

**ASSESSMENT OF AMBIENT PARTICULATE  
MATTER (PM<sub>10</sub>, PM<sub>2.5</sub>, PM<sub>1</sub>) AND PARTICLE  
NUMBER CONCENTRATION DURING DIWALI  
AT A RESIDENTIAL SITE IN DELHI**

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**by**

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**24/ENE/09**

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This work is dedicated to the citizens of Delhi who bear the health consequences of severe episodic air pollution, in the hope that studies such as this contribute to evidence-based policy decisions for a cleaner urban environment.

**Urjit Sharma**



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## **CANDIDATE'S DECLARATION**

I, Urjit Sharma, hereby certify that the work presented in this thesis entitled "ASSESSMENT OF AMBIENT PARTICULATE MATTER ( $PM_{10}$ ,  $PM_{2.5}$ ,  $PM_1$ ) AND PARTICLE NUMBER CONCENTRATION (PNC) DURING DIWALI AT A RESIDENTIAL SITE IN DELHI", in partial fulfilment of the requirements for the award of the degree of Master of Technology in Environmental Engineering, submitted in the Department of Environmental Science & Engineering, Delhi Technological University, is an authentic record of my own work carried out during the period August 2025 to October 2025 under the supervision of Dr. Rajeev Kumar Mishra.

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other University or Institution.

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### **CERTIFICATE BY THE SUPERVISOR(S)**

Certified that **Urjit Sharma (Roll No. 24/ENE/09)** has carried out the research work presented in this thesis entitled “ASSESSMENT OF AMBIENT PARTICULATE MATTER (PM<sub>10</sub>, PM<sub>2.5</sub>, PM<sub>1</sub>) AND PARTICLE NUMBER CONCENTRATION (PNC) DURING DIWALI AT A RESIDENTIAL SITE IN DELHI for the award of the degree of Master of Technology in Environmental Engineering from the Department of Environmental Science & Engineering, Delhi Technological University, Delhi, under my supervision. The thesis embodies results of original work, and the studies have been carried out by the student himself. The contents of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University or Institution.

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**ABSTRACT**

Delhi is known for its bad air quality and the ambient air quality gets worse during the post-monsoon season, and the burdens of Diwali festival are heavy pollution stress on an already stressed Delhi air quality. No previous study had measured PM mass fractions (PM<sub>10</sub>, PM<sub>2.5</sub>, PM<sub>1</sub>) and PNC at a less-trafficked residential location in Delhi, which was necessary to isolate the firework signal from vehicular emissions. This study addresses this by conducting a continuous monitoring campaign at Palam, south-west Delhi, for 6 days between 19–25 October 2025, using a GRIMM Aerosol OPC 11D at 1 min resolution, which produced 8,555 quality-controlled data for four phases: Pre-Diwali, Diwali Day, Post-Diwali 1 and Post-Diwali 2. On all monitoring days, the Indian NAAQS 24-hour guideline was violated; while the pre-festival baseline was exceeded by  $2.37\times$  the PM<sub>2.5</sub> and  $3.61\times$  the PM<sub>10</sub> limits. The Diwali evening episode (20 October, 18:00–24:00 h) produced the campaign's peak aerosol loading: PM<sub>10</sub> = 1,542.7 µg/m<sup>3</sup>, PM<sub>2.5</sub> = 834.7 µg/m<sup>3</sup>, PM<sub>1</sub> = 531.4 µg/m<sup>3</sup>, and PNC =  $9.661 \times 10^6$  particles/cm<sup>3</sup>. The evening 6-hour mean PM<sub>2.5</sub> was 405.6 µg/m<sup>3</sup>, which was 6.8 times the NAAQS limit and 27 times the WHO guideline for 24 hours. Most importantly, the post-Diwali episode of smog (21 October) had the highest mean of PM<sub>2.5</sub> during the study period (264.7 µg/m<sup>3</sup>; EF = 4.41) and the highest excess exposure (2,945 µg·h/m<sup>3</sup>). The Mann–Whitney U test showed no significant difference in distribution between Diwali Day and Post-Diwali 1 ( $p = 0.261$ ), indicating that the hazardous air quality event persisted for 3 days. The Pearson correlations were very high ( $r \geq 0.997$ ) between PM<sub>1</sub>, PM<sub>2.5</sub> and PNC and the Fine Fraction Ratios were consistently above 0.7, reflecting the dominance of sub-micron combustion aerosols throughout. Excess PM<sub>2.5</sub> above background was found to be 35–46% pyrotechnic activity. During Diwali week, all the analysed elements recorded significantly higher levels than the national and international standards. The results could help policymakers and regulatory bodies

assess the effectiveness of existing regulations for festivals on the ground and enact measures to limit air pollution from firecrackers and their impact on public health.

**Keywords:** Diwali, Firework Emissions, Particle Number Concentration (PNC), PM<sub>1</sub>, PM<sub>2.5</sub>, PM<sub>10</sub>.

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## LIST OF SYMBOLS, ABBREVIATIONS AND NOMENCLATURE

|                          |                                                                     |
|--------------------------|---------------------------------------------------------------------|
| CER                      | Coarse Exclusion Ratio                                              |
| CPCB                     | Central Pollution Control Board                                     |
| DD                       | Diwali Day                                                          |
| DER                      | Diwali Enhancement Ratio                                            |
| DTU                      | Delhi Technological University                                      |
| EC                       | Excess Concentration                                                |
| EF                       | Exceedance Factor                                                   |
| FF                       | Firework Fraction                                                   |
| FFR                      | Fine Fraction Ratio                                                 |
| IEF                      | Instantaneous Exceedance Factor                                     |
| IMD                      | India Meteorological Department                                     |
| IQR                      | Interquartile range                                                 |
| K-W                      | Kruskal–Wallis non-parametric test                                  |
| $\mu\text{g}/\text{m}^3$ | Micrograms per cubic metre (SI unit for PM mass concentration)      |
| MWU                      | Mann–Whitney U pairwise non-parametric test                         |
| NAAQS                    | National Ambient Air Quality Standards                              |
| NCT                      | National Capital Territory                                          |
| OPC                      | Optical Particle Counter                                            |
| SD                       | Standard deviation                                                  |
| PBL                      | Planetary Boundary Layer                                            |
| PD                       | Pre-Diwali Phase                                                    |
| PM                       | Particulate Matter                                                  |
| $\text{PM}_{10}$         | Particulate Matter with aerodynamic diameter $\leq 10 \mu\text{m}$  |
| $\text{PM}_{2.5}$        | Particulate Matter with aerodynamic diameter $\leq 2.5 \mu\text{m}$ |
| $\text{PM}_1$            | Particulate Matter with aerodynamic diameter $\leq 1 \mu\text{m}$   |
| PNC                      | Particle Number Concentration ( $\#/\text{cm}^3$ )                  |
| PoD1                     | Post-Diwali Phase 1                                                 |
| PoD2                     | Post-Diwali Phase 2                                                 |
| SD                       | Standard deviation                                                  |
| WHO                      | World Health Organization                                           |

# CHAPTER 1

## INTRODUCTION

### 1.1 OVERVIEW

Air pollution has become one of the most critical environmental and public health problems of the 21st century, and South Asian countries are particularly affected. South Asian countries like India, Pakistan, and Bangladesh are among the most impacted as they have high population densities, high levels of industrialization, and it is estimated that about 99% of the World's population is living in areas where WHO guidelines for air quality are being breached regularly (Saini, 2025). The World Air Quality Report 2025 ranks India as the sixth most polluted country in the World, with an average  $\text{PM}_{2.5}$  concentration of  $48.9 \mu\text{g}/\text{m}^3$ , more than 9.78 times the WHO annual guideline of  $5 \mu\text{g}/\text{m}^3$  (IQAir, 2026). Delhi is in a very alarming situation as the national capital of India. Air Quality Index in Delhi is frequently in "severe" or "hazardous" category due to multiple sources of air pollution, including industrial emissions, vehicle traffic, landfills, deforestation, construction dust, and crop burning in contiguous states (Bhuyan et al., 2025). Short-term exposure to pollution levels as high as  $700\text{--}1,000 \mu\text{g}/\text{m}^3$  is often driven by meteorological conditions and by high combustion seasonal events, such as festivals and agricultural stubble burning, which can cause acute episodes of extreme health vulnerability (de Bont et al., 2024). The effects of such chronic exposure on health are significant and far-reaching. The most hazardous pollutant is  $\text{PM}_{2.5}$ , which is capable of entering deep into the lungs, and is directly related to higher incidence of COPD (chronic obstructive pulmonary disease), non-smoker lung cancer and cardiovascular disease, with the WHO estimate of about 4.2 million premature deaths caused by ambient air pollution every year (Observer Research Foundation, 2026). Air pollution claimed 17,188 lives in Delhi in 2023 alone, accounting for 15% of total mortality, up from 16,284 deaths in 2018, and was the

city's biggest single cause of death (Observer Research Foundation, 2026). In addition to cardiorespiratory disease, new studies link long-term exposure to reduced cognitive functioning, increased stroke and dementia risk, hormone disruption, decreased immune response, and stunted lung development in children, as well as increased lifelong vulnerability to respiratory diseases (Observer Research Foundation, 2026). Combined, these data highlight that air pollution is not just a problem in India and Delhi, but a public health emergency that is crying out for action grounded in scientific evidence and policy.

## **1.2 Air Quality, Particulate Matter & Particle Number Concentration**

Air pollution is considered a primary environmental and public health problem of the modern world and is reported to be the fourth biggest cause of deaths worldwide, responsible for around 6.7 million deaths per year (World Health Organization [WHO], 2022). Suspended particulate matter (PM) is the main pollutant responsible for the structural pathogenicity and is operationally divided into coarse PM ( $PM_{10}$ ), fine PM ( $PM_{2.5}$ ) and sub-micron PM ( $PM_{1}$ ) mass fractions (Schraufnagel, 2020). Fine and sub-micron particles can penetrate deeply into the sensitive alveolar spaces of the lung without efficient upper airway clearance, whereas coarse particles tend to be trapped in the nose, mouth, and throat. Sub-micron fractions from polluted air or the vapors you inhale can pass through the very fine membranes of your lungs, and into your blood. They enter your bloodstream and travel throughout your body, directly causing chemical stress, irritation and damage to the heart, blood vessels and brain. This heavy damage increases the chances of heart attack, stroke or long-term illnesses of the lungs, such as chronic bronchitis and emphysema, over time. (Pope & Dockery, 2006;Kwon et al., 2020). Modern health-detective and environmental risk assessments are moving towards coupled monitoring setups that monitor both PM mass concentrations and microphysical particle size distributions (Schraufnagel, 2020).

Ambient particulate loading is disproportionately high and shaped by a highly complex pre-existing ambient mixture of vehicular exhaust, industrial emissions, construction dust, and agricultural residue burning during the agricultural season, culminating in India having 39 of the world's 50 most polluted cities (IQAir, 2024). A high

background level of pollutants is continually exposed to extreme short-term fluctuations due to episodic cultural events, particularly the festival of lights, Diwali, which is celebrated in India and across the World with intense fireworks, causing short-term, localised disruptions to urban air quality. The simultaneous bursting of commercial firecrackers during a restricted period of the season creates a huge stock of heavy metals, carbonaceous species and secondary aerosol precursor which leads to a significant rise in the mass concentration of fine particulate matters (PM<sub>10</sub> and PM<sub>2.5</sub>) and regularly exceeds the National Ambient Air Quality Standards (NAAQS) 24-hour limit (100 µg/m<sup>3</sup> and 60 µg/m<sup>3</sup>, respectively) set by Central Pollution Control Board (CPCB) 2009. Diwali-induced PM presents a unique toxicological hazard because of its suddenness, and the huge surface area for its size of a record-breaking amount of fine and sub-micron-sized combustion particles that provide an enhanced surface area to adsorb and transport toxic metal ingredients and organic compounds deep within the respiratory system of humans and animals (Gani et al., 2020; Kwon et al., 2020). Ambient particle number concentrations (PNC) created by this blanket of firework smoke on residential populations into unprecedented measurement ranges of 10<sup>4</sup> to 10<sup>7</sup> particles/cm<sup>3</sup> – some of the highest human aerosol exposure concentrations recorded globally and severe acute cardiorespiratory risks (Gani et al., 2020; Rajagopal et al., 2024a).

