Chemical characterization of PM$_{10}$ and PM$_{2.5}$ combusted firecracker particles during Diwali of Lucknow City, India: air-quality deterioration and health implications

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Abstract
Urban air pollution is a growing menace leading to human discomfort, increased hospitalizations, morbidity, and mortality. This study deals with deteriorated air quality due to firecracker bursting during Diwali in Lucknow. Inhalable particulates and gaseous pollutants were monitored during Diwali 2020 using air samplers. Elements, ions, and surface morphology of particles were analyzed using ICP-MS, ion chromatograph, and SEM-EDX, respectively. PM$_{10}$, PM$_{2.5}$, SO$_2$, and NO$_2$ were 558, 352, 44, and 86 μg/m$^3$ during Diwali night and 233, 101, 17, and 40 μg/m$^3$ on pre-Diwali night while 241, 122, 24, and 43 μg/m$^3$ on Diwali day. Concentrations surged for PM$_{10}$: 139% and 132%, PM$_{2.5}$: 249% and 189%, SO$_2$: 159% and 83%, and NO$_2$: 115% and 100% on Diwali night compared to pre-Diwali night and corresponding Diwali day, respectively. Al, K, Ba, and B showed dominance in PM$_{10}$ whereas Zn, Al, Ba, and K in PM$_{2.5}$ on Diwali night. The order of metal abundance in PM$_{2.5}$ was Cd < Co < Ag < As < Cr < Ni < Cu < Bi < Pb < Mn < Sr < Fe < B < Zn < Al < Ba < K. Cations NH$_4^+$, K$^+$, Mg$^{2+}$, Ca$^{2+}$, and anions F$^-$, Cl$^-$, NO$_3^-$, Br$^-$, NO$_2^-$, SO$_4^{2-}$, PO$_4^{3-}$ showed a 2–8 fold increase on Diwali night relative to pre-Diwali night. Average metal concentrations varied by 2.2, 1.6, and 0.09 times on Diwali than pre-Diwali in residential, commercial, and industrial areas, respectively. PM$_{10}$ concentration increased by 458% and 1140% while PM$_{2.5}$, 487%, and 2247% than respective NAAQS and WHO standards. Tiny firecracker particles vary in toxicity as compared to vehicular emissions and have enhanced bioavailability leading to severe threat in terms of LRI, COPD, and atherosclerosis for city dwellers. It is imperative to recognize the present status of ambient air quality and implement regulatory strategies for emission reduction.

Keywords Diwali · firecracker · elements · ionic species · particulate pollution

Introduction
The celebration of Diwali with the burning of firecrackers across India is a commemoration of the return of Lord Rama to his kingdom after 14 years of exile and subsequent victory over the mighty devil king, Ravana. It is celebrated during the astral months of Ashvina and Kartika (October–November) and is believed to be symbolic of the victory of good over evil in Hindu mythology. This festival is marked by bright festive lights, firing of crackers, and lighting of bonfires. This festival is also celebrated in different parts of the world viz. Singapore, Malaysia, the USA, and many other countries. The burning of firecrackers during the nights of the 3–4 day-long Diwali celebration has become an inseparable component of the festivities, and with the development of knowledge base regarding ambient air pollution, the adverse impact of such activities has become conspicuous.
Also, the festival is concurrent with the onset of the winter season when unfavorable atmospheric conditions like high humidity, low temperatures, calm winds, and the occurrence of nighttime inversion layer reduce the mixing height to ~250 m from the ground (Jayamurugan et al. 2013), restricting the vertical and horizontal dispersal of pollutants.

Pyrotechnics obtain their colorful radiance from different temperatures of hot glowing metals, and from the light emitted by burning chemical compounds. Apart from these, firecrackers contain strong oxidizers like nitrates, chlorates, or perchlorates (potassium nitrate, potassium chlorate, or potassium perchlorate) which supply oxygen to facilitate combustion. After bursting, firecrackers release different sizes of particles ranging from non-inhalable (> 100–10 μm) to inhalable (<10–1 μm) and ultrafine particles (<0.1 μm). Firecracker combustion particles are mixed or crusted with metallic and non-metallic compounds and vary in chemical composition as compared to particles generated during other seasons and activities.

The urban population is routinely exposed to severe episodes of air pollution (WHO 2018; Burnett et al. 2018) which rises unprecedentedly during high-impact events like the Diwali celebration, leading to increased hospital admissions and even mortality. The burnt firecracker particulates reach up to the alveolar sac by way of penetrating deep into the lungs from where they get transported to other organs through blood circulation and cause systemic poisoning. Air pollution primarily causes diseases like asthma, chronic obstructive pulmonary disease (COPD), lower respiratory infections (LRIs), allergies, and even death in extreme cases (Lelieveld et al. 2015). Air pollutants present in the atmosphere damage the climate and environment, while also causing harm to human health and other living organisms.

In India, 12 critical pollutants are monitored to evaluate the air quality of a particular location viz. PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, CO, NH$_4$, O$_3$, C$_6$H$_6$ (benzene), BaP (Benzo-a-pyrene, a carcinogenic polyaromatic hydrocarbon), and particle-phase metals Pb, Ni, and As. Some other significant pollutants viz. carbon dioxide (CO$_2$), methane (CH$_4$), chlorofluorocarbons (CFCs), ammonium and nitrate salts, and biological molecules (pollen grains, bacterial/fungal/algal spores, etc.) are also present in the atmosphere and need to be monitored. The concentrations of PM$_{2.5}$, i.e., fine particulate matter and nanoparticles (0.001 μm), are of utmost concern because of their size and greater interactive surface area with respect to their mass (Xu et al. 2022; Burnett et al. 2018; Liu et al. 2017). There are notable persistent sources of fine particles over urban areas such as industrial and vehicular emissions, stubble/trash burning, use of coal/kerosene/biofuels for heating and cooking, and roadside restaurant emissions (Singh and Chauhan 2020; Kumari et al. 2019; Gurjar et al. 2016). It was observed that during the COVID-19 infection period, South Italy suffered fewer casualties than North Italy. One of the several explanations offered by experts is attributed to the higher loading of fine particulate matter during the infection spreading period which acted as “carrier of the virus particle” (Comunian et al. 2020; Al Huraimel et al. 2020; Ali and Islam 2020; Mahato and Ghosh 2020). Both PM$_{10}$ and PM$_{2.5}$ are inhalable, and their concentrations (pre-COVID-19) in most urban cities were often 4 to 6-fold higher in comparison with the National Ambient Air Quality Standards (NAAQS). Regulatory measures have resulted in little success in the management of air pollution because the characteristics of the source of pollutants are often complex to understand, and their respective pollution loads in the atmosphere are difficult to estimate.

