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Chapter – 1

Introduction

The Union Territory of Delhi ranks amongst one of the most polluted cities across the world, having concentrations of PM less than 2.5 micrometers exceeding 350 micrograms per cubic meter of air recorded and analyzed in May 2014 (Kanawade et al., 2020). The elevated levels of PM are attributed to increased vehicular emissions and a large number of coal-fired power plants across the urban regions, which contributes to the different sizes of particles which are present in the atmosphere (Guttikunda & Gurjar, 2012). Pollution poses a significant threat to human health and does harm to human well-being. Research conducted by the WHO states that around seven million individuals have died globally due to air pollution related factors (Shivani et al., 2019). This includes mortalities caused due to exposure to numerous harmful pollutants in both indoor and outdoor environment (Sharma et al., 2023). Vehicular fugitive emissions and industrial pollutants are the key contributors to air pollution both in India and across the world (Sahu et al., 2011). Evidence of fossil fuel residues in form of soot, carbon particles, and fine metal particles emitting from vehicles and industrial activities serve as key examples of these external contaminants (Singh et al., 2018). All such emissions include noxious gases such as SO₂, CO, and NO₂, among others. In addition to this there are numerous hazardous gases released due to burning of fuels during cooking, smoking etc. (Sengupta et al., 2022). In most developing nations, urban air pollution is one of the critical health issue. Most megacities experience deteriorating air quality levels which exceeds the stipulated national standards or norms for ambient air quality. The rapid increase in pollution sources and the improper implementation of control measures makes it hard to assess and maintain air quality in these big cities. Urban spaces consist of numerous activities which cause pollution and degrade quality of air. India's capital, Delhi, exhibits elevated levels of pollution in comparison to other major cities in developing countries. The rapid pace of population growth fuels the growth of associated sectors of economy such as

commercial, residential, and logistics and transportation, which subsequently leads to increased energy usage. Delhi has seen significant growth in number of motor vehicles over the past 15 years, which has grown from 34.56 million in 2000 to 104.83 lakh in 2017. Further, the rapid pace of commercial activities has led to increase in the number of DG sets, restaurants, hotels and other ancillary activities. This increase in the usage of products derived from crude petroleum has contributed to severe air pollution (Gulia et al., 2021). Historically, the impulse of industrialization and urban sprawl in Delhi has been key contributor to the escalating levels of pollution in the city. While this rapid transformation has stimulated the economic growth, however it also severely compromised the standards of air quality due to increase in industrial emissions, vehicular pollution, and other contaminants. Additionally various geographical and meteorological factors exacerbate the situation, which renders Delhi's air pollution as a complex, challenging and critical issue with extensive repercussions. Owing to which extensive researches have been conducted on impact of Delhi's air pollution on health of human and animals alike. The Prolonged exposure to sub-standard air quality can lead to long-term impacts and morbidities, as studies have linked it to various pulmonary and cardiovascular diseases like Bronchitis, Asthma etc. PM in the air of Delhi, especially PM_{2.5} and PM₁₀, plays a significant role in health issues experienced by majority of residents (Deshpande et al., 2024). Moreover, studies have indicated that vulnerable demographic cohorts, like children, the elderly, and individuals with underlying health conditions, are more severely affected by air pollution. This demographic aspect underscores and highlights the importance of targeted interventions and need of affirmative policy actions. The economic burden of health issues in Delhi owing to air pollution is another critical consideration. The substantial direct and indirect expenses—which encompasses healthcare costs and it includes major chunk of Out-of-Pocket Expenditure, borne by lower and middle class, and reduced productivity—underscore the importance of effective pollution management and mitigation strategies. In summary, the alarming air pollution crisis in Delhi poses a significant

public health challenge and a serious environmental issue, which requires urgent redressal. Also due to its intricate effects on the economy, social life, public health, and at-risk populations, it is essential to comprehend, monitor, assess and address the air pollution via a holistic bottom-up approach (Deshpande et al., 2024). Living a healthy and disease life requires clean air; however, air pollution has emerged as a global conundrum, with urban areas being particularly at a large risk due to their highly dense agglomerations. Asian megacities like Beijing, Delhi have gained significant global attention over time. Air quality of India's megacities, at the onset of winters is prominently highlighted in both print and media, with special emphasis on Delhi, being the capital city. Air pollution is seen as a contemporary plague like epidemic with intricate links to increased instances of mortality and morbidity, which significantly impacts the developing countries especially those with lower incomes. Air pollution now stands as a leading risk factor for disease burden and premature deaths globally. Its detrimental impacts can be felt by individuals anywhere across the world, irrespective of their birthplaces. Indian cities are undeniably ranked as one of the most severely affected polluted regions. Out of the thirty cities with the severe pollution levels worldwide, twenty-two of them, are situated in India, with Delhi, occupying the top slots, as its annual $PM_{2.5}$ concentrations is nearly ten times over the prescribed standards set by the WHO. Delhi is also enmeshed in the negative cycle of air pollution and health standards. This has led to alarmingly high AQI readings across Delhi, which is the largest city in the country and has attracted significant media and political attention in recent years; there are doubts amongst the residents about the desirability of living in megacities now (Fig 1.1). At the same time, these big cities show great global diversity and are prone to dwindling air quality due to increase in levels of PM. The struggle to combat the menace of pollution in megacities is hindered by the lack of comprehensive understanding about the complex origins of air pollution and its varying mix of natural and anthropogenic sources (Sahu et al., 2023). Numerous studies have revealed that megacities experiencing alarming pollution levels, particularly affecting the

