoke upon burning. A child breathes around 300 mL of air with every breath and does so around 20 times a minute; hence, over a period of 3 min, a child would have inhaled around 18–20 L of this extremely polluted air into the lungs.

Children love to burn sparklers in their hands and very often burn two at a time. While doing so, they are exposed to a huge dose of over 10,000 mcg/m^3 of $PM_{2.5}$ over a period of 2 min while burning one sparkler. When they burn a dozen of these sparklers, they are exposed to a massive personal dose of over 10,000 mcg/m^3 for at least over 45 min, not to forget the additional $PM_{2.5}$ dose coming from the burning of other firecrackers in parallel.

The least polluting firecracker was the flower pot, which produced peak $PM_{2.5}$ levels of 4800 mcg/m^3, which is also way above any safety limits. The reason why the flower pot produced the least amount of $PM_{2.5}$ was because the pollution monitor was kept at a height of 3 feet and distance of 6 feet to simulate a real-life exposure. Although the flower pot produces massive amounts of smoke, it is all pushed upward and the smoke therefore remains at a much higher distance. While this firecracker may increase the ambient levels of $PM_{2.5}$ hugely, personal exposures are smaller compared to other firecrackers. The garland of 1000 sounding firecrackers and the chakris are burnt on the ground surface and therefore produce very high levels of $PM_{2.5}$ at the breathing zone, thereby exposing a large number of people to its harmful effects.

Our study primarily focused on personal exposures to $PM_{2.5}$ during the burning of different types of individual firecrackers, and we report extremely high levels of personal exposures. When many such firecrackers are burnt in parallel at the same time as happens in real life, the dose of personal exposures to $PM_{2.5}$ will be even greater. Such massive exposures to $PM_{2.5}$ over a short period may have significant adverse health effects that can vary from short-term effects to long-term effects. Children with already compromised lungs such as those having asthma or underlying respiratory tract infections, adults with underlying chronic lung diseases such as asthma and COPD, those having underlying cardiovascular disease, and the elderly with compromised lung defenses are likely to be the most vulnerable population to the harmful effects of Diwali firecrackers.

We only measured $PM_{2.5}$ levels during the burning of individual firecrackers. The composition of the $PM_{2.5}$ is likely to vary between each firecracker, and it is likely that different components of $PM_{2.5}$ may have different adverse health effects. Various types of metals are added to the firecrackers to produce different colors, and each of these metals may likely have differential adverse health effects. Apart from $PM_{2.5}$, firecrackers produce a variety of different gaseous pollutants, including SO_2, NOx, CO, and ozone, which we did not measure in this study. In an earlier study, we measured the levels of SO_2 in a residential society during the Diwali festival and reported levels of 5.5 parts per million, which are 200 times above the safety limits prescribed by the World Health Organization (personal unpublished data). Burning of Diwali firecrackers produces a wide variety of different air pollutants, the collective effects of which will be much greater on health than individual pollutants. Although this is one of the major limitations of the study, $PM_{2.5}$ on its own is considered to be a major air pollutant with the most significant adverse health effects.

CONCLUSION

Our study is the first to show that dose of personal exposures to $PM_{2.5}$ during the burning of individual firecrackers is extremely high. The snake tablet was found to produce the highest $PM_{2.5}$ pollution, followed by the garland of 1000 crackers, pulpul, sparklers, chakri, and flower pot. Such massive bursts of short-term personal exposures are likely to have significant short-term and long-term health effects, especially among children, those with underlying chronic lung diseases, those with cardiovascular diseases, and the elderly. It makes prudent sense to avoid the burning of firecrackers during the Diwali festival, and we believe that the banning on the sale of firecrackers by the Supreme Court in 2017 is a step in the right direction.

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Conflicts of interest

There are no conflicts of interest.

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