Adding to the menace, the multifaceted emission profiles of firecrackers along with their intricate metal and non-metal ratios offer a substantial challenge to the researcher involved in the quantification of their atmospheric loading. In this context, green crackers are said to be 30% less polluting than normal crackers regarding PM emissions and seem to be the only safe alternative to ensure a “less-polluting Diwali.” Reduced pollution caused by green crackers can be attributed to the replacement of harmful compounds like potassium nitrate and barium nitrate and metals like lithium, antimony, arsenic, mercury by their lesser polluting alternatives like copper and nitrogen-bearing compounds (Steinhauser and Klapötke 2008). The impact of firecrackers on air quality during Diwali has been studied by different authors in many parts of India (Kotnala et al. 2021; Sateesh et al. 2018; Parkhi et al. 2016; Chatterjee et al. 2013; Thakur et al. 2010). During this time duration, an abrupt deterioration of urban air quality due to the bursting of firecrackers and consequent increase in carbon monoxide, carbon dioxide, and other pollutant levels can be witnessed. Pollutant build-up happens, and consequently, levels of oxygen drop in the breathing zone. Urban air becomes toxic to inhale and remains as such for a few days without any sign of improvement.

Keeping this in view, an attempt is made to measure the magnitude of air quality deterioration by monitoring particles and gaseous pollutants during the Diwali festival days. In the present study, seven locations representing air pollution hotspots across Lucknow city were identified for monitoring of particles (PM$_{2.5}$ and PM$_{10}$), gaseous pollutants (SO$_2$ and NO$_2$), 17 metallic elements, and 10 water-soluble cationic and anionic species during Diwali, 2020 with the following objectives: (i) to determine the concentrations of particles (PM$_{10}$ and PM$_{2.5}$) and gases (SO$_2$ and NO$_2$) during Diwali day and night times, (ii) to find out the relative abundances of water-soluble cations and anions and 17 other elements linked with PM$_{10}$ and PM$_{2.5}$ aerosol during pre-Diwali as compared to Diwali and post-Diwali concentrations, (iii) to identify the pattern of potential chemical markers for cracker emissions in ambient PM$_{10}$ and PM$_{2.5}$.
and (iv) to increase mass awareness about firecrackers that choke the city’s atmosphere and subsequent adverse health effects faced by urban dwellers.

**Materials and methods**

**Study area and sampling locations**

The study of air monitoring during Diwali was carried out at 7 categorically diverse areas of Lucknow city. Lucknow is the capital of the most populous province of India, Uttar Pradesh. It is a popular commercial and industrial hub housing many industries in Northern India. It is spread over an area of 631 sq km and is the 11th most populous city of India. The current population is close to 3.0 million and is expected to increase to around 3.5 million by the year 2035 considering a decadal growth rate of ~ 20%. The river Gomti flows across the city, and the city has a subtropical climate. The average annual rainfall is ~ 100 cm, ambient temperatures 35–45 °C during summer and 3–18 °C in the winters. The urban air pollution
sources can be grouped as point sources (industrial emission), and line sources (from vehicular traffic). Besides, there are numerous non-point as well as fugitive emission sources viz. from the city railway stations, diesel shades, airport terminal, trash, and solid waste burning, burning of bio-fuels for domestic cooking/heating, plying of old phased out vehicles, coal/tire burning during winters, traditional cremation practices using semi-dried wood, building/infrastructure construction, cookstove emissions, roadside restaurants, traffic jams, haphazard urbanization and industrialization, lack of long-term city planning, frequent digging and road cutting, and narrow congested roads. Moreover, the lack of a sensible public attitude towards a clean and green environment is also a contributing factor leading to escalating ambient pollution levels. Sometimes, especially during the winter season, the city gets covered by a pollution dome that persists for a few days due to the formation of thermal inversion which lowers atmospheric mixing height. The air sampling locations with geographical coordinates are shown in Fig. 1 and Table 1.

| Sampling site | Coordinates         | Urban category |
|---------------|---------------------|----------------|
| Aliganj       | 80°56'38" N 26°53'57" E | Residential area |
| Vikas Nagar   | 80°57'53" N 26°53'43" E | Residential area |
| Gomti Nagar   | 81°00'21" N 26°51'22" E | Residential area |
| Charbagh      | 80°55'48" N 26°50'28" E | Commercial area |
| Alambagh      | 80°53'44" N 26°48'16" E | Commercial area |
| Aminabad      | 80°55'28" N 26°50'53" E | Commercial area |
| Amausi        | 80°52'17" N 26°46'10" E | Industrial area |

Fig. 2 Field sampling and analytical instruments used for the study
Quality assurance and quality control

Calibrated sampling instruments were used for this investigation. Before sampling, samplers were operated for 8 h to check electronic and pneumatic components. Filter papers (Teflon and EPM) used were procured from Whatman, USA, since they offer a good flow rate and minimum bias during chemical speciation. Sampled filters were analyzed at the earliest to avoid cross-contamination and analytical errors. All sampled filters were kept in desiccators to remove the moisture content and were subjected to similar pre- and post-conditioning before weighing. Standard AR chemicals and reagents with impurities restricted to trace levels were used during analytical procedures and were procured from Merck, Delhi. Glasswares were cleaned using chromic acid and Milli-Q water and were free of contaminants. Precision and accuracy were maintained by analyzing replicates. Sample blank and triplicate samples were tested on inductively coupled plasma coupled with mass spectrometry (ICP-MS) for metal estimation. Instruments were calibrated and validated regularly. Limit of quantification, below detection limit, and limit of detection were ensured before the final calculation of results for heavy metals. Through repetition, the error percentage is assumed to be within 2.5%.

Monitoring and analysis of particulates

The air samplers were placed approx. 10 feet above ground level to avoid ground-level turbulence. Particulate matter monitoring for PM \(_{10}\) and PM \(_{2.5}\) was carried out for 12 h duration during daytime (06:00 a.m. to 06:00 p.m.) and nighttime (06:00 p.m. to 06:00 a.m.), respectively at 7 sampling locations following the NAAQS monitoring and analysis guidelines Volume-I by Central Pollution Control Board (CPCB), New Delhi. At each location, calibrated respirable dust sampler (Model-460 BL, Envirotech, New Delhi) was operated at a flow rate of 1.0–1.2 m\(^3\)/min for PM \(_{10}\) collection whereas a flow rate of 16.67 l/min was maintained in the fine particulate sampler (Model AAS 127 MINI, Ecotech, New Delhi) for collection of PM \(_{2.5}\) particles. Pre-conditioned and pre-weighed (8-inch \(\times\) 10-inch) EPM 2000 filters and 47 mm-diameter Quartz/Teflon-ringed PTFE filters were used for the collection of PM \(_{10}\) and PM \(_{2.5}\) respectively. A graphical image of materials and methods is shown in Fig. 2. After sampling, gravimetric analysis of sampled filters was carried out to establish the concentrations of particulate matter in ambient air and expressed in \(\mu g/m^3\).

\[
\text{Concentration (\(\mu g/m^3\)) of } PM_{10}/PM_{2.5} = \frac{(\text{Final Filter Weight} - \text{Initial Filter Weight}) \text{in gm}}{\text{Vol.of air sampled, m}^3} \times 10^6
\]

Monitoring and analysis of gaseous pollutants

Sulfur dioxide and oxides of nitrogen were collected using additional gaseous sampling attachment with RDS having sodium hydroxide and trichloromercurate absorbing media for NO\(_2\) and SO\(_2\), respectively. They were analyzed following IS-5182 Part-II for SO\(_2\) and Part-VI for NO\(_2\). Color intensity was measured by UV-Vis spectrophotometer (Labman, Dynamica Scientific Limited). The blue-purple pararosaniline methyl sulfonylic acid complex formed by SO\(_2\) was read at 560 nm whereas the stable pink azo dye formed by NO\(_2\) was read at 540 nm.