Cultural practices that involve large firework smoke displays are a source of acute, high-concentration pulses of physical and chemical stresses to urban airsheds, short-lived enough to be masked by background levels from routine industrial and mobile sources (Brimblecombe & Lai, 2020; Li et al., 2025). In the context of Diwali, this can be seen as polluting the air for a long time, lasting several hours, in highly populated residential neighbourhoods, where firecrackers and sparklers are lit in large numbers across these areas. The chemistry of these large emission compositions is based mainly on black burning powder formulations consisting of potassium nitrate (KNO<sub>3</sub>), elemental sulfur, and charcoal, with some special metallic additives—such as aluminum, magnesium, barium nitrate, strontium carbonate, and copper complexes—as propellants, oxidizers, and flame coloring agents. These hypergolic mixtures are ignited by their high rate of combustion producing an excessive number of particles

by rapid supersaturation and nucleation of the vaporized metals and chemical species, which is not just a shift in coarse mass fractions. The new pyrotechnic aerosol inventory is shown to be microphysically characterized by a strong numerical dominance of discrete particles in the Aitken mode (30–100 nm) and in the lower accumulation mode (100–500 nm). Therefore, most of the mass is contained in the fine fraction and the number of particles is enormous, moving the urban aerosol size distribution towards the regimes of ultra-fines and sub-microns, which have a huge active surface area that can carry transient chemical hazards deep into the human respiratory tract (Gani et al., 2020). A hyper-concentrated PNC has a unique temporal trajectory, with a first stage of atmospheric behavior highly hazardous due to the localized firework busting activity and a second stage of micro-meteorological evolution, which is seasonal (Singh et al., 2019a). The primary firework phase takes place during the period of about 18:00 to 24:00 h of the evening of the event, characterized as a sharp near-exponential increase in ambient PNC and PM mass as a result of the highest emission rates of sources at ground level (Singh et al., 2019a). These ultra-fine and accumulation-mode particles are entrained into Delhi's rapidly collapsing boundary layer, which is quite stable during the post-monsoon season (Kanawade et al., 2020; Singh et al., 2019a). This creates a second phase in which the pollution is trapped for a long time. This is called the delayed smog effect. The dirty air cannot rise or blow away because the atmosphere acts like a heavy lid, the ground winds are nearly still, and a layer of warm night air traps the cold, dirty air right above the ground (Ren et al., 2025; Singh et al., 2019a). In this second phase (which can last 2-5 days), there are still plenty of tiny particles in the air. The smoke from this firework remains low to the ground, slowly condenses particles together and collects moisture. This process helps convert a short holiday event into a long-term public health hazard (Ren et al., 2025; Singh et al., 2019b).

### **1.3 Diwali Firework Emissions: Sources, Composition and Atmospheric Fate**

Cultural traditions and traditional customs (particularly large-scale holiday activities with smoke displays) impose significant, short-term stresses on the urban environment, often above normal economic and industrial emission baselines (Lai & Brimblecombe, 2017; Li et al., 2025). One of the most extreme forms of this is the

pan-Indian festival of lights, Diwali. The festival is marked by an intense 4- to 6-hour window when firecrackers and sparklers are set off simultaneously across large urban areas. The major chemical components of these firecracker compositions are potassium nitrate ( $\text{KNO}_3$ ), sulfur, charcoal, and various metallic components (Al, Mg,  $\text{Ba}(\text{NO}_3)_2$ ,  $\text{SrCO}_3$ , Cu compounds) used as propellants and colouring agents. The subject of particular interest is the production of particulate matter from the explosive combustion of these materials, with the majority of these particles being microscopic. Actually, the highest number of these are ultrafine, from the thickness of a thousand times thinner than a human hair all the way down to the size of a virus. The elemental speciation of these trace metals is not the focus of the present study, but the physical mass fractions of  $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$ , and  $\text{PM}_1$ , and their total dynamics, are of interest.

Diwali emissions exhibit a typical two-stage atmospheric evolutionary trend. The primary firework phase, which lasts from 18:00 to 24:00 h on the celebration evening, sees a sudden and fast increase in PM and PNC because of the huge firework instantaneous rates of emissions (Singh et al., 2019). The newly emitted pyrotechnic aerosol inventory then gets entrained in the collapsing and stable nocturnal boundary layer (Singh et al., 2019). This trapping starts a secondary trapping period, or “smog lag”, that can last for 2 to 5 days, depending upon the normal October weather conditions (Singh et al., 2019). At these celebratory times, the weather is often unfavourable and can make the emission reductions difficult to detect and can even completely stop the dispersion of pollutants into the atmosphere, extending the festive days into a multi-day public health hazard (Ren et al., 2025).

#### **1.4 Objectives of the study**

To address the critical research gaps surrounding sub-micron aerosol exposure during extreme episodic events, the specific objectives of this study are:

- To quantify the mass concentrations of Particulate Matter,  $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$  and  $\text{PM}_1$  in residential areas during the Diwali festival.
- To determine the Particulate Number Concentration (PNC) within residential environments during the Diwali period.
- Evaluating the Fine Fraction Ratio (FFR) and Coarse Exclusion Ratio (CER) Ratio as an Indicator of Emission Source Transitions

These goals will directly address an important methodological deficit in the existing environmental literature on clean attribution of firework emissions. Previous studies on air pollution in the city of Delhi have mostly been conducted in roadside areas with heavy traffic on arterial roads or near institutional campuses, which naturally mask the high concentration of emissions from fireworks against the ongoing routine emissions from vehicles. These factors are excluded from the study by deliberately avoiding the inclusion of a traffic receptor site, thus allowing for the study to capture the unadulterated microphysical fingerprint of festival emissions as they affect vulnerable populations in their "home". Moreover, quantification of sub-micron mass fraction ( $PM_1$ ) along with Particle Number Concentration (PNC) is imperative for understanding the severe health risks which are experienced during these transient events. The current national regulatory schemes focus solely on monitoring  $PM_{10}$  and  $PM_{2.5}$ , but this study aims to show that the real toxicological impact of holiday pyrotechnics is overwhelmingly driven by the highly penetrable regime of pyrotechnics below the micron scale (Sharma), (2026). The research will help to understand the intricate process of trapping these parameters in time-resolved inter-fraction mass ratios and thus, provide a scientifically sound basis for updating public health warnings and Urban Air Quality standards (UAQS).

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Overview

The present study builds on a large volume of international, national and institution-specific literature that carefully documents the impact of culturally episodic combustion events on urban air quality, which are very different from the continuous baseline pollution levels emitted by traffic, industry and fossil fuel combustion (Foreback et al., 2022; Lai & Brimblecombe, 2017; Li et al., 2025; Ren et al., 2025; Ye et al., 2016). At the international level, studies on the Chinese New Year (CNY) in Beijing have recorded PM<sub>2.5</sub> concentrations rising from background levels of approximately 50 µg/m<sup>3</sup> to between 250 and 1,593 µg/m<sup>3</sup> within hours of peak celebrations, with causal analysis across 335 Chinese cities confirming AQI increases of 57% and PM<sub>2.5</sub> surges of 89% attributable to unrestricted pyrotechnics (Li et al., 2025; Ye et al., 2016); a 20-year multi-site analysis of the United States Independence Day across 315 EPA monitoring stations demonstrated a consistent 42% national elevation in 24-hour PM<sub>2.5</sub> providing a phase-based methodological reference directly applicable to the pre, during, and post-event design employed in the present study (Foreback et al., 2022; Seidel & Birnbaum, 2015; Singh et al., 2019) the United Kingdom's Guy Fawkes Night, which combines aerial fireworks with communal bonfires under autumn atmospheric stability conditions closely analogous to Delhi's post-monsoon meteorological regime, has recorded PM<sub>2.5</sub> peaks exceeding 326 µg/m<sup>3</sup> — more than 13 times the WHO 24-hour guideline (Pope et al., 2016; Public Health Wales, 2023; Singh et al., 2019a); and the multi-day Las Fallas festival in Valencia established the chemically distinctive metalliferous tracer fingerprint — barium, strontium, copper, potassium, and lead — that has since become a standard tool for attributing festival-related particulate loading across the field (Moreno et al., 2007; Singh et al., 2019). The results of the work carried out by Tiwari et al. (2012) indicate that PM concentrations are high during Diwali days, particularly in urban areas like

Delhi, and at the national level are  $1,200 \mu\text{g}/\text{m}^3$ . This underscores the importance of simultaneous measurements of  $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$ , and  $\text{PM}_1$ , as well as the need for a different approach to measuring and attributing the signal from clean pyrotechnics in urban datasets, given the traffic confounder effect. Patel et al. (2021), Reyes-Villegas et al. (2021) confirmed the influence of regional agricultural burning on loading of submicron particles in autumn, and Gani et al. (2020) showed that there is a critical decoupling between the mass and the particle number of  $\text{PM}_{2.5}$ , which means there was little relationship between the number of particles in a size range and the loading of  $\text{PM}_{2.5}$ , with direct implications for the health impacts of fireworks, and directly informed the monitoring approach of this study by Sharma et al. (2025); the statistically significant reductions in  $\text{PM}_{2.5}$  by the Supreme Court's firework ban through 2021 – 2022. All these studies define the state of knowledge and give a detailed overview of the current challenges that the present study endeavours to tackle: lack of simultaneous monitoring of multiple fractions and particle number at a single residential location, lack of traffic-free source attribution and under-quantification of secondary smog accumulation episode during post-Diwali period.

## **2.2 International Studies on Festival Air Quality**

There is considerable international literature documenting the effects of large-scale firework events on air quality. Due to the episodic nature of culture-related activities, degradation of urban air quality has become a critical sub field of atmospheric sciences (Foreback et al., 2022; Lai & Brimblecombe, 2017; Li et al., 2025; Ren et al., 2025; Ye et al., 2016). There are cultural traditions and traditional customs that tend to impose harsh and short-term environmental impacts on the environment, mainly through the practice of big party celebrations, which are characterized by the use of pyrotechnic products and are often neglected in the field of economic or industrial regulation. Seasonal festivities are highly concentrated chemical pulses, whereas common urban air pollution models conceptually consider continuous baselines such as traffic emission, industrial processing and fossil fuel consumption. Internationally, these are recorded on different days within different cultures, such as Independence Day (USA), Bonfire Night (UK), Las Fallas (Spain). The Chinese New Year (CNY) in East Asian

countries and the Diwali festival of lights in India are among the most disruptive times for the environment.

### **2.2.1 The Chinese New Year (CNY)**

The Chinese New Year (CNY) culture is one of the most widely studied cultural emission anomalies, where fireworks and firecrackers are traditionally fired off to ward off malevolent spirits, known as “Nian” (Lai & Brimblecombe, 2017; Ye et al., 2016). This behavior results in sudden and extreme atmospheric loading of fine particulate matter (PM<sub>2.5</sub>), inhalable particulate matter (PM<sub>10</sub>), and trace gases (sulfur dioxide (SO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO)). In the case of major megacities, such as Beijing, long-term multi-year observations have shown that during the peak celebration night (NYE), PM<sub>2.5</sub> mass concentrations often rise quite rapidly, from the normal background level of 50 µg/m<sup>3</sup> to dangerous levels of 250 µg/m<sup>3</sup> to 600 µg/m<sup>3</sup> within a few hours. Unrestricted holiday pyrotechnics have been found to cause a catastrophic rise in regional air quality, with results from robust causal identification strategies, including Regression Discontinuity Designs (RDD) across 335 Chinese cities, showing a causality increase of 57% in overall Air Quality Index (AQI), 89% in PM<sub>2.5</sub>, 44% in PM<sub>10</sub>, and 69% in SO<sub>2</sub> (Li et al., 2025).