geriatric population and small children, show increase in instances of respiratory and cardiovascular ailments. The sharp decline in Delhi's air quality during winters is largely attributed to stubble burning in North-western states of Punjab and Haryana. To alleviate the pollution load and provide respite, the then government of Delhi, introduced the Odd and Even vehicle policy on roads; however, its impact was minimal. The blame-game for the pollution dilemma is frequently shifted from one state (or agency) to another, with each entity offering its own perspective on addressing the escalating levels of pollution in Delhi. Researchers worldwide have observed that Delhi's air quality has not improved despite various efforts and actions by numerous stakeholders. It has been confirmed that the air in Delhi remains unsafe to breathe, with minimal improvement. A deep understanding of the complexities and extent of pollution sources in a megacity is requisite for studies on air quality, regional atmospheric chemistry, and climate considerations. However, due to the numerous of primary and secondary factors which contribute to the issue, coupled with the complex technologies used in combustion processes, it becomes challenging to accurately identify and quantify the neglected sources. The wide range of pollution sources and their changing nature adds further complexity to this pressing issue (Sahu et al., 2023).

1.1 Common air pollutants

Poor air quality carries significant socio-environmental consequences, which makes it a serious global concern, warranting urgent measures to redress it. It not just represents a major threat to the climate and ecosystems but also poses significant risks to human health (Dalai et al., 2024). Furthermore, inventorization of emission sources are done for a range of fugitive pollutants emanating from various sectors, which encompass non-energy sources such as road dust, C&D dust and other airborne emissions from fuel management, and storage, as well as energy sources like logistics, transportation, power generation, industry, and residential areas. Emission inventories generally include criteria pollutants that act as precursors to secondary PM and O₃.

These pollutants consist of NH_3 , VOCs, NO_x , SO_2 , CO, PM_{10} , and $\text{PM}_{2.5}$ (Gupta et al., 2022). Additionally, the origin of air pollutants are numerous and difficult to quantify, and manifests as either natural or anthropogenic. Common air pollutants among these include:

1.1.1 Sulfur dioxide (SO_2)

SO_2 is a non-flammable gas that transforms into sulfates, and are precursors to secondary particles. It is usually generated by the combustion of fossil fuels and biomass and also occurs naturally from volcanic eruptions, producing a colorless, toxic non-flammable gas.

1.1.2 Nitrogen Oxides (NO_x)

NO_x refers to a noxious combination of nitric oxide and nitrogen dioxide created through combustion processes. It primarily emits as NO, which is then converted into NO_2 by reactions with ozone. The concentration of NO_x in ambient air may vary significantly, and both these components have their own air quality standards respectively.

1.1.3 Particulate Matter (PM)

PM is categorized as per its particle size, which includes Total Suspended Particles (dust), PM_{10} , $\text{PM}_{2.5}$, and ultrafine particles. Primary PM is emitted directly into the atmosphere as minute solid particles, while secondary PM forms by reactions which involves atmospheric gases. Its sources include road dust, agricultural practices (stubble burning), vehicular emissions, wood burning, forest fires, and industrial activities (cupola furnace, metal ingot castings etc). A notable chunk of $\text{PM}_{2.5}$ consists of secondary PM, which can arise from NO_x , SO_2 , and NH_3 .

1.1.4 Carbon Monoxide (CO)

CO is a colourless and odourless gas that is formed due to the incomplete burning of fossil fuel, industrial activities, and natural occurrences such as wildfires.

1.1.5 Volatile Organic Compounds (VOCs)

VOCs are organic substances like benzene, ethylene glycol, and formaldehyde that vaporize easily under atmospheric conditions. These compounds act as precursors to ground-level O₃ and particulate matter, thereby contributing to formation of tropospheric smog. Natural emissions tend to outweigh anthropogenic ones.

1.1.6 Ozone (O₃)

Ozone occurs naturally in atmosphere and in troposphere it is formed by chemical reactions between NO_x and VOCs in the presence of sunlight. While it protects against ultraviolet radiation in the upper atmosphere, it can lead to health problems when present at ground level.

1.1.7 Ammonia (NH₃)

Ammonia is a highly reactive substance that leads to the formation of ammonium sulfate and ammonium nitrate, which are the principal constituents of secondary PM, accounting for 94% of NH₃ emissions in Europe (European Environment Agency, 2017).

1.2 Health effects of air pollution

Air pollution is associated with numerous negative health impacts on the general population, such as an increase in respiratory illnesses, compromised ventilatory function, eye irritation, a rise in cardiovascular-related conditions, and a weakened immune response. Additionally, air pollution contributes to short-term mortality from respiratory and cardiovascular diseases, as well as long-term mortality linked to the carcinogenic nature of certain pollutants. It is a leading contributor to non-communicable diseases, with at least 3% of cardiopulmonary deaths and 5% of lung cancer fatalities attributed to PM. In 2016, ambient air pollution accounted for 7.5% of worldwide deaths,

with 27.5% of fatalities from Lower Respiratory Tract Infections and 26.8% from COPD connected to air pollution (Mark LI & Léo Mallat, 2018).