Analysis of elemental constituents associated with particulate matter

For elemental constituents, 129 punched-out samples (126 representing day and night time matured filters of pre-Diwali, Diwali, and post-Diwali +3 filter blanks) were analyzed. A total of 17 elements were detected in the samples. Three 50-mm diameter circles were punched out from a 20 \(\times\) 25-cm sampled filter, and another three 5-mm diameter circles were punched out from a 47-mm-diameter filter to determine the PM \(_{10}\) and PM \(_{2.5}\) associated elemental concentrations (Zarandi et al. 2018; Sharma et al. 2015). This was done in order to proportionally reflect the targeted characteristics of the PM load as well as to maintain precise representative sample for each filter analyzed. Circular punch-outs were dipped in a flask containing 20-ml digestion mixture of HClO\(_4\)/HNO\(_3\) (v/v 1:4) and gently refluxed to dryness on a hot plate until the appearance of white fumes from the samples. The contents of the flask were washed down and made up to 10 ml using 1% HNO\(_3\) post-filtration through a Whatman 42 filter. The filtrate was subjected to ICP-MS for the estimation of elemental constituents. The ICP values of the blank filter of each metal were deducted from the sample value for final calculations.

Analysis of water-soluble ionic constituents

Ion chromatography is a modern analytical tool to provide complete and accurate information on the ionic compositions of samples. It utilizes two different sets of conditions for the separation and determination of the ionic species, respectively. Water-soluble ionic species (cations and anions) were extracted from PM \(_{10}\) and PM \(_{2.5}\) filters using an ultrasonic extractor for 60 min.
Single-punch each of 50 mm-diameter for PM_{10} and 5 mm-diameter for PM_{2.5} filters was used for extraction of ionic species in 20 ml and 10 ml of Milli-Q water, respectively. Extracted solutions were filtered through a syringe filter (Whatman) having 0.22-μm pore size and subjected to ion chromatography (Metrohm-conductivity channel, Germany) analysis. Values of anions and cations were analyzed by ion chromatography coupled with 940 Professional IC Vario1 and 945 Professional IC Vario1 while MetrosepA Supp 5-250/2.0 column and MetrosepB-Supp 5-250/2.0 column were used for anions and cations, respectively. The flow rate was 1.0 ml/min, and the run time was 30 min. The temperature of the column was 35 °C and pressure 5MPa.

**SEM-EDX analysis**

Two samples of PM_{2.5} for 12 h representing normal night time and Diwali night time were subjected to SEM-EDX analysis. The SEM-EDX analysis was carried out with the help of computer-controlled field emission scanning electron microscope (FE-SEM, QUANTUM FEG 450, FEI, the Netherlands) equipped with an energy-dispersive X-ray system. All samples were placed on a conducting carbon tube over an aluminum shell. Samples were coated with platinum coater (SC7620, QUANTUM Technology, UK) and were examined under FE-SEM (Quanta FEG 450, FEI, the Netherlands) coupled with EDX for their surface morphology and elemental analysis.

**Meteorological parameters**

Weather conditions especially relative humidity, wind speed and direction, temperature, rainfall, and solar radiation play a key role in the dispersal and dilution of air pollutants released into the atmosphere. Meteorological data of Lucknow was collected from the automatic weather stations set up by CPCB, Lucknow. The observation of meteorological parameters was based on hourly data input during day and night time, and their mean values were calculated for 12 h. The wind rose diagrams were drawn to graphically display wind speed and direction and frequency of wind speed for the Lucknow region during the Diwali period.

**Statistical analysis**

Pearson correlation analysis and ANOVA were performed to determine the relationship among heavy metal concentrations associated with both PM_{10} and PM_{2.5} particles by using IBM SPSS ver.26 software. It aims to summarize the linear relationship of the pre-Diwali night with Diwali night and post-Diwali night with Diwali night. Such measurements highlight the cumulative residence time of environmental contaminants associated with the firecracker event (Garg and Gupta 2018; Singh et al. 2010). Statistical tests with the single factor analysis of variance (ANOVA) between all heavy-metals of PM_{2.5} and PM_{10} samples were performed to access the statistical significance among different groups (pre-Diwali, Diwali, and post-Diwali samples) and the significance reported ($P < 0.05$ and $P < 0.01$).

**Results and discussion**

**Particulate concentration**

The average daytime PM_{10} concentrations measured during pre-Diwali, Diwali, and post-Diwali for all seven locations ranged from 119.4 to 302.4 (avg. 222.5 ± 59.9), 202.3 to 271.4 (avg. 240.9 ± 20.8), and 216.7 to 378.2 (avg. 278.7 ± 58.4) μg/m³, respectively, whereas average daytime PM_{2.5} concentrations were 59.9 to 145.9 (avg. 100.3 ± 24.6), 48.2 to 164.8 (avg. 121.8 ± 39.8), and 112.8 to 244.5 (avg. 155.2 ± 44.3) μg/m³, respectively. The corresponding values of night time PM_{10} concentrations were 191.3 to 272.1 (232.8 ± 25.9), 315.8 to 913.7 (avg. 558.0 ± 224.0), and 139.9 to 270.9 μg/m³ (avg. 196.2 ± 44.5) respectively, while those for PM_{2.5} were 52.8 to 151.4 (101.4 ± 28.0), 173.6 to 652.9 (avg. 352.0 ± 183.6), and 78.9 to 141.2 (avg. 96.1 ± 19.2). During Diwali period, the concentrations of PM_{10} exceeded by 458% and 1140% than NAAQS (100 μg/m³) and WHO (45 μg/m³) while PM_{2.5} exceeded by 487% and 2246% than NAAQS (60 μg/m³) and WHO (15 μg/m³) standards respectively.