In addition, PM<sub>2.5</sub> concentrations at specialised urban tracking stations have been recorded to reach an extraordinary 1593 µg/m<sup>3</sup> during extreme peak hours in the past (Ye et al., 2016). This pyrotechnic envelope is very different from the background winter pollution, as it contains co-emitted tracer elements, very high concentrations of black carbon (BC), massive primary gas phase precursors.

### **2.2.2 Independence Day (United States)**

The United States Independence Day (4 July) is one of the most systematically studied firework-related air quality events in the Western World, offering a uniquely clean experimental design because the celebration date is fixed, nationally synchronized, and occurs during otherwise stable summer air quality conditions. A landmark multi-site study (Seidel & Birnbaum, 2015) analysing hourly PM<sub>2.5</sub> concentrations at 315 EPA monitoring sites across the contiguous United States found that the national average 24-hour PM<sub>2.5</sub> level is elevated by 42% (approximately 5 µg/m<sup>3</sup>) above control days, with peak hourly increases of 21 µg/m<sup>3</sup> occurring at 21:00–

22:00 h local time on 4 July, declining to pre-event levels by noon on 5 July. Sites adjacent to large display events recorded 24-hour  $\text{PM}_{2.5}$  increases as high as  $48 \mu\text{g}/\text{m}^3$  (370% above control). A 20-year analysis from 2001–2021 using the EPA’s Air Quality System database (Foreback et al., 2022) confirmed this as a consistent, repeatable nationwide pattern, with peak  $\text{PM}_{2.5}$  signals concentrated between 21:00–23:00 h local time and particularly pronounced in large urban centres.

Chemical speciation data from 379 EPA Chemical Speciation Network sites across the USA (2000–2014) identified barium (Ba), strontium (Sr), potassium (K), copper (Cu), and lead (Pb) as reliable pyrotechnic tracers in the  $\text{PM}_{2.5}$  fraction during Independence Day (Singh et al., 2019). Site-level studies in the greater Los Angeles metropolitan area recorded hourly ambient particulate concentrations exceeding  $500 \mu\text{g}/\text{m}^3$  in 2020 and  $300 \mu\text{g}/\text{m}^3$  in 2021 during peak celebration periods (Singh et al., 2019). The EPA formally recognises the culturally episodic nature of this exceedance by permitting states to demonstrate fireworks influence and exclude 4–5 July  $\text{PM}_{2.5}$  spikes from annual standard attainment determinations (Seidel & Birnbaum, 2015). From a methodological standpoint, Independence Day provides a well-constrained reference case: the single-night, nationally simultaneous firework signal can be cleanly separated from background pollution using the preceding and following days as controls — a phase-based design logic directly analogous to the Pre-Diwali, Diwali Day, and Post-Diwali study phases employed in the present thesis.

### **2.2.3 Bonfire Night (United Kingdom)**

Guy Fawkes Night (5 November), commonly referred to as Bonfire Night, is the annual event that generates the highest single-night particulate spike recorded in the United Kingdom, and it stands apart from purely aerial firework festivals through its combination of fireworks with the widespread burning of large communal bonfires (Singh et al., 2019a). This dual-source structure produces a distinctive aerosol composition: fine combustion particles from the pyrotechnics are co-emitted with bonfire-generated coarser particles, resulting in a broader particle size distribution and a higher coarse mass fraction ( $\text{PM}_{10}$ – $\text{PM}_{2.5}$ ) relative to purely aerial events such as Diwali or Independence Day. Monitoring in Reading, UK, found  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  levels on the Bonfire Night weekend elevated by up to seven times the 2009 annual

average, while a satellite-based study using Aerosol Optical Depth (AOD) reported a 2–4-fold increase in column aerosol loading across the UK on the same night (Pope et al., 2016). An individual PM<sub>2.5</sub> monitor in Sheffield recorded a peak concentration of 326 µg/m<sup>3</sup> — more than 13 times the WHO 24-hour guideline of 25 µg/m<sup>3</sup> — and multi-year monitoring at 19 Welsh sites (2017–2022) confirmed that 5 November consistently produces the highest daily maximum PM<sub>10</sub> of the year, with concentrations peaking from approximately 17:00 h onwards (Public Health Wales, 2023).

Singh et al. (2019a) noted that Bonfire Night occurs during the UK autumn-winter season when atmospheric stability conditions — low boundary layer heights, surface temperature inversions, and weak surface winds — closely parallel the post-monsoon meteorological regime of Delhi during Diwali. This seasonal alignment produces a secondary aerosol trapping mechanism structurally similar to the “smog lag” documented in Delhi studies, with elevated PM concentrations persisting into the morning after the event. The bonfire contribution additionally enriches the coarse fraction relative to purely aerial firework events, making Bonfire Night a particularly instructive comparator for inter-fraction mass ratio studies and underscoring the importance of simultaneously measuring PM<sub>10</sub>, PM<sub>2.5</sub>, and PM<sub>1</sub> alongside PNC to disentangle pyrotechnic from biomass burning aerosol contributions — an approach directly adopted in the present study.

#### **2.2.4 Las Fallas (Spain)**

Las Fallas is a six-day festival held annually across Valencia and the surrounding Valencian Community provinces of Spain, culminating on the night of 18–19 March (the feast of San José) with the Cremà, the simultaneous ceremonial burning of thousands of large sculptural wooden monuments across the city. Uniquely among major international pyrotechnic festivals, Las Fallas combines three temporally distinct combustion sources: the daily afternoon Mascleta (intense ground-level percussion fireworks), nightly aerial firework displays, and the Cremà itself, in which hundreds of large falla structures constructed from painted wood, foam, and pyrotechnic charges are set alight simultaneously across hundreds of urban locations. This multi-source, multi-day emission structure creates a sustained aerosol loading

scenario — escalating over several days rather than peaking on a single evening — and was among the first European festival events to receive systematic atmospheric characterisation (Moreno et al., 2007).

The landmark study by Moreno et al. (2007), who collected inhalable PM<sub>10</sub> aerosol samples over six consecutive days at a Valencia urban background station during Las Fallas 2005 and added comparative data from Barcelona, Castellón, and London (Guy Fawkes), established the chemically distinctive metalliferous fingerprint of recreational firework pollution. Pyrotechnic tracer elements — barium (Ba), strontium (Sr), copper (Cu), potassium (K), magnesium (Mg), zinc (Zn), and lead (Pb) — were found at dramatically elevated concentrations relative to the urban background aerosol (Moreno et al., 2007). The Valencia site recorded the most extreme PM<sub>10</sub> exceedances during peak firework episodes, with the Mascleta events producing short-duration coarse PM pulses from ground-level deflagrating charges and the Cremà generating sustained fine and sub-micron particle loading from high-temperature combustion of metallic additives and structural materials simultaneously. Primary aerosols from these pyrotechnic sources were dominated by fine and ultrafine particles (100–500 nm), consistent with the Aitken and lower accumulation modes documented across firework events globally (Moreno et al., 2007; Singh et al., 2019). The Western European regulatory context of Las Fallas — where PM<sub>10</sub> daily limits (50 µg/m<sup>3</sup>) are routinely breached during the festival despite stringent EU ambient air quality directives — mirrors the regulatory challenge posed by Diwali in India, and reinforces the broader argument of the present thesis that mass-only PM standards are insufficient to capture the full public health burden of short-term, high-intensity pyrotechnic events. The Las Fallas case thus serves as a key Western reference point for the multi-fraction, number-based monitoring approach adopted in the present study.

### **2.3 National Studies on Festival Air Quality**

In the national context, the burning of firecrackers during festivals has been a topic of growing scientific interest to understand the impact of post-monsoon pollution associated with festivals. To gain knowledge and understanding of particle dynamics, Gani et al. (2020) conducted an extensive, highly time-resolved analysis of particle size distributions at the Delhi Aerosol Supersite. One of the key results of their

research was the decoupling of mass and number concentrations: although accumulation-mode particles make up the bulk of the  $PM_{2.5}$  mass, the number of particles in the ultrafine particle (UFP) fraction dominates the particle number (PN) concentrations. This set the foundation for the atmospheric context whereby specific mass reductions during extreme pollution days are not necessarily proportional to specific number reductions of particles, which is important for assessing the combustion of fireworks. Patel et al. (2021) quantified the chemical and source dynamics of submicron particles ( $PM_1$ ) during the most polluted season in Delhi. They identified the sources of submicron aerosols during autumn onset using positive matrix factorization, and showed that regional agricultural burning is a dominant source. Moreover, they deliberately applied their inorganic fragment ratios to remove the large-scale localised effects of metal emissions from the Diwali festival. To emphasize the spatial heterogeneity of these  $PM_1$  sources, Reyes-Villegas et al. (2021) carried out multi-site  $PM_1$  source apportionment in Delhi. The primary aerosol sources at typical urban background sites were dominated by traffic emissions. This highlights the importance of isolated monitoring of residents' emissions in areas without traffic to correctly allocate emissions from festivals away from everyday vehicle emissions.

Lastly, the meteorological processes responsible for holding these emissions have been vigorously investigated. Building on the record-breaking air pollution episode of November 2016, reported by Kanawade et al. (2020). A recent study by Agarwal et al. (2023) quantified the regional meteorology of northern India during this time period. They found that high levels of haze during the post-monsoon season are strongly amplified by a combination of nighttime dispersion failures, low boundary-layer heights, and local urban and biomass-burning emissions. These abated weather conditions, combined with primary emissions, mean that secondary smog are frequently long-lasting, and that daily mean  $PM_{2.5}$  levels exceed standard levels by 20-40 times.

#### **2.4 Delhi Studies on Air Quality during Festival**

One of the most air-polluted megacities in the World, Delhi suffers its worst episodic air quality degradation during the annual Diwali festival, when the concentrated burning of firecrackers adds a high-intensity pulse of fine particulate matter, toxic trace

metals and gaseous pollutants to the already chronically poor atmospheric quality, making it a critical scientific phenomenon for study. The earliest systematic particulate mass characterisation of Diwali-related firecracker emissions in Delhi was established by (Pandey et al., 2016) used the monitoring network data to analyse the trends of PM<sub>10</sub> and PM<sub>2.5</sub> between 2010 and 2015 at six monitoring stations in Delhi to determine the multi-year trend and establish the NAAQS violations at every station and year (with EF = 5–15× for PM<sub>2.5</sub> during Diwali night). This study has also shown that Diwali results in the worst air quality event of the year at all the monitored sites, even when meteorological conditions change from year to year.

The first time a regulatory impact assessment of the Supreme Court's judicial fireworks ban (introduced for Diwali 2017) was conducted by comparing air pollution concentrations of PM<sub>2.5</sub>, NO<sub>x</sub> and CO during Diwali events in 2015, 2016, 2017 and 2018 at DTU campus. The ban was effective and brought about statistically significant reductions in Diwali peak PM<sub>2.5</sub> (from ~400–450 µg/m<sup>3</sup> in 2015-2016 to ~300–360 µg/m<sup>3</sup> in 2017-2018), but the 24-hour average continued to exceed the NAAQS of 3–6x (Yadav et al., 2022b). Later, PNC was identified in 2019 during Diwali, when the use of fireworks was prohibited and replaced with ‘green crackers’. The composition change did not stop the particle number concentrations from staying at hazardous levels (PNC peak > 5 × 10<sup>6</sup> /cm<sup>3</sup>), indicating that, from a public health the particle number concentrations emitted by green crackers did not indicate a significant health risk (Yadav et al., 2022c).

For the first time, the quasi-ultrafine PNC characterisation and the size-resolved elemental distribution of trace metals during Diwali 2018 at the DTU campus were measured using the GRIMM OPC family instrument. This study is the most instrumentally similar one before the present work (Yadav et al., 2022a). Extended the ban impact analysis to the events of Diwali 2021 and 2022, and noticed that the PNC level at Bawan-Badli road was still in the dangerous range even during enforcement years, measured using PNC data obtained from the SMPS (Rajagopal et al., 2024). The first indoor UFP characterisation in a Diwali environment was conducted by Sharma et al. (2025) in a Delhi household, where the PNC inside the house was found to be

higher than outdoors during Diwali activities in the immediate vicinity of the house. This result is directly applicable to the present study's residential monitoring setting.