AIR QUALITY INDEX (AQI)	CATEGORY
0-50	Good
51-100	Satisfactory
101-200	Moderate
201-300	Poor
301-400	Very Poor
401-500	Severe

Figure.1.1 Air Quality Index (Aastha Ahuja, 2019)

1.3 GRAP

The NCR of India, which includes Delhi and nearby districts, has been addressing air pollution through a collection of policies and initiatives known as the GRAP. The GRAP involves a number of actions by various government agencies aimed at preventing the deterioration and degradation of air quality in the Delhi-NCR area. The MoEF&CC announced this plan in 2017. The CAQM is responsible for implementing the GRAP. The GRAP scheme comprises of a series of emergency responses implemented in four phases, depending on the severity of air pollution, which is evaluated using the AQI. According to the SAFAR, the stges are classified as Stages I, II, III, and IV and are labeled "Poor" (AQI 201–300), "Very Poor" (AQI 301–400), "Severe" (AQI 401–450), and "Severe +" (AQI >450), respectively (CAQM, 2022).

1.3.1 GRAP Stage I

During GRAP Stage I, which corresponds to 'Poor' Air Quality (when AQI ranges from 201 to 300), the government enforces measures aimed at reducing dust and improving environmental management for C&D projects on sites larger than 500 sqm. These measures include registration of projects on an online platform for monitoring, collection and disposal of various types of waste, sweeping and misting roads to curb dust, utilizing both mobile and mounted anti-smog guns, prohibiting the open burning of biomass and MSW, ensuring compliance with traffic flow and minimizing the road congestions, taking necessary action against polluting industrial units, enforcing pollution control regulations across different sectors, and encouraging the public to report pollution-related incidents on various apps like: Green Delhi App, Sameer etc. The document also includes a citizen charter which enlists the recommendations on how individuals can contribute to pollution control drive (CAQM, 2022).

1.3.2 GRAP Stage II

In GRAP Stage II, further strict measures for controlling air pollution are implemented. These include daily road sweeping, increased water spraying and the use of dust suppressants to mitigate dust, rigorous enforcement of dust control measures at C&D sites like: ban on excavation of foundation, restrictions on fuel usage, traffic management, increase in parking fees, enhancements to public transport, and a citizen charter. Mechanical or vacuum-based sweeping is used to remove dust and debris, and dust control approaches involve frequent watering to suppress the dust. Hotels and restaurants are required to use appliances that run on clean fuels or electricity and prohibits use of coal-based tandoors. Power supply mechanisms must ensure a consistent electricity supply, and traffic management plans should facilitate smoother movement and position workers at traffic crossings. Radio, television, and newspapers help in raising public awareness. To prevent open burning of biomass and MSW during winter, residential welfare

associations also provide electrical heaters for security personnel and improve public transportation services (CAQM, 2022).

1.3.3 GRAP Stage III

The NCR has implemented various measures to control and mitigate air pollution during GRAP Stage III. These actions include mechanical sweeping of roads, enhancing public transportation options, banning the use of unauthorized fuels in industries, issuing closure directions to violating industrial units, and prohibiting the C&D activities. However, activities such as carpentry, electrical work, plumbing, and other non-polluting trades are allowed to proceed. Restrictions have also been placed on industrial activities, which encompass mining, Ready Mix Concrete plants, hot mix plants, stone crushers, and brick kilns. State governments may impose restrictions on vehicles with non-valid Pollution under Control certificates. Furthermore, a citizen charter that encourages working from home, consolidating errands, and walking to carry out tasks is being implemented. To avoid open burning during winter, security personnel are provided with electric warmers and are advised against using coal, biomass and wood for heating purposes. State governments have the power to restrict the LMVs that are classified as BS III gasoline and BS IV diesel (CAQM, 2022).

1.3.4 GRAP Stage IV

In GRAP Stage IV, a series of measures have been enacted to manage vehicular movement of heavy commercial vehicles in Delhi. Trucks are barred from entering the city, except those responsible for transporting essential goods or providing necessary services. Only electric trucks and CNG trucks are allowed. Diesel-operated MGVs and HGVs registered in Delhi are forbidden, unless they are delivering essentials or providing essential services. The use of four-wheeler diesel LMVs is prohibited in Delhi and the neighboring areas of NCR unless the vehicles comply with

BS-VI standards or are utilized for emergency or vital services. Industries that use unapproved fuels directed to cease operations. C&D activities are also restricted for linear public projects such as highways, roads, flyovers, overpasses, electricity transmission, and pipelines. The GNCTD and NCR State Governments may permit 50% occupancy for public, municipal, and private workplaces, with the remaining employees working remotely and implementation of staggered office timings to reduce peak traffic load. Central Government offices may likewise allow for remote working arrangements. Additional emergency measures include a vehicle operating system, restrictions on non-contingency commercial operations, and the closure of schools, universities, and educational institutions. Citizens especially those having underlying chronic illness, and are susceptible to pollution, are encouraged to remain indoors and avoid outdoor activities, (CAQM, 2022).

1.4 Objectives of the study

The aims of the current study are as follows:

1. To assess the effectiveness of GRAP at construction sites for reducing pollution levels in the study.
2. To analyze the change in air quality ($PM_{2.5}$ and PM_{10}) before, during, and after execution of GRAP.
3. To examine the change in quantity of PM (% change) during different phases of the GRAP in the C&D sites.