Table 2 and Fig. 3 show the concentrations of PM_{10} and PM_{2.5} and their associations with meteorological parameters during Diwali. The average night-time concentrations of PM_{10} values surged exorbitantly by 130.3%, 203.9%, and 64.2% w.r.t. average day time PM_{10} concentrations while the night-time average of PM_{2.5} concentrations exceeded their corresponding day time values by 295.9%, 242.4%, and 43.7% for residential, commercial, and industrial areas respectively. The highest spike, 57.3% in PM_{10} concentration was found in commercial area during Diwali daytime. Furthermore, the highest spike of PM_{2.5} concentration by 198.7% and that of PM_{2.5} concentrations by 314.3% was found in commercial area during Diwali night.

Ambient temperatures greatly fall during the winter season in northern areas of India due to infiltration of northern Himalayan cold front winds. Furthermore, night-time drop in air temperatures coupled with decreased mixing height or formation of inversion layer facilitates the build-up of aerosol particles along with their toxic components near the ground surface. Such a phenomenon is the causative factor behind the increased toxicity of nighttime emissions as in the case of Diwali. Furthermore, lowered wind speed during...
the night restricts particle dispersal which further augments the surface loading of aerosol particles. On the contrary, day time increase in mixing height owing to the higher temperature and increased wind speed dilutes the surface aerosol concentrations.

The aforementioned causative factors lower the Diwali day aerosol concentrations as compared to night time; however, during post-Diwali day time, the aerosol load remains intensified and is attributed to the emissions of the previous night (Chatterjee et al. 2013). PM$_{10}$ aerosol showed...
maximum Diwali (558.0 μg/m³) night concentration followed by pre-Diwali (232.8 μg/m³) and post-Diwali (196.2 μg/m³). The pre-Diwali, Diwali, and post-Diwali night concentrations of PM₁₀ were 2.3, 5.6, and 2.0-fold higher than the permissible NAAQS of 100 μg/m³. Maximum bursting of firecrackers occurred during Diwali night followed by pre-Diwali and post-Diwali nights, and subsequent particulate concentrations indicate the impact of fireworks on atmospheric PM loading (Kotnala et al. 2021). Furthermore, daytime particulate concentrations tend to remain constant owing to little change in daytime activities even during the festive period. Results for the spike in particulate concentration hold close likeness to values reported in earlier studies (Chauhan and Singh 2017; Pervez et al. 2016; Chatterjee et al. 2013; Perrino et al. 2011; Sarkar et al. 2010; Singh et al. 2010) which are attributable to augmented emissions coming from firecracker bursting during Diwali. Besides, the 24-h mean particle concentration at all locations during the pre-Diwali, Diwali, and post-Diwali days were significantly higher than NAAQS. Health impacts to the exposed population during the festival days have extensively been studied by several researchers (Prakash et al. 2019; Beig et al. 2013; Sarkar et al. 2010; Ravindra et al. 2003). Studies conducted in India on Diwali festival estimated an increase in ratios of cardiovascular and respiratory mortalities to those of normal days by up to ~ 3.5 (Beig et al. 2013). Similarly, Gurjar et al. (2010) estimated an increase of 1600 cases per year in Delhi around the festive season.

As an atmospheric phenomenon, larger and heavier particles tend to settle by gravitational force whereas the major fractions of fine and ultrafine particles remain suspended as aerosol for more than a week. The atmosphere worsens due to the additive impact of the burning process of firecrackers every evening for 3 to 4 days of the festival. Cumulative trends indicate the use of green crackers, as has been prompted by both govt. organizations and non-govt. bodies alike, is one of the means to prevent ambient air pollution caused during Diwali. Owing to a reduction in use or absence of toxic chemicals, green crackers can be understood to be the only safe alternative to ensure a “less-polluting Diwali”. In this context, CSIR-National Environmental Engineering Research Institute introduced green crackers with improved formulation promising a 30% reduction in particulate matter emission and significant reduction in NO₂ and SO₂. Also, thermite-driven crackers using self-continuing exothermic reactions pitch a 70% emission reduction as opposed to their non-green counterparts (Junghare et al. 2022; Steinhauser and Klapötke 2008).

Many epidemiological studies have established the fact that increased particulate concentration is directly associated with hospitalization and mortality for respiratory and cardiovascular diseases and a decrease in lung function (Prakash et al. 2019; Beig et al. 2013; Perrino et al. 2011). Also, the fine particulate pollution typically acts as a medium to disseminate the viruses and keep them in the atmosphere for a certain period and is also a cause for the pandemic (Comunian et al. 2020; Zhou et al. 2020).

### Gaseous concentration

The day and night averages of SO₂ (μg/m³) for all locations on pre-Diwali, Diwali, and post-Diwali were 18.8 ± 4.0, 24.0 ± 9.5, and 29.2 ± 5.2 μg/m³ and 16.7 ± 3.8, 43.7 ± 4.7, and 16.7 ± 1.9 μg/m³, respectively. Similarly, the NO₂ averages were 30.8 ± 6.5, 42.9 ± 3.7, and 58.9 ± 15.2 μg/m³ for daytime and 40.0 ± 11.4, 85.5 ± 14.1, and 45.2 ± 7.1 μg/m³ for nighttime, respectively. The average night-time concentrations of SO₂ on Diwali night exceeded their corresponding daytime values by 141.8, 177.6, and 9.4 % for residential, commercial, and industrial areas, respectively. The corresponding increment in NO₂ values was that of 115.1, 116.2, and 64.9%, respectively. As compared to pre-Diwali night, the average concentrations of SO₂ and NO₂ increased by 161.7% and 113.8% on Diwali night and dropped by 61.8% and 47.2%, respectively, on post-Diwali night. The highest spike in Diwali nighttime values above corresponding pre-Diwali values of 244.4% and 125.1% was in the commercial area for SO₂ and NO₂ each. Table 3 and Fig. 4 represent SO₂ and NO₂ concentrations and their associations with meteorological parameters during Diwali.

Ravindra et al. (2003) had reported a 10-fold increase in SO₂ concentrations and a 3-fold increase in NO₂ concentrations during Diwali in Haryana. SO₂ in ambient air in such high concentrations with high humidity conditions might lead to the formation of sulfate ions (particulate form) by the process of photochemical oxidation (Pervez et al. 2016). Meanwhile, the concentrations of NO₂ showed a relatively lower spike compared to SO₂ which might be attributed to the fact that firecrackers primarily contain sulfur-bearing compounds (Prakash et al. 2019; Wang et al. 2007) as compared to nitrogen-bearing compounds.

On the one hand, firecrackers consume a lot of oxygen to burst, and on the other hand, they produce a substantial amount of carbon monoxide, PAHs, SO₂, NOₓ, and CO₂ resulting from incomplete combustion (Mandal et al. 2021). Spontaneously, moisture gets absorbed on particles/gas molecules which may produce toxic secondary pollutants. Moisture increases the density of pollutants while reducing their buoyancy in air which leads to their fallout and accumulation in the breathing zone. Hence, the population is exposed to a higher concentration of pollutants during morning hours as compared to daytime. Moreover, since CO₂ is relatively heavier than air, it remains in the breathing zone reducing and replacing the ground-level oxygen molecules. CO is the cause

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of cold and cough, PAHs cause eye irritation, and the surge of pollutants has synergistic effects on respiratory and cardiovascular systems. Besides these, several other forms viz. carcinogenicity, neurotoxicity, mutagenicity, and teratogenicity have been reported earlier (Låg et al. 2020; Khaparde et al. 2012).