## 2.4 Research Gaps

Despite the extensive international, national, and institution-specific literature detailing episodic festival emissions, a rigorous review identifies several critical, unfilled gaps that the present thesis systematically addresses are; (i) Lack of Clean Source Attribution (The Traffic Confounding Factor): Previous outdoor ambient Diwali studies – including large source apportionment studies (Reyes-Villegas et al., 2021) and campus evaluation at DTU (Rajagopal et al., 2024) have been conducted at roadside, institutional, or urban background locations. The influence of traffic exhaust makes it difficult to extract a true smoke signal from previous urban PNC datasets. Caution is needed when attributing PM and PNC peaks to localized fireworks as there is a distinct lack of data from carefully selected residential sites with almost negligible traffic pollution to clearly separate the fireworks from other sources. (ii) Simultaneous Multi-Fraction and Number Characterization, No previous study has used OPC to simultaneously characterize the entire mass spectrum ( $PM_{10}$ ,  $PM_{2.5}$ ,  $PM_1$ ) and the total Particle Number Concentration (PNC) in the outdoor environment at the same location. (iii) Unquantified Sub-Micron ( $PM_1$ ) Dynamics and Diagnostic Ratios:  $PM_1$  is the most health-relevant deep-lung penetrating mass fraction and has largely remained uncharacterizable in high-resolution ambient Diwali data. Also, this is the first study in Delhi that calculates time-resolved inter-fraction mass ratios such as Fine Fraction Ratio (FFR:  $PM_1/PM_{2.5}$ ) and Coarse Exclusion Ratio (CER:  $PM_{2.5}/PM_{10}$ ) to dynamically diagnose the atmospheric transition from the coarse mechanical firework debris to fine, persistent combustion aerosols during the holiday period. (iv) The Under-Evaluation of the Secondary Post-Diwali Smog Episode: Prior Diwali studies have focused on the celebration night and there is evidence from research such as Agarwal et al. (2023) that the secondary post-Diwali smog event is systematically trapped by the meteorology of the post-monsoon season. The extended (secondary) smog accumulation episode 24-48 hours after Diwali has not been fully quantified in absolute cumulative exposure metrics ( $\mu g \cdot h/m^3$ ) for all four parameters ( $PM_{10}$ ,  $PM_{2.5}$ ,  $PM_1$  and PNC).

## CHAPTER 3

### METHODOLOGY

#### 3.1 Study Site: Palam Residential Locality

The monitoring site was in the Palam residential locality of south-west Delhi (latitude 28°35' N, longitude 77°04' E, elevation ~208 m AMSL). The site was chosen because the following criteria were met, all of which were confirmed by on-site inspection before monitoring began:

There is no arterial or service road within 200 m of the deployment point of the instrument: No industrial or construction or burning of waste sources within 500 m. Adequate ventilation from all directions of the compass without significant physical barriers to aeration in the building, within 50 m. The surrounding residential neighbourhood actively engaged with the celebrations of the festival 'Diwali' and fireworks were used within the immediate neighbourhood, thus providing an attenuated firework emission signal at the measurement location.

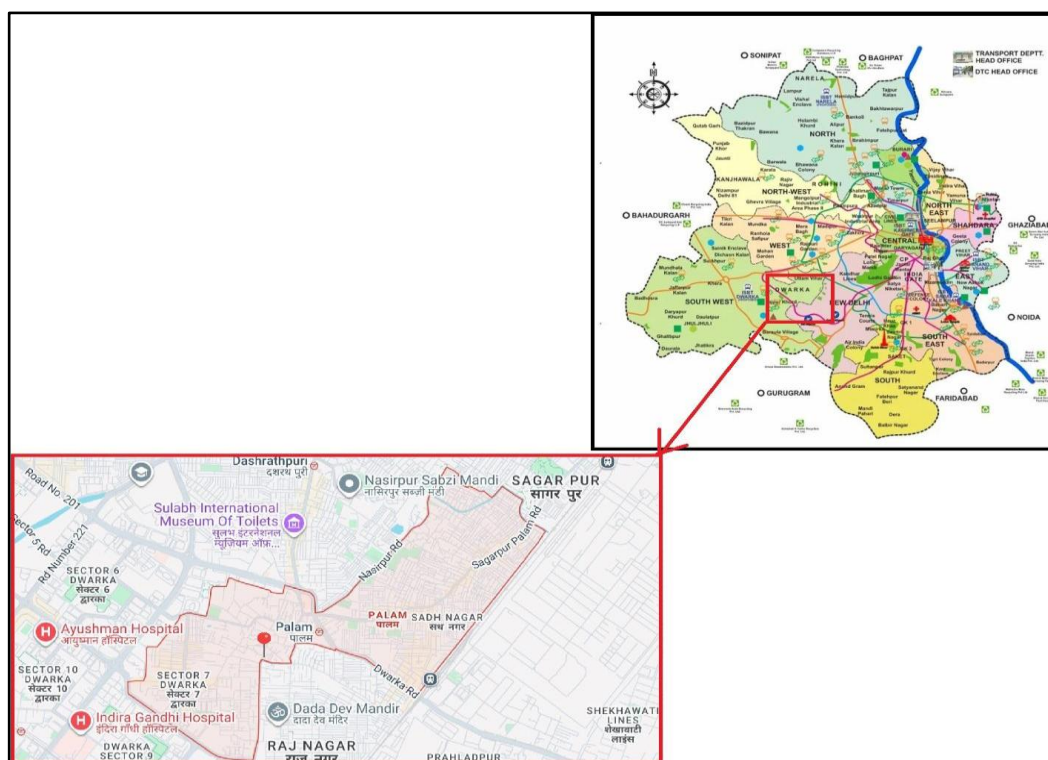


**Fig.3.1:** Map showing Palam monitoring site location within Delhi NCT.

### 3.2 Instrumentation

Ambient air monitoring was carried out using a GRIMM model 11D (Aerosol Optical Particle Counter, GRIMM Aerosol Technik GmbH and Co. KG, Ainring, Germany). The OPC 11D is based on laser light scattering from individual particles, according to the Mie scattering theory: ambient air is drawn through a controlled flow rate of 1.2 L/min, to the sensing volume illuminated by a 655 nm diode laser; the intensity of the light scattered from each particle is proportional to its aerodynamic equivalent diameter, and allows for simultaneous size-resolved counting and deriving the mass concentration over 31 size channels from 0.25 to 32  $\mu\text{m}$ . The PM mass concentrations are derived from particle counts collected in size channels, assuming a particle density and spherical particle geometry (Mie equivalent sphere). The instrument was factory-calibrated before deployment and was checked with filter gravimetric measurements co-located in the field. The GRIMM OPC 11D has been widely tested in aerosol monitoring applications in urban environment, such as in Delhi (Burkart et al., 2010; Yadav et al., 2022a).

**Table 3.1:** Technical specifications of the GRIMM Aerosol OPC 11D.

| Parameter             | Specification                                                                                               |
|-----------------------|-------------------------------------------------------------------------------------------------------------|
| Measurement principle | Single-particle laser light scattering (Mie theory)                                                         |
| Size range            | 0.25 to 32 $\mu\text{m}$ (31 size channels)                                                                 |
| PM fractions reported | PM <sub>1</sub> , PM <sub>2.5</sub> , PM <sub>10</sub> ( $\mu\text{g}/\text{m}^3$ , gravimetric-equivalent) |
| Total PNC reported    | Total particle number concentration ( $\#/\text{cm}^3$ )                                                    |
| Time resolution       | 1 minute (continuous real-time logging)                                                                     |
| Sample flow rate      | 1.2 L/min (temperature-controlled)                                                                          |
| Laser wavelength      | 655 nm diode laser                                                                                          |
| Factory calibration   | Manufacturer-certified pre-deployment calibration with polystyrene latex (PSL) reference particles          |
| Counting efficiency   | $\geq 90\%$ for particles $> 0.3 \mu\text{m}$                                                               |
| Operating temperature | 0 to $+40^\circ\text{C}$                                                                                    |

### 3.3 Monitoring Period and Campaign Design

The study was conducted over 6 days, from 19 to 25 October 2025. The monitoring period was divided into four phases: Pre Diwali (PD), During Diwali (DD), Post Diwali (PD), The period was classified based on the outdoor activities associated with the festival. A 6-day monitoring period includes: Pre-Diwali (19<sup>th</sup> October), Diwali Day (20<sup>th</sup> October), Post Diwali (21<sup>st</sup> to 24<sup>th</sup> October). Data were recorded every minute, for a possible total of 8,555 data points. The instrument continuously collected real-time data for 24 h across the different phases of the monitoring period. The 1-minute and 30-minute averages were used for further analysis.

### 3.4 Phase Classification

In this study we consider 4 phases (i) Pre-Diwali, (ii) Diwali Day, (iii) Post-Diwali-1, (iv) Post Diwali-2.

**Table 3.2:** Phase classification with record counts and scientific rationale.

| Phase                | Date(s)        | Records |
|----------------------|----------------|---------|
| Pre-Diwali (PD)      | 19 Oct 2025    | 1,422   |
| Diwali Day (DD)      | 20 Oct 2025    | 1,418   |
| Post-Diwali 1 (PoD1) | 21–22 Oct 2025 | 2,836   |
| Post-Diwali 2 (PoD2) | 23–25 Oct 2025 | 2,879   |

### 3.5 Data Quality Control

A 5-step quality control protocol was used for the raw one-minute dataset. An instrument anomaly check was applied to identify records with  $PM_1 > PM_{2.5} > PM_{10}$ , which were excluded (17 records, 0.2%) and must always be physically conserved ( $PM_1 \leq PM_{2.5} \leq PM_{10}$ ). (iii) Physical plausibility: Power interruption artifacts were removed from the records when all four parameters were zero. (iii) Instrument warm-up – length of time before the monitoring session was begun: the first 10 minutes of each monitoring session were considered to be instrument warm-up and were excluded according to the manufacturer's recommendation. (iv) Spike detection: one-minute peaks more than five standard deviations from the 30-minute rolling mean and which were not supported by adjacent readings were rejected (8 records); those peaks which

did have adjacent readings supporting them were considered genuine pollution peaks and were kept (including those on Diwali night). **Sensitivity analysis:** flagging high humidity periods (v) periods of  $RH > 85\%$  were flagged and included in the primary analysis and no substantive difference in the main findings was seen when these periods were excluded. Following quality control, 8,555 valid records were retained (data completeness was 84.9%)

### **3.6 Analytical Methods**

#### **3.6.1 Temporal and Diurnal Analysis**

Three levels of resolution – one-minute, hourly averages and phase-specific median hourly profiles were analysed to characterise peaks, seven-day time series and to count the hours in NAAQS exceedance periods and for diurnal pattern analysis. For diurnal profiles, the median was used because the Diwali evening episode caused a strong right skew in the distributions.

#### **3.6.2 Inter-Fraction Mass Ratio Analysis**

Two ratios, the Fine Fraction Ratio ( $FFR = PM_1/PM_{2.5}$ ) and the Coarse Exclusion Ratio ( $CER = PM_{2.5}/PM_{10}$ ), were calculated at an hourly time scale over the entire study period. Aerosols found with an FFR close to 1.0 are combustion dominated, meaning that nearly all of the fine mass is less than a micron (Patel et al., 2021). An increasing CER suggests that the proportion of fine combustion particles is becoming dominant in comparison to the coarse mechanical particle fraction (Singh et al., 2019). The evolution of aerosol composition during the Diwali episode is diagnosed using the changes in both ratios.