Chapter – 2

Literature Review

2.1 International Studies on Air Pollution

The research underlines the importance of air environmental audits in order to control pollution and the possibility of implementing similarly placed audit and assessment frameworks to enhance environmental governance. The investigation into air environmental audits in China underlines and demonstrates their considerable impact on mitigation of air pollution. It was observed that such audits have led to a reduction in emissions across 261 prefecture-level cities between 2004 and 2018. The effectiveness of these audits varied across different pollutants, with PM_{2.5} levels showing the quickest decline, whereas reductions in industrial emissions of sulfur dioxide and smoke were more gradual. The research also emphasizes the necessity of adaption of tailor-made audit strategies to suit the local conditions and priorities. Recommendations include intensification of audits with special emphasis on lowering sulfur dioxide and industrial smoke emissions, along with the need for frequent audits, prompt corrective action based on findings, and customization of audit methodologies. Furthermore, the study posits that the auditing mechanism in China could serve as a blueprint for other developing nations, which are facing environmental sustainability hurdles and challenges owing to economic growth (Rong Ge et al., 2023).

In China, the study regarding the varied relation among environmental regulations, technological innovation and interventions, and environmental pollution highlights the critical role of market-based incentive mechanisms and public involvement in attaining environmental objectives. The research determined that command-and-control regulatory mechanisms had little impact on reducing environmental pollution. Conversely, regulations focused on market-based incentives and public engagement produced ill effects, contributing to reduction in pollution. Technological advancements have partially intervened the link between these regulations and pollution levels.

Process innovations have proved to be much more effective in emission reduction rather than product innovations. Nonetheless, a disconnect between technological innovation and environmental regulation resulted in sub-optimal environmental outcomes. The impact of various environmental regulatory tools differed over time, with command-based regulations losing their effectiveness as time progressed (You et al., 2024).

The research investigates the effectiveness of collective measures in combating air pollution in China under the Air Pollution Prevention and Control Action Plan. Utilizing the data from 290 cities between 2007 and 2021, the findings reveal a notable reduction in pollutant emissions, particularly within the urban areas of the Yangtze River Delta and Pearl River Delta. The study advocates for the establishment of cross-regional coordination mechanisms, a clear demarcation of cost and benefit sharing, and increased environmental monitoring to maximize air pollution mitigatory efforts (Wu, 2023).

The research on air pollution in East African nations uncovers diverse patterns, with hotspots displaying elevated pollution levels while cold spots show reduction. It identifies four primary periods of pollution and long-range transport from various regions. Meteorological conditions and climatic factors also play a major role in influencing concentrations of pollution. Spatial analysis reveals variation in pollution trends, driven mainly by human activities and biomass burning. A thorough understanding of pollution persistence and fluctuation can inform policy decisions and prioritize interventions in areas facing enhanced pollution levels (Kalisa et al., 2023).

The study on governance of air pollution in China and India reveals that China employs a centralized, top-down controlled administrative approach, while India adopts a decentralized bottom-up system. Chinese policies have resulted in notable improvement in air quality, whereas India's effectiveness has been relatively limited. This research highlights the crucial importance of strong political commitment, accountability, willingness, opportunities for course correction in policy adjustments, and prioritization of cost-effective strategies. The study recommends linking

overarching goals with on-the-field actions, taking advantage of opportunities, and emphasizing efficient measures (Wang et al., 2023).

The investigation in Malaysia on strategies for combat the smog and pollution highlights the global crisis caused by air pollution and the necessity of statutory frameworks to mitigate its impacts. It advocates for a collaborative approach involving all the stakeholder like: policymakers, legal experts, and environmental advocates to protect air quality and foster a healthier future while complying with WHO air quality guidelines (Usman et al., 2023).

Pollution Mapper, a research initiative aimed at pinpointing global air pollution sources, has discovered that significant $PM_{2.5}$ sources are accountable for 80% of mortalities across the world. Utilizing NOAA's HYSPLIT wind dispersion model, the mixed-methods model effectively captured the seasonal fluctuations of $PM_{2.5}$. This model can be adapted for other cities alike, assisting policymakers in creating successful interventions. With Pollution Mapper, policymakers have the capability to assess the impacts of policy measures on air quality, facilitating informed decisions. Future research intends to focus on hyper-localized factors and conduct causal assessments (Agarwal et al., 2024).

The investigation w.r.t the implementation of the PROAIR in Baja California, Mexico, indicates limited advancements since its introduction in 2000. This program encompasses multi-pronged strategies addressing various sectors, including industry, trade, services, transportation, urban management, ecological restoration, and international agreements. Mexicali has gained advantages from environmental protocols like the Border 2012 Program between Mexico and the USA. The research advocates for enhancing environmental results in Mexicali and other regions (Quintero-Nuñez & Nieblas-Ortiz, 2008).

The study in the USA investigates the spatial and temporal trends of traffic-related air pollutants, specifically $PM_{2.5}$ and NO_x , in urban areas by employing a new dispersion model, RLINE and an extensive emissions inventory. The findings reveal that vehicular traffic is a major contributor to

pollutants, with peak concentrations observed near key road stretched. High-resolution mapping is essential for accurate measurement of fluctuating nature of pollutant levels. The research also underscores the necessity for comprehensive, real-time monitoring to understand the pollution dynamics effectively. These results have implications for health and policy (Batterman et al., 2015).

The report titled "Indoor Air Sources of Outdoor Air Pollution, Health Consequences, Policy, and Recommendations" by experts from various disciplines underscores the considerable influence of indoor air pollution on both indoor and outdoor air quality. It advocates for source control and filtration as practical solutions to control indoor pollution and suggests switching from gas based stoves to electric operated ones and moving towards smell free products (Nassikas et al., 2024).