### Elemental constituents

The increased elemental concentrations on Diwali night as compared to pre-Diwali night spanned across many elements. Metallic concentrations viz. Cu, As, K, Pb, Zn, Al, Sr, Ba, and Bi showed an increase of 1.05, 1.19, 1.46, 1.54,
**Fig. 5** Concentrations of metals associated with PM$_{10}$ particles during Diwali festival

**Fig. 6** Concentrations of metals associated with PM$_{2.5}$ particles during Diwali festival
1.58, 2.59, 10.81, 14.73, and 35.97-fold, respectively. Order of abundance of the elemental constituents is Cd < Co < Ag < As < Cr < Pb < Mn < Cu < Bi < Ni < Sr < Fe < Zn < B < Ba < K < Al with respect to PM$_{10}$ and Cd < Co < Ag < As < Cr < Ni < Cu < Bi < Pb < Mn < Sr < Fe < B < Zn < Al < Ba < K with respect to PM$_{2.5}$. Figs. 5 and 6 represent PM$_{10}$ and PM$_{2.5}$ associated metal concentrations during the Diwali festival.

Firework bursting during pre-Diwali and Diwali night has a strong influence on the metal concentrations during this period. The findings of this investigation are in corroboration with other researchers, reported at different time points (Tsai et al. 2012; Perrino et al. 2011; Sarkar et al. 2010; Vecchi et al. 2008). However, the daytime concentrations of the metals were augmented during post-Diwali days from pre-Diwali owing to nighttime Diwali emissions. Metal constituents associated with particles have detrimental effects on almost all organ systems in the human body, causing systemic poisoning and even inducing toxic and carcinogenic effects from time to time. Toxic compounds released during the Diwali festival make the atmosphere unfit for human beings, especially for susceptible elders and infants and people suffering from asthma/bronchitis, respiratory and cardiovascular impairments, and animals (Singh et al. 2010). Fe, Ni, Cr, Cu, Zn, etc. are transition metals that cause the production of reactive oxygen species in cells, leading to cell damage (Zeng et al. 2016; Chen and Lippmann 2009). Lead, included in NAAQS-2009 due to its respiratory, neurological, and carcinogenic effects on human health, is regulated by the standard of 1000 ng/m$^3$ (CPCB 2020). Cr, Zn, Co, etc. are certain other elements not governed by any regulation at this moment. The ratios of 12-h average nighttime (6 P.M.–6 A.M.) concentrations of elements associated with PM$_{10}$ and PM$_{2.5}$ aerosols during pre-Diwali, Diwali, and post-Diwali are shown in Table 4.

### Water-soluble ionic constituents

Cations ($\text{NH}_4^+$, $\text{K}^+$, $\text{Mg}^{2+}$, $\text{Ca}^{2+}$) and anions ($\text{F}^−$, $\text{Cl}^−$, $\text{NO}_2^−$, $\text{Br}^−$, $\text{NO}_3^−$, $\text{SO}_4^{2−}$, $\text{PO}_4^{3−}$) associated with PM$_{10}$ and PM$_{2.5}$ were determined by ion chromatography for pre-Diwali, Diwali, and post-Diwali day and night times at commercial, residential, and industrial areas, and the analyzed data are summarized in Tables 5, 6, and 7. Similar to PM$_{10}$ and PM$_{2.5}$ concentrations, the water-soluble cationic and anionic species also registered a 2- to 8-fold higher levels on Diwali night when compared to pre-Diwali night. The acidic/basic nature of aerosols can be determined by calculating the cation-anion ratio in terms of micro equivalents, which was carried out following a standardized procedure from earlier

**Table 4** The ratio of metal concentrations associated with PM$_{10}$ and PM$_{2.5}$ during Diwali

| Element | Residential area | Commercial area | Industrial estate |
|---------|-----------------|-----------------|--------------------|
|         | Pre-Diwali | Diwali | Post-Diwali | Pre-Diwali | Diwali | Post-Diwali | Pre-Diwali | Diwali | Post-Diwali |
| B       | 2.2       | 1.8    | 2.4       | 1.8       | 1.8    | 2.1       | 1.5       | 2.0       | 3.0       | 8.6     |
| K       | 1.4       | 3.2    | 1.9       | 1.4       | 1.9    | 2.8       | 2.1       | 8.8       | 1.7       | 5.6     |
| Cr      | 1.6       | 5.1    | 0.8       | 1.0       | 2.0    | 2.0       | 0.6       | 20.4      | 1.2       | 1.3     |
| Mn      | 1.9       | 3.8    | 0.9       | 0.9       | 2.5    | 0.9       | 31.8      | 0.3       | 0.3       | 2.2     |
| Fe      | 5.7       | 4.5    | 1.9       | 3.0       | 4.2    | 3.2       | 39.1      | 2.0       | 2.0       | 4.9     |
| Co      | 6.6       | 24.0   | 1.2       | 1.2       | 3.8    | 2.0       | 67.8      | 2.4       | 2.4       | 4.4     |
| Ni      | 14.2      | 71.6   | 2.0       | 0.9       | 6.4    | 0.7       | 96.8      | 3.0       | 3.0       | 9.5     |
| Cu      | 7.4       | 8.9    | 2.6       | 1.8       | 6.6    | 3.9       | 69.3      | 3.0       | 6.2       | 3.0     |
| Zn      | 0.1       | 0.9    | 1.4       | 0.4       | 0.2    | 0.5       | 0.5       | 0.1       | 4.4       | 4.4     |
| As      | 1.2       | 2.2    | 0.9       | 0.7       | 4.4    | 1.2       | 9.3       | 1.2       | 2.5       | 2.5     |
| Sr      | 0.6       | 6.0    | 3.2       | 1.4       | 5.5    | 4.3       | 5.1       | 1.9       | 8.3       | 8.3     |
| Ag      | 2.9       | 10.1   | 2.6       | 0.8       | 1.8    | 0.4       | 68.0      | 2.9       | 9.4       | 9.4     |
| Cd      | 7.7       | 5.3    | 2.5       | 8.0       | 5.2    | 4.3       | 16.5      | 2.3       | 6.3       | 6.3     |
| Pb      | 6.4       | 4.9    | 4.2       | 4.5       | 3.9    | 5.2       | 20.5      | 3.0       | 7.6       | 7.6     |
| Bi      | 16.3      | 12.7   | 5.6       | 7.6       | 9.9    | 14.6      | 4.4       | 12.0      | 7.7       | 7.7     |
| Al      | 2.4       | 10.3   | 3.1       | 2.9       | 8.1    | 4.4       | 25.0      | 3.3       | 8.7       | 8.7     |
| Ba      | 0.1       | 3.6    | 0.8       | 0.3       | 2.8    | 0.8       | 0.4       | 0.7       | 2.2       | 2.2     |
| Mn      | 0.06      | 0.87   | 0.75      | 0.33      | 0.24   | 0.35      | 0.35      | 0.10      | 1.32      | 1.32    |
| Max     | 16.25     | 71.62  | 5.61      | 8.04      | 9.88   | 14.60     | 96.81     | 12.00     | 9.47      | 9.47    |
| Avg ± SD| 4.6 ± 4.5 | 10.5 ± 16.6 | 2.3 ± 1.3 | 2.3 ± 2.1 | 4.3 ± 2.4 | 2.9 ± 3.4 | 29.6 ± 28.4 | 2.7 ± 2.6 | 5.8 ± 2.7 |
references (Pervez et al. 2016; Tao et al. 2013; Zhang et al. 2011).