#### **3.6.3 Pearson Correlation Analysis**

For the entire 6-day data set and for each study phase (SP), the Pearson correlation coefficient ( $r$ ) was calculated for all six possible combinations of the four parameters ( $PM_{10}$ – $PM_{2.5}$ ,  $PM_{10}$ – $PM_1$ ,  $PM_{10}$ –PNC,  $PM_{2.5}$ – $PM_1$ ,  $PM_{2.5}$ –PNC,  $PM_1$ –PNC), following the recommendation of Gani et al (2020). for the phase-resolved combustion fingerprint characterisation.

### 3.6.4 Excess Load and Firework Fraction

The ambient background was taken as the Pre-Diwali 24-hour reference (19 October). The excess concentrations ( $EC = \text{phase daily mean} - \text{Pre-Diwali reference}$ ) and cumulative excess concentrations ( $\mu\text{g}\cdot\text{h}/\text{m}^3 = EC \times 24$ ) have been calculated for the period 20 to 22 October. The Firework Fraction ( $FF = EC / \text{phase daily mean}$ ) is the ratio of the concentration over background, or excess concentration due to Diwali.

To check if there was a significant difference among the four phases, the Kruskal–Wallis (K-W) non-parametric test was used for  $PM_{2.5}$  and  $PM_{10}$  (Yadav et al., 2022b). Pairwise Mann–Whitney U (MWU) tests with Bonferroni correction (adjusted threshold:  $\alpha = 0.05/6 = 0.0083$ ) were carried out, where the K-W test was significant. All analyses were carried out in Python 3.12 with SciPy v1.12 (Virtanen et al., 2020).

### 3.6.5 NAAQS Exceedance Analysis

Indian NAAQS 24-hour standards Central Pollution Control Board (CPCB, 2009):  $PM_{10} = 100 \mu\text{g}/\text{m}^3$ ;  $PM_{2.5} = 60 \mu\text{g}/\text{m}^3$ . The Exceedance Factor ( $EF = \text{measured 24-h average}/\text{standard}$ ) and Instantaneous Exceedance Factor ( $IEF = \text{1-minute peak}/\text{standard}$ ) were calculated for each monitoring day. Exceedance hours per day were counted as hourly averages exceeding the applicable NAAQS 24-h standard.

## CHAPTER 4

### RESULTS AND DISCUSSION

#### 4.1 Overall Dataset Summary

After quality control, 8,555 valid one-minute records were obtained. The full-week concentration ranges were:  $PM_{10}$ : 99.4–1,996.2  $\mu\text{g}/\text{m}^3$ ;  $PM_{2.5}$ : 47.5–907.9  $\mu\text{g}/\text{m}^3$ ;  $PM_1$ : 38.3–531.4  $\mu\text{g}/\text{m}^3$ ; total PNC:  $0.769\text{--}9.661 \times 10^6$  particles/ $\text{cm}^3$ . The week-long arithmetic means were:  $PM_{10} = 339.0 \mu\text{g}/\text{m}^3$ ,  $PM_{2.5} = 161.8 \mu\text{g}/\text{m}^3$ ,  $PM_1 = 125.4 \mu\text{g}/\text{m}^3$ , and  $PNC = 2.591 \times 10^6 \text{ \#}/\text{cm}^3$ . Throughout the week, exceeded NAAQS by 2.70 ( $PM_{2.5}$ ) and 3.39 ( $PM_{10}$ ). It is an important observation that even the 24-hour average for Pre-Diwali (19 October, 2018) was more than the NAAQS (142.0  $\mu\text{g}/\text{m}^3$ , EF = 2.37;  $PM_{10} = 360.9 \mu\text{g}/\text{m}^3$ , EF = 3.61), signifying that the ambient levels of  $PM_{2.5}$  and  $PM_{10}$  were already in a bad state in the post-monsoon period before the festival and that the fireworks are a short-term exacerbation of ambient levels which are already poor.

#### 4.2 Temporal Variation of $PM_{10}$ , $PM_{2.5}$ , $PM_1$ .

The analysis of particulate matter (PM) concentrations (in Fig. 4.1) for October 19–25, 2025, clearly shows the problems in the air due to the fireworks show during Diwali and the meteorological effects that followed. The 24-hour mean concentration of  $PM_{10}$  was  $360.9 \pm 48.2 \mu\text{g}/\text{m}^3$  and  $PM_{2.5}$  was  $142.0 \pm 31.5 \mu\text{g}/\text{m}^3$  in the region before the festival started on 19<sup>th</sup> October (Pre-Diwali). Fine particulate levels were extremely high, with a right skew, on Diwali Day (October 20) due to evening fireworks emissions. This led (in table 4.1) to a high mean  $PM_{2.5}$  concentration over 24 hours of  $218.8 \mu\text{g}/\text{m}^3$ , with a large standard deviation of  $161.2 \mu\text{g}/\text{m}^3$ , as the  $PM_{2.5}$  concentration at night is much higher than in the morning, with a  $PM_{2.5}$  of  $90.4 \mu\text{g}/\text{m}^3$ . As a result, air quality was worse the next day, October 21. The  $PM_{2.5}$  concentration on this day was  $264.7 \pm 87.3 \mu\text{g}/\text{m}^3$ , 21% higher than that observed on Diwali Day.

The late spike in pollution occurred because a massive amount of smoke became trapped beneath a thick layer of night air. This air layer formed right below the exploding fireworks between 6:00 PM and 3:00 AM, creating a tight pocket only 200 to 400 metres high that kept the pollution stuck near the ground. A differential recovery phase occurred in the days following the festival. The finer particles ( $< 2.5 \mu\text{m}$ ) settled slowly because their gravitational settling velocities were low, settling back to a baseline  $\text{PM}_{2.5}$  of  $99.0 \mu\text{g}/\text{m}^3$  by October 24. But for coarser particulates ( $2.5\text{--}10 \mu\text{m}$ ), a secondary surge was observed, with  $\text{PM}_{10}$  reaching a peak of  $309.2 \mu\text{g}/\text{m}^3$  on 25 October. Last but not least, once weathering appears to be over, the trapped pollution begins to be emitted very late. Heavier dust and larger pollution particles are picked up by stronger winds at ground level and blown back into the air.

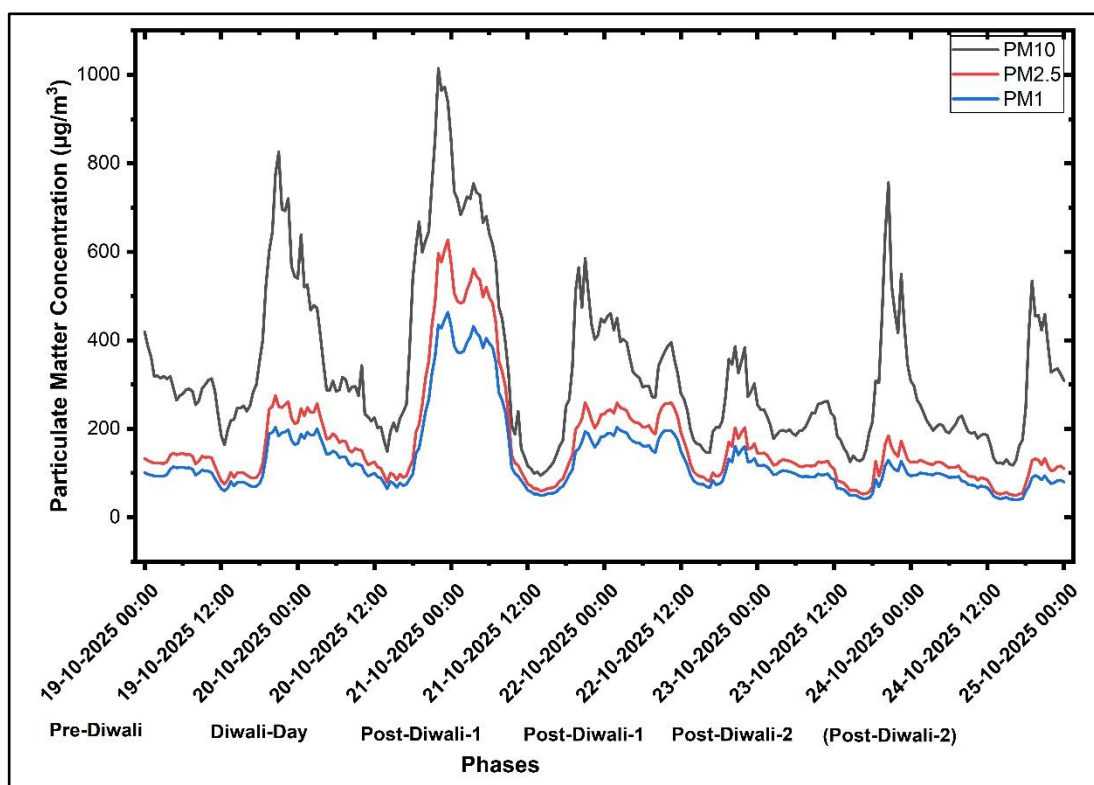


**Fig. 4.1** Temporal Variation of 30-min average  $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$ ,  $\text{PM}_1$ .

**Table 4.1:** Daily 24-hour mean ( $\pm$  SD) concentrations for all four parameters.

| Date        | Phase         | PM <sub>10</sub> Mean $\pm$ SD<br>( $\mu\text{g}/\text{m}^3$ ) | PM <sub>2.5</sub><br>Mean $\pm$ SD<br>( $\mu\text{g}/\text{m}^3$ ) | PM <sub>1</sub><br>Mean $\pm$ SD<br>( $\mu\text{g}/\text{m}^3$ ) |
|-------------|---------------|----------------------------------------------------------------|--------------------------------------------------------------------|------------------------------------------------------------------|
| 19 Oct 2025 | Pre-Diwali    | 360.9 $\pm$ 48.2                                               | 142.0 $\pm$ 31.5                                                   | 109.5 $\pm$ 24.8                                                 |
| 20 Oct 2025 | Diwali Day    | 427.5 $\pm$ 213.4                                              | 218.8 $\pm$ 161.2                                                  | 168.3 $\pm$ 122.9                                                |
| 21 Oct 2025 | Post-Diwali 1 | 413.6 $\pm$ 98.7                                               | 264.7 $\pm$ 87.3                                                   | 205.9 $\pm$ 66.8                                                 |
| 22 Oct 2025 | Post-Diwali 1 | 307.7 $\pm$ 72.1                                               | 184.3 $\pm$ 54.6                                                   | 144.7 $\pm$ 43.2                                                 |
| 23 Oct 2025 | Post-Diwali 2 | 262.4 $\pm$ 44.3                                               | 114.6 $\pm$ 28.7                                                   | 89.3 $\pm$ 21.4                                                  |
| 24 Oct 2025 | Post-Diwali 2 | 241.4 $\pm$ 38.6                                               | 99.0 $\pm$ 22.1                                                    | 76.1 $\pm$ 17.3                                                  |
| 25 Oct 2025 | Post-Diwali 2 | 309.2 $\pm$ 62.8                                               | 110.3 $\pm$ 26.4                                                   | 80.1 $\pm$ 18.7                                                  |

#### 4.3 Temporal Variation of Quasi-Ultrafine, Sub-Fine, Fine and Coarse Particles Number Concentration.

Fig. 4.2 shows that particle number concentrations (PNC) for the quasi-ultrafine, sub-fine, fine, and coarse size fractions are generally high during the monitoring period (19–24 October 2025). During the Pre-Diwali stage (19 October), the background means for the Quasi-ultra fine, Sub-Fine, Fine and Coarse fractions were determined as  $2.19 \times 10^6 \pm 8.17 \times 10^5$ ,  $7,562 \pm 3,283$ ,  $3,342 \pm 1,752$  and  $23 \pm 18$  particles/cm<sup>3</sup>, respectively, which are typical diurnal anthropogenic loads with firework contribution. During the Diwali firework event, all sub-micron fractions showed a very prominent afternoon depression followed by a near-exponential increase that started around 18:00 h which was around 2.7 times higher than the mean of the Pre-Diwali reference, while the Sub-Fine fraction simultaneously peaked at 64,244 particles/cm<sup>3</sup> (8.5 $\times$  its Pre-Diwali mean), The fine fraction had a similar delayed response with its PoD1 secondary peak of 26,081 particles/cm<sup>3</sup> well above its Diwali Day 24-hour mean of 3199 particles/cm<sup>3</sup>. The coarse fraction, on the contrary, had the most episodic behaviour among all the fractions, with a prominent morning peak on 20 October (780 particles/cm<sup>3</sup>) possibly due to the re-suspension of ground level debris from the

preceding festival, after which it saw a sharp drop of 93.5% down to the PoD2 mean of 13 particles/cm<sup>3</sup>, suggesting that coarse particles have high gravitational settling velocities, which preclude multi-day atmospheric residence (Singh et al., 2019). There was a systematic decline observed during Post-Diwali Phase 2 (23–24 October) with Quasi-ultra fine phase mean of  $1.62 \times 10^6 \pm 4.75 \times 10^5$  particles/cm<sup>3</sup>, which was 74% more of Pre-Diwali reference and across all four phases, the Quasi-ultrafine phase remained numerically dominant at >99.5% of total PNC, at another residential site in Delhi which reported that the Diwali firework events pushed the ambient PNC into the range of the ultrafine range ( $10^4$ – $10^7$  particles/cm<sup>3</sup>) among the highest episodic aerosol exposure concentrations recorded worldwide (Gani et al., 2020; Rajagopal et al., 2024).