The analysis illustrates that perceptions of air pollution are subject to interpretation among individuals due to sensory experiences and brain reception. There is a chasm between public perception and measurable data, shaped by factors such as socio-economic backgrounds and emotional responses. Social media and the internet have profoundly influenced the perception of risk. Customized communication strategies are necessary to reconcile the differences between public views and findings based on scientific insights. Strong frameworks and a perception index can improve communication and enhance understanding for the masses. (Giri & Nagendra S.M.S, 2024).

The research on spatial patterns of PM_{2.5} air pollution in Jakarta, conducted through mobile monitoring with Google Street View vehicles, identified temporal variability, intra-neighborhood differences, and the proximity to sources of pollution. The study emphasized the importance of factoring in local sources of emission while assessing air pollution exposure in urban regions. The findings also pointed out exposure disparities, indicating that various socio-economic groups are impacted differently to the air pollution within the same urban area (Ghaida et al., 2024).

The literature review on the impacts of air pollution on human health reveals a research gap regarding its impact on human well-being. It indicates that elevated levels of air pollution can contribute to a cognitive decline in aged population and negatively affect cognitive health. The report recommends utilizing theoretical frameworks such as Particulate matter Theory, Oxidative Stress Theory, and Inflammatory Response Theory for future studies. Healthcare systems should be equipped to handle the impact on health owing to air pollution, and governments ought to judiciously allocate resources for the further needful. (Maknae, 2024).

2.2 National Studies on Air Pollution

This study implements a comprehensive approach to design sustainable solutions aimed at reducing air pollution in Delhi and the NCR. It critically analyzes current literature and proposes new policy interventions that takes in account factors such as topography, meteorological conditions, emissions, construction activities, waste management, and inter-agency coordination. The research aspires to connect the socio-economic, political and scientific facets of air pollution, aiming to serve as a reference document for government bodies and other stakeholders. (Bhardwaj & Bhardwaj et al., 2022).

The study seeks to establish an integrated framework for effective air quality management at vulnerable hotspots across Indian cities, concentrating on emission reduction potential, enforcement feasibility, scale of implementation, and their socio-economic viability. It specifically targets the reduction of PM_{2.5} in an urban industrial areas of Delhi, utilizing a methodology comprising data collection, inventorization of emission, control scenario simulations, evaluation of socio-economic aspects, and prioritization of actionable strategies for implementation. Findings indicate that road dust emissions occupy the top spot (45–56%), followed by various industrial emissions (18–21%). The most significant reduction in PM_{2.5} levels can be attained through measures such as mechanized vacuum cleaning, operating industries at

full capacity, installing devices like: bag filters, cyclone dust collectors, and increasing stack heights (Goyal et al., 2022).

An investigation into the effectiveness of numerous control measures and their impact on air quality revealed that over a span of 17 years, RSPM and NO₂ concentrations in Delhi have steadily risen, while SO₂ concentrations have shown reduction. RSPM and NO₂ levels consistently surpassed established standards, while SO₂ concentrations remained within acceptable limits. Correlations between RSPM and NO₂ were found at particular times and locations, suggesting potential sources such as vehicle and industrial emissions. When compared to 2003, RSPM and NO₂ levels were elevated due to a rise in sources such as vehicles and power consumption. Policymakers have introduced several control strategies, highlighting the importance of ongoing systematic monitoring to evaluate improvements (Gulia et al., 2021).

In a study examining SO₂ pollution improvements in India, researchers highlighted the influence of technology and environmental regulations, identifying Central and East India as significant hotspots for SO₂ emissions due to the existence of coal based thermal power plants, refineries, and steel and cement industries. Thermal power plants account for 51% of anthropogenic SO₂ emissions, while manufacturing and C&D activities contribute 29%. SO₂ levels are generally higher in winter and lower during pre-monsoons. Between 1980 and 2010, SO₂ concentrations have gradually risen due to coal usage and technological constraints, while a decline from 2010 to 2020 was observed as a result of environmental regulations and control technologies. The rise of renewable energy production in India post-2010 has led to a reduction in SO₂ emissions. Policy recommendations suggest transitioning to renewable energy, implementing strict environmental regulations, maintaining the emission inventories, and deploying effective control technologies (Kuttippurath et al., 2022).

A study on air pollution trends in Chandigarh from 2019 to 2022, highlighting the meteorological factors, indicates an increase in pollution resulting from vehicular emission, industrial expansion,

and C&D activities. Pollutant level spiked during the rice stubble burning season due to high pressure anticyclonic winter conditions and higher fossil fuel consumption, while wheat stubble burning had a minimal effect due to onset of summers and reduction in atmospheric pressure. However, elevated temperatures resulted in a peak of surface O₃ in spring, a typical pattern for South Asia. The COVID-19 lockdown has led to improved quality of air, stressing the necessity for comprehensive management strategies to safeguard public health and environmental sanctity (Dalai et al., 2024).

The analysis of Delhi's air pollution indicates that PM₁₀ levels in the city have already surpassed safe limits, reaching over ten times the recommended level of 198 µg/m³. The primary sources of pollution identified are fugitive vehicular emissions, dust emanating from C&D activities and industrial activities. Additionally, the research highlights a link between pollution levels and detrimental health outcomes, including increased rates of mortality and disease-burden. Despite efforts over the last decade to reduce pollution levels, the study provides data-driven insights regarding the effectiveness of these efforts (Sharma et al. 2020).