Cation micro equivalents/m³ = \( \frac{NH_4^+}{18} + \frac{K^+}{39} + \frac{Mg^{2+}}{12} + \frac{Ca^{2+}}{20} \)

Anion micro equivalents/m³ = \( \frac{F^-}{19} + \frac{Cl^-}{35.5} \)

Anion/cation (A/C) ratio > 1.0 indicates the particle to be acidic whereas values < 1.0 indicate basic nature (Pervez et al. 2016; Shen et al. 2009). For the PM\(_{10}\) particles, the mean 24-h A/C ratio for non-Diwali days was 0.77 whereas that for Diwali day was 2.22 indicating the acidic nature of the Diwali PM; similarly, values for PM\(_{2.5}\) particles were 2.12 for non-Diwali days and 6.63 for Diwali day. Moreover, 2.37 was the PM\(_{10}\) A/C ratio on Diwali night to 1.0 for the non-Diwali night. PM\(_{2.5}\) had a ratio of 2.05 on Diwali night as compared to 1.99 on non-Diwali nights.

### Table 5 Concentrations of water-soluble ions during Diwali at commercial area

| Ions Name | PM\(_{10}\) | Pre-Diwali | Diwali | Post-Diwali | PM\(_{2.5}\) | Pre-Diwali | Diwali | Post-Diwali |
|-----------|-------------|------------|--------|------------|-------------|------------|--------|------------|
|          |             | Day       | Night  | Day        | Night       | Day       | Night  | Day        | Night     |
| Cation   |             |           |        |            |             |           |        |            |           |
| NH\(_4^+\) | ND          | 3.64      | ND     | 5.38       | 8.57        | 4.21      | 2.04   | 1.67       | 0.72      | 2.40       | 0.76   | 0.56    |
| K\(^+\)   | 1.54        | 3.14      | 3.17   | ND         | 8.15        | 11.46     | 1.27   | ND         | 1.45      | ND         | 3.58   | 1.53    |
| Mg\(^{2+}\) | 0.53        | 0.53      | 0.49   | 1.39       | 0.70        | 1.09      | 0.29   | 0.11       | 0.11      | 0.77       | 0.09   | 0.06    |
| Ca\(^{2+}\) | 2.26        | 3.57      | 1.77   | 2.25       | 3.29        | 2.99      | 0.74   | 0.37       | 0.00      | 1.38       | 0.02   | 0.45    |
| Anion    |             |           |        |            |             |           |        |            |           |            |        |        |
| F\(^-\) | 0.39        | 0.38      | 0.67   | 1.20       | 0.18        | 0.41      | 0.25   | 0.13       | 0.09      | 0.29       | 0.32   | 0.25    |
| Cl\(^-\) | 3.23        | 6.39      | 6.24   | 27.41      | 4.63        | 6.88      | 3.83   | 2.52       | 2.04      | 6.07       | 4.00   | 4.23    |
| NO\(_2^+\) | 0.97        | 5.19      | 3.82   | 0.62       | 2.27        | 0.97      | 0.04   | 3.02       | 0.04      | 0.03       | 0.06   | 0.04    |
| Br\(^-\) | ND          | 0.01      | 0.02   | 8.93       | ND          | ND        | ND     | ND         | ND        | 0.01       | 0.03   | 0.01    |
| NO\(_3^-\) | 9.93        | 5.47      | 9.70   | 14.97      | 7.96        | 6.90      | 3.45   | 3.30       | 3.96      | 6.62       | 7.41   | 5.45    |
| SO\(_4^{2-}\) | 11.77      | 0.00      | 16.37  | 1.86       | 18.68       | 11.33     | 11.29  | 10.02      | 11.17     | 12.04      | 11.23  | 7.32    |
| PO\(_4^{3-}\) | 2.28        | 4.16      | 3.05   | 5.93       | 3.12        | 2.44      | 0.80   | 2.17       | 2.04      | 3.26       | 1.05   | 0.86    |

ND not detected

### Table 6 Concentrations of water-soluble ions during Diwali at residential area

| Ions | PM\(_{10}\) | Pre-Diwali | Diwali | Post-Diwali | PM\(_{2.5}\) | Pre-Diwali | Diwali | Post-Diwali |
|------|-------------|------------|--------|------------|-------------|------------|--------|------------|
|      |             | Day       | Night  | Day        | Night       | Day       | Night  | Day        | Night     |
| Cation |             |           |        |            |             |           |        |            |           |
| NH\(_4^+\) | ND          | 0.99      | ND     | 4.35       | 10.23       | 23.69     | 1.98   | 0.51       | 0.11      | 2.69       | 0.99   | 1.55    |
| K\(^+\)   | 1.77        | 13.52     | 2.30   | 11.23      | 10.42       | 3.53      | 1.47   | 0.00       | 1.63      | ND         | 5.45   | 1.64    |
| Mg\(^{2+}\) | 0.37        | 1.70      | 0.43   | 1.41       | 0.97        | 0.93      | 0.08   | 0.12       | 0.18      | 0.19       | 0.31   | 0.05    |
| Ca\(^{2+}\) | 2.11        | 6.09      | 2.83   | 2.49       | 4.39        | 4.27      | ND     | ND         | 0.03      | 0.23       | 0.01   | 1.74    |
| Anion    |             |           |        |            |             |           |        |            |           |            |        |        |
| F\(^-\) | 0.07        | 0.86      | ND     | 0.73       | 0.29        | 0.59      | 0.37   | 0.20       | 0.34      | 0.30       | 0.48   | 0.40    |
| Cl\(^-\) | 4.08        | 10.87     | 5.68   | 18.07      | 6.47        | 4.38      | 3.70   | 2.09       | 3.65      | 5.16       | 7.83   | 5.67    |
| NO\(_2^+\) | 3.39        | 10.22     | 0.39   | 0.41       | 0.14        | 0.11      | 0.03   | 0.02       | 0.02      | 0.68       | ND     | 0.05    |
| Br\(^-\) | ND          | 1.69      | 0.02   | 3.39       | ND          | ND        | ND     | ND         | 2.25      | 0.01       | 0.05   | ND      |
| NO\(_3^-\) | 4.30        | 3.91      | 11.38  | 12.42      | 5.64        | 12.92     | 3.27   | 2.50       | 3.35      | 2.71       | 9.69   | 2.91    |
| SO\(_4^{2-}\) | 5.81        | 13.34     | 16.95  | 0.99       | 23.41       | 44.63     | 4.94   | 4.88       | 21.48     | 8.22       | 11.54  | 5.95    |
| PO\(_4^{3-}\) | 1.86        | 3.48      | 5.27   | 10.33      | 6.34        | 2.19      | 0.97   | 2.25       | 4.31      | 7.36       | 5.73   | 0.45    |