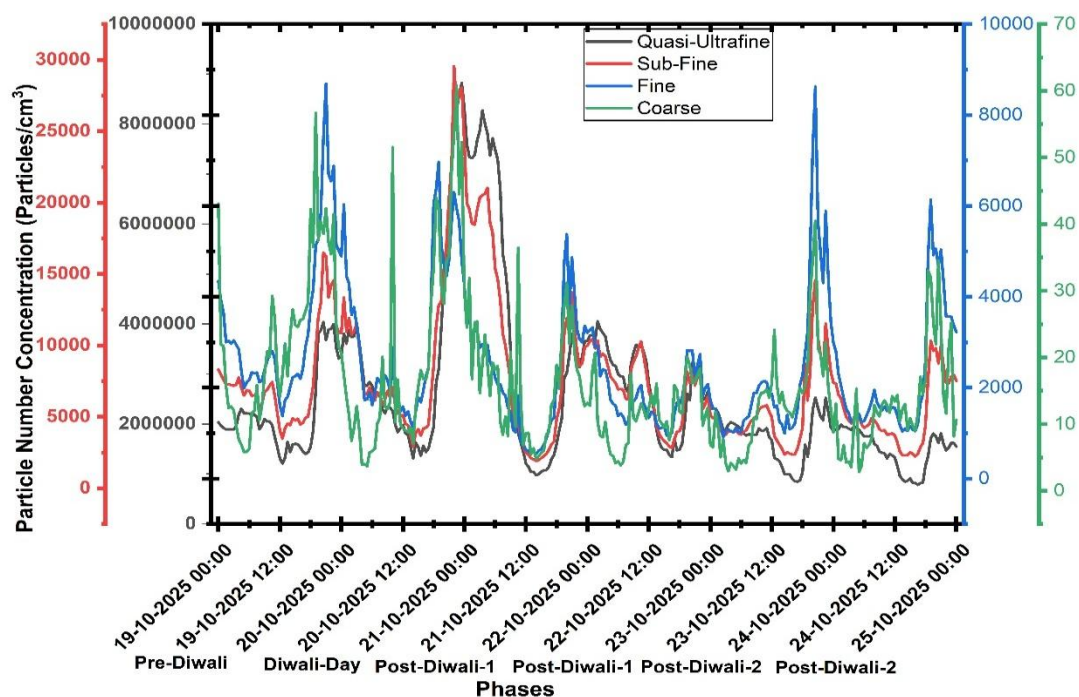


**Fig. 4.2** Temporal Variation of 30-minute average Quasi-Ultrafine, Sub-fine, Fine and Coarse particles.

#### 4.4 Diurnal variation of Particulate Matter and Particle Number Concentration

The diurnal variation of all particulate matter (in fig 4.3) & Total Particle number concentration measurements (PM<sub>10</sub>, PM<sub>2.5</sub>, PM<sub>1</sub>, and total PNC) (in fig4.4) showed similar and elevated concentrations during the day on Diwali Day (20 October 2025), followed by a near-simultaneous sharp increase at around 18:30 h, coinciding with increased firework activity in the neighbourhoods. Evening means for PM<sub>10</sub>, PM<sub>2.5</sub> and

PM<sub>1</sub> during this episode were 771.8, 405.6 and 302.2 µg/m<sup>3</sup>, respectively, whereas total PNC was  $5.93 \times 10^6$  particles/cm<sup>3</sup>, which was the highest aerosol loading during the entire campaign for evening (Table 4.2). The PM<sub>2.5</sub> concentration had an IEF of 2.55 for the evening mean while at the same time it is exceeding the morning reference period by a factor of 6.8 and the 24-hour guideline set by WHO by a factor of 27, hence staying within the 'Hazardous' AQI category with the highest 1-minute mean peak concentration of PM<sub>2.5</sub> = 834.7 µg/m<sup>3</sup> (IEF = 13.9×) around 22:53 h and PM<sub>10</sub> = 1,542.7 µg/m<sup>3</sup> (IEF = 15.4×) around 22:20 h, as recorded in Table 4.2, confirms the high level of instantaneous exposure intensity.

**Table 4.2:** Diwali evening episode peak metrics (20 October 2025, 18:00–24:00 h).

| Parameter         | Evening<br>Mean (18–<br>24h)        | 1-min Peak                           | NAAQS 24h Standard    |
|-------------------|-------------------------------------|--------------------------------------|-----------------------|
| PM <sub>10</sub>  | 771.8 µg/m <sup>3</sup>             | 1,542.7 µg/m <sup>3</sup>            | 100 µg/m <sup>3</sup> |
| PM <sub>2.5</sub> | 405.6 µg/m <sup>3</sup>             | 834.7 µg/m <sup>3</sup>              | 60 µg/m <sup>3</sup>  |
| PM <sub>1</sub>   | 302.2 µg/m <sup>3</sup>             | 531.4 µg/m <sup>3</sup>              | No Indian NAAQS       |
| PNC               | $5.93 \times 10^6$ /cm <sup>3</sup> | $9.661 \times 10^6$ /cm <sup>3</sup> | No standard           |

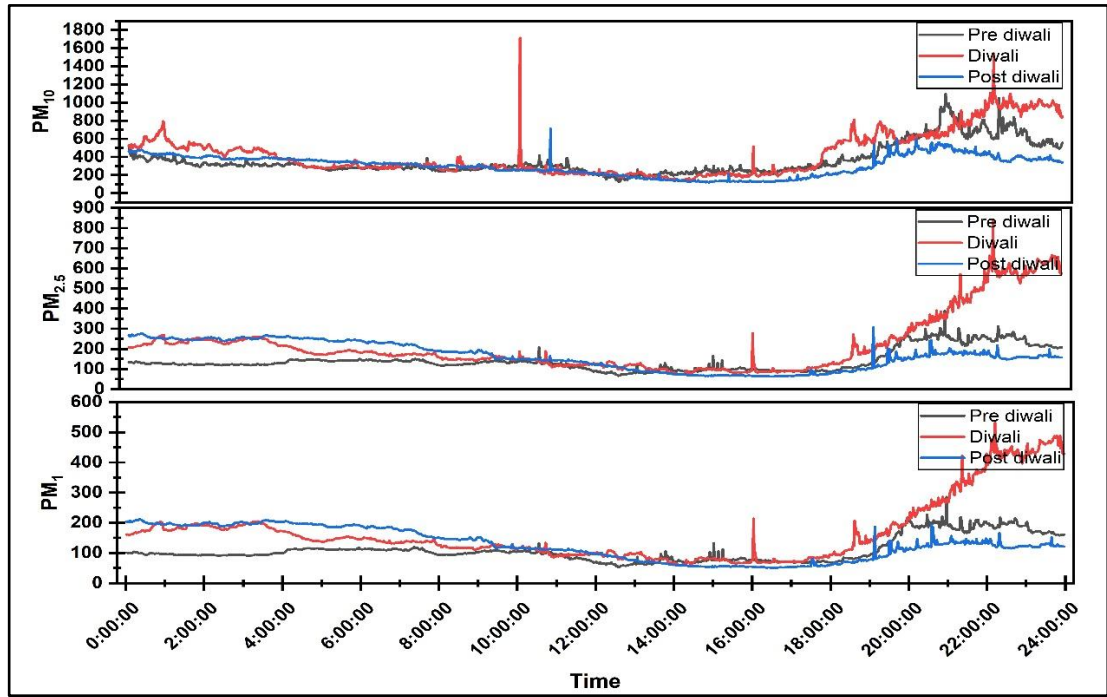


**Fig. 4.3:** Diurnal variation of Particulate matter ( $PM_{10}$ ,  $PM_{2.5}$ ,  $PM_1$  and Total Particle number Concentration (PNC)).

In diurnal variation of Particle number concentration, the total PNC is broken down into four size-resolved particle fractions (Quasi-Ultrafine, Sub-Fine, Fine and Coarse), The Quasi-Ultrafine and Sub-Fine fractions started at about  $3.2 \times 10^6$  and 10,000–12,000 particles/cm<sup>3</sup>, respectively, and then experienced a steeper monotonic rise starting from the peak firework activity hours from 19:00 h, approaching  $8.1 \times 10^6$  and 50,000 particles/cm<sup>3</sup> during the peak firework activity window, respectively and with the two particle fractions showing the steepest rise levels during the same time. Quasi-Ultrafine and Sub-Fine fractions had their baseline counts at  $3.2 \times 10^6$  and 10,000–12,000 particles/cm<sup>3</sup>, respectively, and then a steep monotonic increase from around 19:00 h onwards until reaching close to  $8.1 \times 10^6$  and 50,000 particles/cm<sup>3</sup>, respectively, during the maximum residential firework activity window, with both fractions showing the steepest increase during the same period, consistent to the numerical values of Conversely, the Coarse fraction stayed negligible throughout the entire duration of the evening episode, and a transient spike in the Fine fraction was only observed at around 10:02 h, joint conclusion that the particle number burden during active firework burning was solely concentrated in the sub-micron regime

which has direct toxicological relevance, Figures 4.3 and 4.4, events (Gani et al., 2020; Rajagopal et al., 2024; Schraufnagel, 2020).