Delhi experiences worsening of air quality due to a limited understanding of the emission sources. This research creates a high-resolution, spatially detailed emission inventory at granular level for eight significant pollutants in the Delhi region. The study calculated annual emissions for PM_{2.5}, PM₁₀, CO, NO_x, VOC, SO₂, BC, and OC across the Delhi region in 2020. The decade-long increase in PM_{2.5} and PM₁₀ was at 31% and 3%, respectively, with the logistics and transportation sector witnessing the most significant growth. The research investigates the changes in emissions by sector over the decade in response to evolving policies (Sahu et al., 2023).

The analysis utilizes Delhi as the experimental group and Haryana as the control group, given the lack of clean fuel initiatives in Haryana during the survey. Findings indicate that the introduction of clean fuel options in Delhi led to reduced health issues and economic expenses, improved healthcare costs, decreased loss of productivity, and greater willingness to pay for better quality of

air. However, comparisons between Delhi and Haryana must be approached cautiously due to different socio-economic and demographic set-ups (Chowdhury et al., 2023).

The research assessed indoor and outdoor air quality in Anand Vihar, uncovering seasonal fluctuations, particularly in winter. The findings showed reduced levels of PM and relative humidity indoors but elevated CO levels outdoors. Most parameters exceeded the international standards, indicating risks associated to health. The study also emphasizes on the need for comprehensive air quality monitoring, both through stationary and mobile outdoor sensors and compact sized indoor devices, to reduce health hazards and foster better and healthier living environments (Bhardwaj et al. 2022).

The research provides baseline estimates of level of pollutants in Delhi during winter 2022 using data impacted by sporadic rainfall and COVID-19 lockdowns. Results indicated elevated levels in central regions. The study applied rainfall scavenging, emissions reductions during lockdowns, and meteorological filtering to determine pollution baselines. PM_{2.5} and NO_x levels demonstrated both positive and negative correlations with rainfall. During rainfall and lockdown periods, PM_{2.5} concentrations dropped by 69-73%, while NO_x levels decreased by 26-63%. These findings offer valuable insights for pollution management strategies and improvements for models (Gulia et al., 2024).

The research highlights the significant effect of trans boundary transport of pollutants on Delhi's air quality, with winter showcasing high standard deviations for NO₂ (7.14–9.63%) and SO₂ (4.04–7.42%) from 2019 to 2022. The post-monsoon seasons exhibited increased CO levels due to stubble burning in Punjab, resulting in persistent exceedance days for CO (4.52–8.00%). The study also pinpointed hotspots in Southeast Punjab that contributes to elevated CO levels in Delhi during the post-monsoon in 2019, underlining the necessity of source apportionment studies for effective pollution management and mitigation strategies. It suggests that identifying these

hotspots can help create targeted and hyper localized policies aimed at reducing emissions without hindering economic progress (Nirwan et al., 2024).

The research investigates the seasonal variations of PM in Delhi, India. It reveals that pollution levels are influenced by local sources and meteorological conditions, with North and East Delhi, which are identified as the severely polluted regions. Additionally, it demonstrates that temperature and relative humidity play a major role in affecting PM levels. Long-range dispersion patterns differ according to season, with southeasterly winds during the monsoon and northwestern winds in other seasons contributing to Delhi's pollution (Sharma et al. 2022).

The study analyzed air pollution levels in the Okhla industrial area of Delhi after the COVID-19 pandemic. PM₁₀ concentrations varied from 9.73 to 640.14 µg/m³, PM_{2.5} ranged from 6.18 to 448.06 µg/m³, SO₂ measurements spanned 2.72 µg/m³ to 25.78 µg/m³, and NO₂ levels fluctuated between 14.75 and 219.36 µg/m³. PM₁₀ and PM_{2.5} levels considerably exceeded the standards set by the CPCB, while SO₂ levels remained below the threshold. NO_x levels were higher than the acceptable standards. Wind patterns were characterized by reduced speeds, which correlated with elevated pollutant levels primarily from the southeast region. Overall, the study highlighted a critical pollution situation post-COVID, calling for urgent measures to redress the pollution related grievances in the area (Jha et al., 2023).

Research on PM_{2.5} in Delhi indicated that the highest annual concentrations were observed in R.K. Puram, DTU, and ITO during the years 2018-19 and 2019-20, exhibiting seasonal variability. The winter months recorded the sky-rocketing levels, while post-monsoon months also showed significant concentrations. Peaks in winter were attributed to low mixing heights and calm-suppressed wind conditions aided by high pressure subsidence, while elevated post-monsoon levels may be linked to reduced ventilation coefficients, local activities, and fugitive emissions from various sources. Study emphasized the importance of site-specific interventions and local

source influences for effective air quality management, underlining the need for custom approaches (Jha et al., 2024).

The analysis of surface ozone and its relationship with other pollutants in Delhi from 2013 to 2019 identified significant concentration ranges. O₃ levels averaged between 32.44 ppb and 36.57 ppb, with NO, NO₂, and NO_x concentrations ranging from 19.46 to 28.09 ppb, 20.83 to 26.89 ppb, and 43.04 to 54.99 ppb, respectively, while CO levels ranged between 1.67 and 1.89 ppm. The research noted peak NO_x and CO levels in the early morning and late evening, correlated with higher O₃ levels in the afternoon. Additionally, a negative correlation between O₃ and NO_x concentrations, oxidants, temperature, and humidity were found, emphasizing the pollution sources within the National Capital Region of Delhi. (Sinha et al., 2021).