ND not detected

### Notes

88280

Environmental Science and Pollution Research (2022) 29:88269–88287

88280
SEM-EDX analysis

SEM micrographs and characteristic spectra of some dominant components of particulate matter are shown in Fig. 7. The particle size and numbers of spectra are significantly greater for Diwali micrographs as compared to non-Diwali micrographs. Silica indicates the predominant crustal origin of particulate matter, whereas small spherical agglomerates...
indicate the presence of soot which in turn is indicative of incomplete burning of firecrackers. The presence of the “S” line in the spectrum indicates the presence of sulfates, as it is believed to be formed by the combustion of sulfur-rich firecrackers. The presence of accentuated values of Al, Na, K, Mg, and Ca has been reported earlier (Kumar et al. 2020; Pratap et al. 2020) to indicate firecracker burning during Diwali. The micrograph shows dominant spectra of Si, alkali earth metals such as Al, Na, K, Mg, Ca, and Li which indicate the origin from road dust which is also the dominant source in Lucknow city.

**Meteorological parameters**

The prominent wind direction (speed, frequency) during pre-Diwali, Diwali, and post-Diwali days was north-west (1.5–1.75 m/s, 11.8% and 1.75–2.0 m/s, 7.5%) followed by west (1.5–1.75 m/s, 11.8% and 1.75–2.0 m/s, 7.5%); north (1.50–1.75 m/s, 7.85% and 1.75–2.0 m/s, 3.6%) followed by south (1.75–2.0 m/s, 7.8%); and southeast (1.75–2.0 m/s, 11.7% and 0.5–0.75 m/s, 7.3%) followed by northeast (0.50–0.75 m/s, 7.3%), respectively, as shown in Fig. 8. Calm wind (WS < 0.5 m/s) was recorded for 53.85%, 61.54%, and 38.46% of the times. Calm condition/standstill wind, low temperatures, and high relative humidity prevailed mostly during the Diwali period which reduces the mixing height and chances of vertical dispersal of pollutants into the upper atmosphere (Liu et al. 2022; Murari et al. 2017; Crawford et al. 2016; Tai et al. 2012; Banerjee et al. 2011). As a result, pollutants are trapped in the lower atmosphere, and city dwellers are continuously exposed to high concentrations of lethal gases and particles. Toxic gases are invariably more harmful than particles since organs readily absorb toxic gases.

Moreover, on Diwali day, the wind direction also changed to north-south from north-west subsequently leading to spreading of pollutants to the commercial locations in this direction which might have favored the buildup of pollutants at breathing zone in these locations. Rainfall occurred on the post-Diwali night which led to settling and washout of pollutants to some extent thus neutralizing the pollutant spike for subsequent days.

**Statistical analysis**

Pearson correlation analysis was performed at both 0.05 and 0.01 levels of significance to find out the level of correlation between each heavy metal. The Pearson correlation analysis for PM$_{10}$ associated metals is shown in Table 8. Most of the heavy metals of PM$_{10}$ samples are highly correlated within themselves. The correlation result of pre-Diwali and Diwali night among heavy metals shows that K, Cu, Sr, Mn, Ba, Al, Pb, and Co are highly correlated with Cr, Mn, Ag, Al, and Ba. Results between Diwali night to post-Diwali night showed that B, Cr, Mn, Fe, and Sr are highly correlated with Co, Ni, and Ag. During Diwali night, the huge bursting of firecrackers and vehicular transportation released various pollutants into the atmosphere which led to an increase in heavy metals on Diwali event, correspondingly increasing the correlation among heavy metals.

Correlation between pre-Diwali and Diwali night for PM$_{2.5}$ samples showed that K, Cr, Cu, and Sr is highly correlated with Ag, Cd, Pb, and Al. During Diwali to post-Diwali days, heavy metals like B, K, Cu, and Sr are highly correlated with Zn, As, Pb, Bi, Al, and Ba except for Sr with Hg (r-0.813). Pearson correlation analysis for PM$_{2.5}$ associated metals is shown in Table 9. Correlation results between heavy metals of PM$_{2.5}$ samples during both pre-Diwali to

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**Fig. 8** A wind rose representation of meteorological condition during pre-Diwali, Diwali, and post-Diwali periods
Table 8  Pearson correlation between pre-Diwali and Diwali night for heavy metals associated with PM$_{10}$

|       | PM$_{10}$ | B     | K     | Cr     | Mn     | Fe     | Co     | Ni     | Cu     | Zn     | As     | Sr     | Ag     | Cd     | Hg     | Pb     | Bi     | Al     | Ba     |
|-------|----------|-------|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|-------|
| PM$_{10}$ | 1       |       |       |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| B     | - .561  | 1     |       |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| K     | .627    | .415  | 1     |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Cr    | .344    | .759  | .760  | 1      |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Mn    | .616    | .943** | .654  | .926** | 1      |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Fe    | .410    | .998**| .471  | .782   | .957** | 1      |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Co    | .694    | .946**| .638  | .926** | 1.000**| .958** | 1      |        |        |        |        |        |        |        |        |        |        |        |        |
| Ni    | .660    | .941**| .629  | .932** | .998** | .952** | .999** | 1      |        |        |        |        |        |        |        |        |        |        |        |
| Cu    | .892*   | .704  | .894* | .748   | .814*  | .747   | .800   | .784   | 1      |        |        |        |        |        |        |        |        |        |        |
| Zn    | - .649  | - .041| .520  | .578   | .250   | - .010| .252   | .271   | .183   | 1      |        |        |        |        |        |        |        |        |        |
| As    | .747    | .549  | .851* | .545   | .638   | .596   | .619   | .596   | .962** | .030   | 1      |        |        |        |        |        |        |        |        |
| Sr    | .876*   | - .277| .735  | .152   | - .027| - .216| - .048| - .060| .480   | .406   | .594   | 1      |        |        |        |        |        |        |        |        |
| Ag    | .549    | .961**| .584  | .907*  | .996** | .969** | .997** | .998** | .766   | .210   | .580   | - .115| 1      |        |        |        |        |        |        |
| Cd    | .783    | .501  | .432  | .432   | .504   | .528   | .503   | .486   | .573   | .244   | .526   | .125  | .477  | 1      |        |        |        |        |        |
| Hg    | .052    | - .462| - .670| - .628 | - .573| - .504| - .566| - .550| - .648| - .406| - .586| - .328| - .528| - .737| 1      |        |        |        |        |        |
| Pb    | .869*   | .398  | .957**| .606   | .581   | .455   | .562   | .545   | .931** | .303   | .952** | .767  | .509  | .488   | - .621| 1      |        |        |        |        |
| Bi    | .943**  | - .338| .683  | .080   | - .096| - .280| - .117| - .129| .424   | .358   | .552   | .996**| - .182| .049   | - .248| .723   | 1      |        |        |        |
| Al    | .881*   | .055  | .930**| .513   | .333   | .117   | .314   | .306   | .708   | .564   | .732   | .926**| .249   | .287   | - .545| .902*  | .894*  | 1      |        |
| Ba    | .806    | - .335| .705  | .265   | - .023| - .280| - .039| - .038| .340   | .675   | .380   | .929**| - .104| .023   | - .311| .633   | .920** | .903*  | 1      |