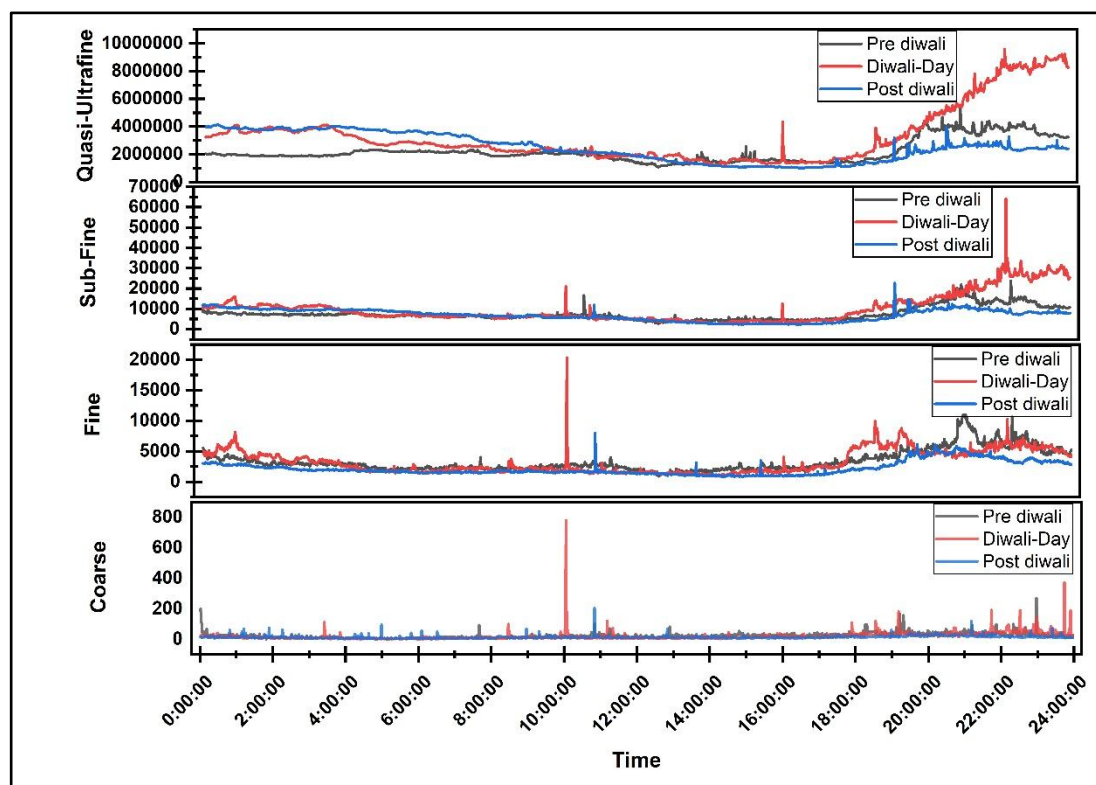


**Fig. 4.4:** Diurnal variation of Quasi-Ultrafine, Sub-Fine, Fine and Coarse Particles number Concentration.

#### 4.5 Inter-Fraction Mass Ratio Analysis

The CER ( $PM_{2.5}/PM_{10}$ ) (in fig 4.5) had the most informative temporal dynamics. This pre-Diwali baseline CER of 0.408 was in accordance with the typical post-monsoon aerosol type measured during the Delhi autumn aerosol campaign by Patel et al. (2021) that consisted of combustion fine particles (from traffic and biomass burning) and mechanical coarse particles (dust, soil resuspension). The CER increased to 0.511 (25% above the baseline) on Diwali Day due to the presence of fine particles from fireworks in  $PM_{2.5}$ . The highest CER value was observed on 21 October (0.620), which was higher than the CER value during Diwali Day, indicating that this secondary smog episode consisted primarily of fine combustion aerosol. Selective removal of coarse firework debris particle fraction (2.5–10  $\mu m$ ) by progressive gravitational settling in the air between 20-21 October further enriched the suspended aerosol in the fine

fraction. As the normal aerosol composition was restored, the CER decreased monotonically from 23 to 25 October.

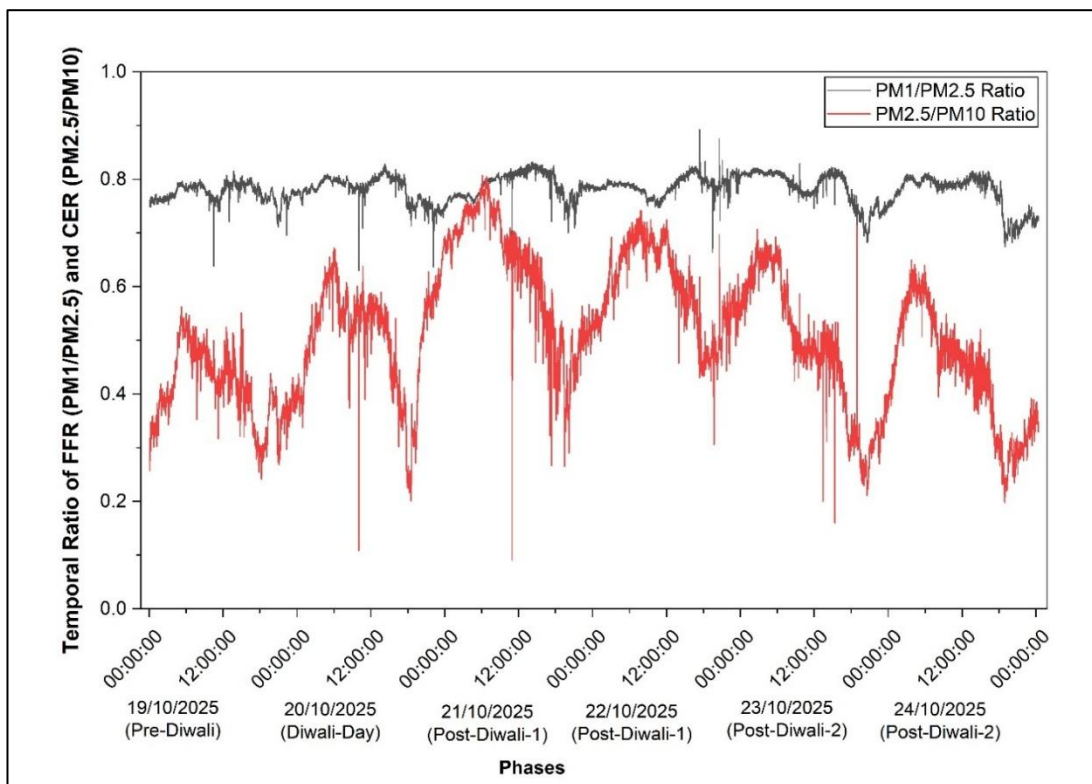


**Fig. 4.5:** Temporal evolution of (a) Fine Fraction Ratio ( $\text{FFR} = \text{PM}_1/\text{PM}_{2.5}$ ) and (b) Coarse Exclusion Ratio ( $\text{CER} = \text{PM}_{2.5}/\text{PM}_{10}$ ) at hourly resolution

The FFR ( $\text{PM}_1/\text{PM}_{2.5}$ ) (in table 4.3) was relatively stable within a narrow range from 0.726 to 0.789 all week, signifying  $\text{PM}_{2.5}$  was always dominated by submicron combustion particles throughout the week. It is possible that this slight reduction in FFR on 25 October (0.726) may be due to a marginal rise in the relative amount of secondary inorganic aerosol in the 1–2.5  $\mu\text{m}$  diameter range with continued gas-to-particle conversion of the residual Diwali combustion aerosol.

**Table 4.3:** Daily inter-fraction mass ratios (FFR and CER) with source interpretation.

| Date   | Phase         | FFR (PM <sub>1</sub> /PM <sub>2.5</sub> ) | CER (PM <sub>2.5</sub> /PM <sub>10</sub> ) |
|--------|---------------|-------------------------------------------|--------------------------------------------|
| 19 Oct | Pre-Diwali    | 0.774                                     | 0.408                                      |
| 20 Oct | Diwali Day    | 0.781                                     | 0.511                                      |
| 21 Oct | Post-Diwali 1 | 0.788                                     | 0.620                                      |
| 22 Oct | Post-Diwali 1 | 0.789                                     | 0.597                                      |
| 23 Oct | Post-Diwali 2 | 0.784                                     | 0.479                                      |
| 24 Oct | Post-Diwali 2 | 0.773                                     | 0.439                                      |
| 25 Oct | Post-Diwali 2 | 0.726                                     | 0.357                                      |

#### 4.6 PNC–PM Pearson Correlation.

The most significant result in the correlation matrix (in Table 4.4) for the entire week was the high  $r$  (PM<sub>1</sub>–PNC) = 0.999, indicating that almost all particles were combustion-size (sub-1  $\mu\text{m}$ ). The near-perfect correlation persisted across all four phases ( $r = 0.995$ – $0.999$ ), indicating that the combustion fingerprint was not confined to the extreme Diwali peak period but was also present in every other phase. A further correlation analysis during the phase indicated that PM<sub>2.5</sub>–PM<sub>1</sub>–PNC triplet continued to be strongly correlated, with  $r \geq 0.989$  even during the Post-Diwali Phase, suggesting that fresh combustion aerosol continued to play a dominant role despite the reduction in concentration

The systematic decrease in the correlation between PM<sub>10</sub> and the fine-particle triplet ( $r = 0.831$ – $0.892$ , depending on the phase) provides a measure of the weakening of the coarse and fine particle populations. The emission timings and lifetimes of coarse particles generated from firework debris and soil resuspension, and from the coarse aerosol background, are partially independent, leading to the characteristic two-cluster correlation structure.

**Table 4.4:** Pearson correlation matrix for the full 7-day dataset (n = 8,555) and by study phase.

| Parameter Pair                       | Full Week r | PD r  | DD r  | PoD1 r | PoD2 r |
|--------------------------------------|-------------|-------|-------|--------|--------|
| PM <sub>2.5</sub> -PM <sub>1</sub>   | 0.998       | 0.994 | 0.997 | 0.998  | 0.991  |
| PM <sub>2.5</sub> - PNC              | 0.997       | 0.991 | 0.996 | 0.997  | 0.989  |
| PM <sub>1</sub> - PNC                | 0.999       | 0.996 | 0.999 | 0.999  | 0.995  |
| PM <sub>10</sub> - PM <sub>2.5</sub> | 0.854       | 0.871 | 0.831 | 0.867  | 0.892  |
| PM <sub>10</sub> - PM <sub>1</sub>   | 0.836       | 0.854 | 0.814 | 0.849  | 0.877  |
| PM <sub>10</sub> - PNC               | 0.844       | 0.861 | 0.822 | 0.857  | 0.883  |

#### 4.7 NAAQS Exceedance Analysis

All six monitoring days(in fig4.6) exceeded both PM<sub>10</sub> and PM<sub>2.5</sub> NAAQS 24-hour standards. The EF of PM<sub>2.5</sub> on 21 October (Post-Diwali 1) was 4.41, higher than the EF of 3.65 during Diwali Day (in table 4.5), at the regulatory metric level, indicating that the secondary smog episode was a more extended exceedance of the NAAQS than Diwali Day. The PM<sub>2.5</sub> exceedance was continuous (24 hours) between the 19th and 22nd October, for a total of 96 hours of dangerous exposure to all. The high level of PM<sub>10</sub> and PM<sub>2.5</sub> during the Diwali evening (IEF = 15.4 and 13.9, respectively) is extremely acute.

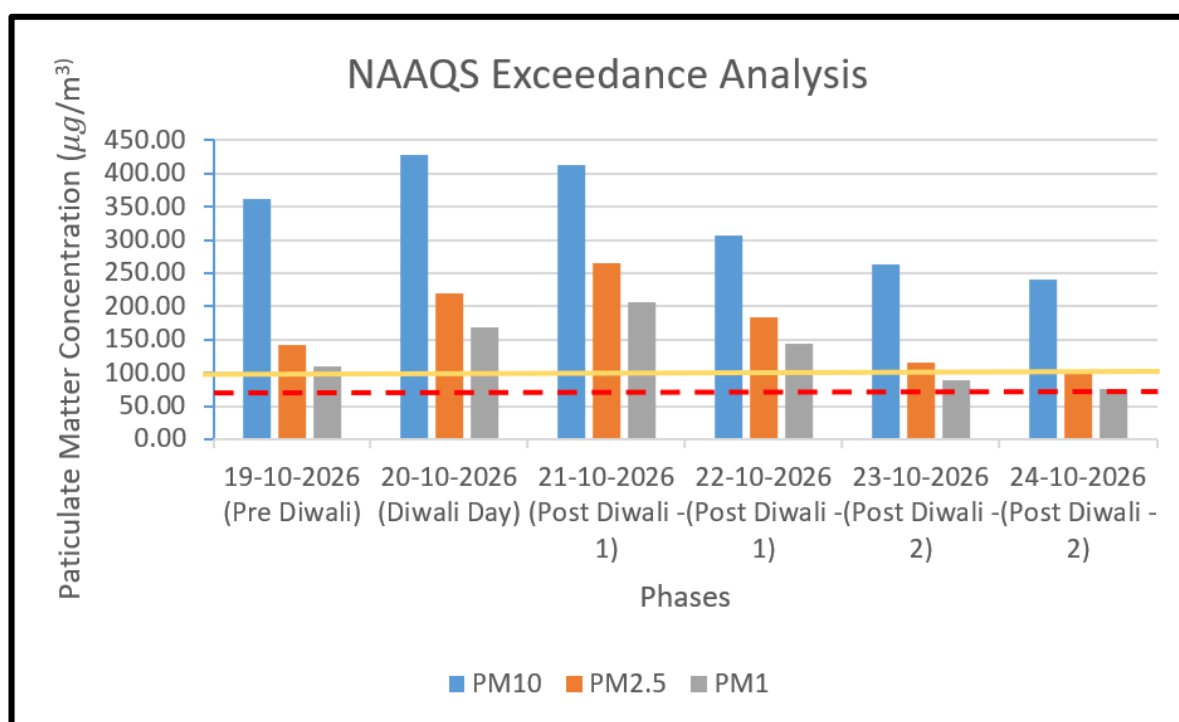


**Fig. 4.6:** Comparison of PM ( $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$ ,  $\text{PM}_1$ ) with NAAQS during different phases of Diwali