This study investigates the sensitivity of surface O₃ to NO_x and NMHCs in Delhi, India, revealing seasonal fluctuations in O₃ levels, particularly during the pre-monsoon and post-monsoon seasons. It established the critical role of NO_x in regulating O₃ concentrations, with conditions for O₃ production being more conducive during the pre-monsoon and post-monsoon periods. The findings highlights the necessity for policies aimed at reducing NO_x emissions to alleviate O₃ pollution in urban environments (Sharma et al., 2021).

The research focuses on NO_x and associated pollutants in the heavily polluted area of Anand Vihar in Delhi, finding that the meteorological factors like temperature and humidity greatly influence NO₂ levels. Seasonal variations were observed, showing lower levels during monsoons and higher concentrations in winters. The study indicated that vehicular activities have a direct effect on pollution levels, with lower atmospheric heights contributing to increase in pollution levels. It also points out the potential benefits of EVs in reducing NO₂ pollution, noting that areas with heavy traffic, which have higher NO₂ concentrations, thus highlighting the urgency for pollution control and sustainable transportation measures (Kaushik & Das, 2023).

A study examining India's coal-fired thermal power plants underlined significant health consequences, including premature deaths and pulmonary illness. Emissions from these power plants releases pollutants such as PM_{2.5}, SO₂, NO_x, CO, VOCs, and CO₂. The estimated economic cost of this pollution ranged from INR 16,000 to 23,000 crores. The research emphasized the need for strict pollution control regulations, especially flue gas desulfurization systems. Adopting these systems could potentially lower PM_{2.5} concentrations by 30-40%, yielding health and environmental advantages. Monitoring emissions through continuous monitoring systems, applying stringent emission standards, enhancing plant efficiency, and updating environmental impact assessment procedures are also critical (Guttikunda & Jawahar, 2014).

This study investigates the correlation between the levels of air pollution and the health outcomes in Delhi-NCR, identifying consistently high levels of pollutants like PM_{2.5} and PM₁₀, especially in winter months. It stresses upon the necessity for comprehensive pollution control methodologies and establishes a direct co-relation between elevated PM_{2.5} levels and respiratory admissions in hospitals. The results advocate for targeted interventions and equitable healthcare access, particularly for socio-economically disadvantaged populations (Ashutosh Deshpande et al., 2024). The research regarding air pollution levels in Delhi, with special focus on respiratory illnesses, indicated that all types of pollutants exceeded the established ambient air quality standards. The pollution situation intensified in 2008, following the implementation of stricter NAAQS. Areas such as Town Hall, Mayapuri, and Najafgarh exhibited enhanced pollution rates, with increased SPM and RSPM levels adversely affecting the health. Seasonal spikes in pollution during winter are linked to a rise in respiratory health issues. Prolonged exposure poses health risks, including lung cancer due to the carcinogenic substances in the pollutants. Immediate actions and changes in lifestyle are essential to combat negative outcomes. (Malhotra et al., 2023).

A study performed at agricultural regions in Delhi aimed to evaluate the health hazards due to aerosols (PM₁₀ and PM_{2.5}) and heavy metals, revealing that air pollution resulting from urban

development and industrial activities poses health risks. The measured concentrations of PM₁₀ and PM_{2.5} lies between 136 to 177 $\mu\text{g}/\text{m}^3$ and 56 to 162 $\mu\text{g}/\text{m}^3$, respectively, at that location. Notably, the peak levels of PM₁₀ and PM_{2.5} were observed in January, followed by December, which exceeded WHO guidelines of 15 and 5 $\mu\text{g}/\text{m}^3$ respectively, particularly during winters. Additionally, surface ozone O₃ and NO_x values were found to be elevated in February and March. The average hazard index for metals remained within acceptable range, suggesting no carcinogen effects. The carcinogenic risk values were also compliant with USEPA standards, indicating no dangers for children and adults. This data can assist in creating effective mitigation strategies (Chaudhary et al., 2023).

A study examining the correlation between asthma and air pollution in India indicated that air pollution levels have risen significantly over the last two decades, resulting in deteriorating air quality. Both indoor and outdoor air pollution are recognized as critical risk factors for asthma, particularly among women aged between 15 and 49. Additional risks include both smoking and passive exposure to smoke, dietary influences, and obesity (Singh et al., 2023).

The analysis of long-term air pollution trends in Hyderabad, demonstrates considerable urban outgrowth over the past twenty years, leading to significant alterations in air quality. The findings indicate that aerosol concentration is most pronounced in spring, with a rising trend in aerosol optical depth and PM_{2.5} concentrations during the winters. The northeastern and southeastern regions experience elevated aerosol loads, while concentrations of NO₂ and SO₂ have increased in the northeastern region, attributed to thermal power plants and urban areas (Jayachandran & Rao, 2024).