**Correlation is significant at the 0.01 level (2-tailed), *Correlation is significant at the 0.05 level (2-tailed)
Table 9 Pearson correlation between pre-Diwali and Diwali night for heavy metals associated with PM$_{2.5}$

|         | PM$_{2.5}$ | B  | K  | Cr  | Mn  | Fe  | Co  | Ni  | Cu  | Zn  | As  | Sr  | Ag  | Cd  | Hg  | Pb  | Bi  | Al  | Ba  |
|---------|------------|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| PM$_{2.5}$ | 1          |    |    |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| B       | 0.049      | 1  |    |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| K       | 0.887*     | 0.499 | 1  |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Cr      | 0.465      | 0.623 | 0.663 | 1  |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Mn      | 0.464      | -0.273 | -0.284 | 0.466 | 1  |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Fe      | 0.521      | 0.365 | 0.586 | 0.878* | 0.451 | 1  |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Co      | 0.356      | 0.377 | 0.425 | 0.667 | -0.021 | 0.837* | 1  |     |     |     |     |     |     |     |     |     |     |     |     |
| Ni      | 0.088      | 0.364 | 0.181 | 0.687 | 0.038 | 0.789 | 0.931** | 1  |     |     |     |     |     |     |     |     |     |     |     |
| Cu      | 0.842*     | 0.273 | 0.825* | 0.655 | -0.180 | 0.293 | 0.242 | 0.259 | 0.177 | 1  |     |     |     |     |     |     |     |     |     |
| Zn      | 0.034      | 0.982** | 0.485 | 0.619 | -0.180 | 0.293 | 0.242 | 0.259 | 0.177 | 1  |     |     |     |     |     |     |     |     |     |
| As      | 0.465      | 0.783 | 0.737 | 0.893* | 0.088 | 0.844* | 0.795 | 0.708 | 0.764 | 0.714 | 1  |     |     |     |     |     |     |     |     |     |
| Sr      | 0.980**    | 0.228 | 0.951** | 0.539 | 0.351 | 0.579 | 0.445 | 0.164 | 0.891* | 0.195 | 0.603 | 1  |     |     |     |     |     |     |     |     |
| Ag      | 0.327      | 0.530 | 0.479 | 0.815* | 0.087 | 0.915* | 0.962** | 0.931** | 0.757 | 0.420 | 0.897* | 0.434 | 1  |     |     |     |     |     |     |     |
| Cd      | 0.755      | 0.467 | 0.830* | 0.775 | 0.175 | 0.798 | 0.832* | 0.661 | 0.950** | 0.390 | 0.859* | 0.827* | 0.819* | 1  |     |     |     |     |     |     |
| Hg      | -0.177     | -0.673 | -0.456 | -0.095 | 0.655 | -0.105 | -0.197 | -0.031 | -0.256 | -0.629 | -0.404 | -0.311 | -0.159 | -0.403 | 1  |     |     |     |     |
| Pb      | 0.969**    | 0.113 | 0.885* | 0.410 | 0.259 | 0.526 | 0.461 | 0.150 | 0.899* | 0.056 | 0.521 | 0.981** | 0.402 | 0.798 | -0.305 | 1  |     |     |     |
| Bi      | 0.988**    | 0.102 | 0.901* | 0.437 | 0.344 | 0.526 | 0.410 | 0.112 | 0.877* | 0.064 | 0.507 | 0.990** | 0.369 | 0.780 | -0.260 | 0.994** | 1  |     |     |
| Al      | 0.919**    | 0.430 | 0.995** | 0.632 | 0.292 | 0.602 | 0.450 | 0.187 | 0.861* | 0.404 | 0.715 | 0.975** | 0.485 | 0.840* | -0.418 | 0.926** | 0.937** | 1  |
| Ba      | 0.669      | 0.770 | 0.934** | 0.760 | 0.143 | 0.574 | 0.440 | 0.272 | 0.694 | 0.764 | 0.849* | 0.781 | 0.550 | 0.789 | -0.586 | 0.676 | 0.690 | 0.898* | 1  |

**Correlation is significant at the 0.01 level (2-tailed), *Correlation is significant at the 0.05 level (2-tailed)
Diwali and post-Diwali night show a similar trend. Also, statistical data showing the inter-correlation of K, Cu, and Sr with Al, Pb, and Ba associated with PM$_{10}$ and PM$_{2.5}$ are indicating that firecracker emissions during Diwali enormously influence ambient air quality of city.

Statistical single-factor ANOVA analysis for all the heavy metals associated with PM$_{10}$ and PM$_{2.5}$ particles was conducted. On pre-Diwali and Diwali night, the F-value for PM$_{10}$ samples is 3.57 > F-critical, and P-value is 0.074 > 0.05 (specified alpha value), which indicates that the differences in the means between different groups of heavy metals are statistically not significant. On Diwali and post-Diwali night, the F-value for PM$_{10}$ samples is 4.582 > F-critical, and P-value is 0.025 < 0.05 (specified alpha value), which indicates that the differences in the means between different groups of heavy metals are statistically significant.

On pre-Diwali and Diwali night, the F-value for PM$_{2.5}$ samples is 15.7 > F-critical, and P-value is 0.063 > 0.05 (specified alpha value), which indicates the differences in the means between different groups of heavy metals are not statistically significant. During the Diwali period, the concentrations of PM$_{10}$ exceeded by 458% and 1140% than NAAQS (60 μg/m$^3$) and production and usage of ‘greener crackers’ in the future.

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**Data availability** All the data generated during this study has been included as supplementary information.

**Declarations**

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Conflict of interest** The authors declare no competing interests.

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