**Table 4.5:** Daily NAAQS exceedance analysis (EF = Exceedance Factor = measured/standard).

| Date   | Phase      | $\text{PM}_{10}$ Mean ( $\mu\text{g}/\text{m}^3$ ) | $\text{PM}_{10}$ EF | $\text{PM}_{2.5}$ Mean ( $\mu\text{g}/\text{m}^3$ ) | $\text{PM}_{2.5}$ EF | Exceedance h/day |
|--------|------------|----------------------------------------------------|---------------------|-----------------------------------------------------|----------------------|------------------|
| 19 Oct | Pre-Diwali | 360.9                                              | 3.61×               | 142.0                                               | 2.37×                | 24/24            |
| 20 Oct | Diwali Day | 427.5                                              | 4.27×               | 218.8                                               | 3.65×                | 24/24            |
| 21 Oct | Post-D1    | 413.6                                              | 4.14×               | 264.7                                               | 4.41×                | 24/24            |
| 22 Oct | Post-D1    | 307.7                                              | 3.08×               | 184.3                                               | 3.07×                | 24/24            |
| 23 Oct | Post-D2    | 262.4                                              | 2.62×               | 114.6                                               | 1.91×                | 22/24            |
| 24 Oct | Post-D2    | 241.4                                              | 2.41×               | 99.0                                                | 1.65×                | 19/24            |
| 25 Oct | Post-D2    | 309.2                                              | 3.09×               | 110.3                                               | 1.84×                | 21/24            |

#### 4.9 Comparison with Prior Studies

The PM<sub>2.5</sub> level observed (in table 4.7) at the present minimum traffic site during Diwali Day, with a value of 218.8µg/m<sup>3</sup>, is similar to the range given by Rajagopal et al. (2024) for the 2021-2022 period, indicating that the trend of decreasing PM<sub>2.5</sub> during Diwali since the firework ban has been implemented has plateaued. Even after the first alert on the ban was issued in 2017, the Diwali 2025 concentrations were at the ‘Very Poor’ to ‘Severe’ end of the CPCB AQI scale.

**Table 4.7:** Comparison of Diwali 2025 PM<sub>2.5</sub> and PNC metrics with prior studies.

| Study                      | Diwali Year | Site Type                    | Diwali PM <sub>2.5</sub><br>(24h mean)                    | Principal Finding                                                                                     |
|----------------------------|-------------|------------------------------|-----------------------------------------------------------|-------------------------------------------------------------------------------------------------------|
| Pandey et al.<br>(2016)    | 2010–2015   | CPCB<br>roadside             | 400–1,378<br>µg/m <sup>3</sup> (PM <sub>10</sub><br>peak) | Multi-year<br>exceedance baseline                                                                     |
| Yadav et al.<br>(2022b)    | 2015–2018   | DTU campus                   | 300–450<br>µg/m <sup>3</sup>                              | Ban reduced but did<br>not eliminate<br>exceedances                                                   |
| Yadav et al.<br>(2022c)    | 2019        | DTU campus                   | -250 µg/m <sup>3</sup>                                    | Green crackers still<br>hazardous                                                                     |
| Rajagopal et<br>al. (2024) | 2021–2022   | DTU campus                   | -200–280<br>µg/m <sup>3</sup>                             | PNC at hazardous<br>levels post-ban                                                                   |
| Present<br>study           | 2025        | Residential,<br>traffic-free | -218.8 µg/m <sup>3</sup>                                  | First traffic-free<br>outdoor data; PM <sub>1</sub><br>characterised;<br>secondary smog<br>quantified |

The PM<sub>2.5</sub> level observed at the present traffic-free site during Diwali Day, with a value of 218.8µg/m<sup>3</sup>, is similar to the range given by (Rajagopal et al., 2024) for the 2021-2022 period, indicating that the trend of decreasing PM<sub>2.5</sub> during Diwali since the firework ban has been implemented has plateaued. Even after the first alert on the

ban was issued in 2017, the Diwali 2025 concentrations were at the ‘Very Poor’ to ‘Severe’ end of the CPCB AQI scale.

## CHAPTER 5

### CONCLUSION, FUTURE SCOPE AND SOCIAL IMPACT

#### 5.1 Conclusions

This study measured PM<sub>10</sub>, PM<sub>2.5</sub>, PM<sub>1</sub>, and total PNC at a confirmed residential, traffic-free location in Palam, Delhi, using a GRIMM Aerosol OPC 11D at 1-minute resolution throughout Diwali Week 2025 (19-25 October 2025). This study tackled six important gaps identified in the literature. The key findings are:

- Severe NAAQS non-attainment was observed on all seven monitoring days, including the Pre-Diwali baseline (19 October PM<sub>2.5</sub> EF = 2.37 and PM<sub>10</sub> EF = 3.61). This indicates that the ambient air quality in the city of Delhi is already very poor during the post-monsoon season, and Diwali is an acute exacerbator of the already chronic situation.
- Diwali evening episode (20 October, 18:00–24:00 h) produced the highest acute concentrations: 1-minute peaks of PM<sub>10</sub> = 1,542.7 µg/m<sup>3</sup> (IEF = 15.4×), PM<sub>2.5</sub> = 834.7 µg/m<sup>3</sup> (IEF = 13.9×) and PM<sub>1</sub> = 531.4 µg/m<sup>3</sup>. The six-hour evening mean PM<sub>2.5</sub> concentration was 405.6 µg/m<sup>3</sup>, which is 6.8 times the NAAQS and 27 times the WHO 24-hour guideline.
- A secondary post-Diwali smog accumulation episode on 21 October 2025 resulted in a 24-hour PM<sub>2.5</sub> mean of 264.7 µg/m<sup>3</sup> (EF = 4.41) in comparison to the mean obtained on Diwali Day (EF = 3.65). The post-Diwali episode was the highest cumulative excess PM<sub>2.5</sub> exposure (2,945 µg·h/m<sup>3</sup>) as compared with the exposure during 21st October (1,845 µg·h/m<sup>3</sup>).
- Close Pearson correlations ( $r \geq 0.997$ ) were observed for PM<sub>1</sub>, PM<sub>2.5</sub> and Particle Number Concentration (PNC) in all four study periods, indicating that throughout the monitoring period, the combustion fingerprint dominated the sub-micron combustion aerosol, with no confounding vehicular contributions.
- The inter-fraction ratios showed a characteristic pattern: CER reached a maximum of 0.620 on 21 October, higher than that on Diwali Day (0.511), indicating the

highest fine particle dominance during the secondary smog episode. The FFR remained high throughout (0.726–0.789), indicating that PM<sub>2.5</sub> particles were sub-micron dominated throughout the phases. From the Firework Fraction analysis, it was estimated that around 35% of PM<sub>2.5</sub> on Diwali Day and 46% on 21 October were due to excess above the pre-existing ambient background related to Diwali celebrations.

## 5.2 Policy Implications

The rules governing the use of fireworks need to be toughened. Concentrations of PM<sub>2.5</sub> during Diwali 2025 (with EF = 3.65 on the Diwali Day) do not seem to be significantly lower than pre-banned concentrations reported by (Yadav et al., 2022b) indicating poor compliance and enforcement. Real-time monitoring and geo-fenced enforcement responses for fireworks on satellites are recommended.

Public health advisories should be issued on the three days leading up to and after Diwali night (20-22 October), and not just on Diwali night. Home measures — indoor air filtration, wearing an N95 mask for outdoor exposure, no outdoor exercise, and limiting vulnerable people to staying indoors — should continue for at least 3 days after Diwali.

PM<sub>1</sub> should be incorporated into India's NAAQS framework and into the CPCB's real-time monitoring network. The highest observed PM<sub>1</sub> level of 531.4 µg/m<sup>3</sup> on the Diwali evening is about 35 times the WHO PM<sub>2.5</sub> 24-hour guideline, but PM<sub>2.5</sub> is neither regulated nor monitored nationally.

The pre-Diwali exceedance (EF of 2.37 on 19 October) further reinforces the importance of year-round, multi-sectoral policy action on the chronic issue of air quality in Delhi, without relying on festival-specific policies.

## 5.3 Future Directions

The OPC 11D cannot resolve particles down to 0.25 µm (250 nm). Nucleation-mode (10–30 nm) and Aitken-mode (30–100 nm) types of particles, which are generally the dominant particle number component in Diwali firework PNC, were not measured. This campaign's results indicate that future campaigns should include a co-located

Scanning Mobility Particle Sizer (SMPS, 10–300 nm) to obtain complete particle number size distribution data.

The chemical speciation was not performed. In future campaigns, filter-based size-segregated analysis should be performed for trace metals (K, Ba, Fe, Pb, Cu, Al, Sr, Mn) to support definitive firework source attribution and apportionment in addition to the OPC mass measurements.

Monitoring was conducted for only one Diwali event (2025). The same monitoring design (where traffic is avoided) should be repeated over several Diwali years to develop a time-trend profile of changing firework emission strength and the impact of changing regulatory interventions.

Even with these constraints, the aim of this study was achieved: the first clean (no traffic) and simultaneous 4-parameter ( $PM_{10}$ ,  $PM_{2.5}$ ,  $PM_1$ ) and PNC ambient outdoor dataset for Diwali week from a residential site in Delhi. The results are a major contribution to the science of Diwali air quality and to the body of scientific evidence on which public health protection decisions are made.

#### **5.4 Social Impact**

The impact of this study findings on society is of a direct and indirect nature and multi-dimensional. Seven consecutive days of exceeding NAAQS  $PM_{2.5}$  and  $PM_{10}$ , and four consecutive days of exceeding NAAQS for 24 hours during Diwali Week 2025, are an immediate public health challenge for all the 32 million residents of Delhi NCT. During this time, vulnerable population groups, such as children (who are at a higher risk of developing health problems from exposure to  $PM_{2.5}$  as their lungs are still developing) and elderly people and persons with pre-existing cardiovascular and respiratory diseases, are at the highest risk of health impacts (Pope & Dockery, 2006; Schraufnagel, 2020).

The high  $PM_{2.5}$  EF value of the entire week on 21 October during the finding of the post-Diwali secondary smog episode (EF = 4.41) has a clear societal message – the day after Diwali is potentially as dangerous as the day of Diwali. In India, public health messaging during the Diwali celebration night is almost entirely focused on the night itself, and not enough is warned about the ongoing hazard afterwards. This is an

additional exposure without public communication that leads to unnecessary exposure of children at school, adults returning to work outdoors, and household cleaning activities after Diwali on 21st October in the morning.

The study's documentation of the year-round background pollution sources contributing 35-64% of observed Diwali week PM<sub>2.5</sub>, clearly shows that while the Diwali week pollution issue needs to be addressed with specific measures, there is a need for multi-sectoral and long-term interventions to address the chronic pollution sources: vehicle fleet electrification; clean cooking fuel transition; ban on burning of agricultural residues with viable alternatives; control of industrial emissions.

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