The study highlights that PM levels in India have risen significantly, with state of Uttar Pradesh recording the highest PM rate in 2021 at 5.754. Additionally, Himachal Pradesh and Jammu & Kashmir displayed the highest CAGR of 0.429 and 0.421, respectively. Conversely, states like Karnataka, Odisha, Punjab, Telangana, and West Bengal have stable and relatively lower PM

growth rates, indicating the effective air quality management practices. Factors contributing to PM growth include post-pandemic influences, economic shifts, and localized events. The study advocates for state-level policies, long-term strategies, and tailor-made approaches for an effective management of air quality. (Ramakrishna et al., 2023).

The research titled Air Pollution; A Major Threat to Sustainable Development identifies six primary pollutants: PM, ground-level O₃, CO, SO₂, NO_x, and Pb. These pollutants adversely affect air, soil, and the water quality, posing huge risk to human health and contributing to climate change, global warming, and acid rain. The study underscores the necessity for mitigation strategies, individual actions, and collective efforts to combat air pollution for sustainable development (Ravichandran et al., 2021).

The research titled Health and Economic Impact of Air Pollution in India indicates that, as per the Global Burden of Disease Study 2019, air pollution has contributed to 1.67 million fatalities in 2019, accounting for 17.8% of all the deaths. The research also identified considerable economic repercussions, with estimated losses amounting to US\$36.8 billion in 2019, which corresponds to 1.36% of India's GDP. The findings emphasize the combined challenges of health implications and financial losses, highlighting that effective reduction strategies could enhance public health and promote economic development, supporting India's ambition of achieving aim of \$5 trillion economy by 2024 (Pandey et al., 2021).

The examination of vehicular emissions in Kanpur City showed that accelerated urban growth and industrial development have resulted in heightened emissions, leading to air pollution. This research concentrated on three primary pollutants: PM₁₀, SO₂, and NO₂. The vulnerability assessment indicated that PM₁₀ levels consistently exceeded the NAAQS, showing heightened particulate matter pollution. SO₂ levels remained compliant with the prescribed standards, whereas NO₂ levels surpassed the standards at 5 out of the 8 monitored locations (Yadav & Ganguly, 2023). The study titled Dispersion Modelling of Air Pollutants in a Hilly City in India

discovered that vehicular emissions play a major role in urban air pollution. This research assessed two air quality dispersion models like STREET and CALINE 4, to forecast PM₁₀ levels in Shimla, Himachal Pradesh (Ganguly et al., 2021).

Delhi faces severe air pollution, with particularly high levels of PM₁₀ and PM_{2.5}, primarily due to vehicular emissions, industrial smoke, C&D dust, and seasonal factors like stubble burning. Multiple studies highlight that despite ongoing pollution control measures, pollutants such as PM_{2.5}, PM₁₀, and NO_x continue to exceed safe limits, especially during winter months when meteorological conditions severely impact the air quality. The seasonal and spatial variability of pollutants in Delhi calls for high-resolution monitoring and data-driven studies. For example, pollution hotspots like R.K. Puram and Anand Vihar exhibit elevated PM_{2.5} levels, necessitating localized solutions. Additionally, transboundary pollution from neighbouring regions contributes significantly to Delhi's poor air quality, indicating the need for cross-regional collaboration and coordination. Health studies link high pollutant concentrations to increased respiratory illnesses, cognitive decline, and economic costs, underscoring the urgency of effective policies and public awareness programmes. Policies to promote clean fuels, EVs, and improved air pollution control devices have shown benefits, though on-site enforcement and regular monitoring are needed. Delhi's air pollution challenges mirror global trends, and lessons from global and national studies suggest that combining the regulatory measures, technological upgrades, real-time monitoring, public participation, and socio-economic considerations can lead to holistic improvements in air quality and public health.

Chapter - 3

Methodology

3.1 Site Selection

The National Capital of India, Delhi was chosen to conduct this study. The GRAP was introduced to control and mitigate air pollution in areas of Delhi-NCR, making it a fitting subject for this research. As the largest contributor to India's urban population at around 7.6%, Delhi spans approximately 1485 km² and is home to around 16.8 million residents. Over the last two decades, population density has surged from 9340 individuals per sq. km in 2001 to 11,297 person per sq. km in 2011, reflecting an annual growth rate of 37.6% (Mahato et al. 2020). It lies between the semi-arid territories of Rajasthan to the southwest and the fertile, rain-fed Indo-Gangetic Plain to the east, Delhi's high population density renders, it is one of the most densely populated and highly polluted urban areas globally. The city, lies between the states of Uttar Pradesh and Haryana. The city's geography consists of three main sections: the upper Gangetic plain, the ridge, and the floodplains. Characterized by humid subtropical climate that borders around hot, semi-arid climate, Delhi experiences four distinct seasons: pre-monsoon (March to May), monsoon (June to September), post-monsoon (October and November), and winter (December to February). The temperature range varies from 4–10 °C in winter to 42–48 °C in summer. During the monsoon, gentle southeastern breezes prevail, while the rest of the year is dominated by northwestern winds surpassing 2–3 m/s. Due to its geographical features, Delhi has become a center for urban and regional pollution, which restricts wind movement and limits the dispersal of air pollutants due to dense air. Major contributors in air pollution in the region include vehicular emissions, industries (such as brick kilns), traditional domestic cooking, burning of biomass from seasonal agriculture, and emissions from thermal power facilities (Nirwan et al., 2024). This study includes data from 41 operational monitoring stations in the NCR and Delhi (Fig.3.1). The sources

of data provided are detailed in (Table.3.1), and the various locations chosen for data extraction are enlisted in (Table.3.2).

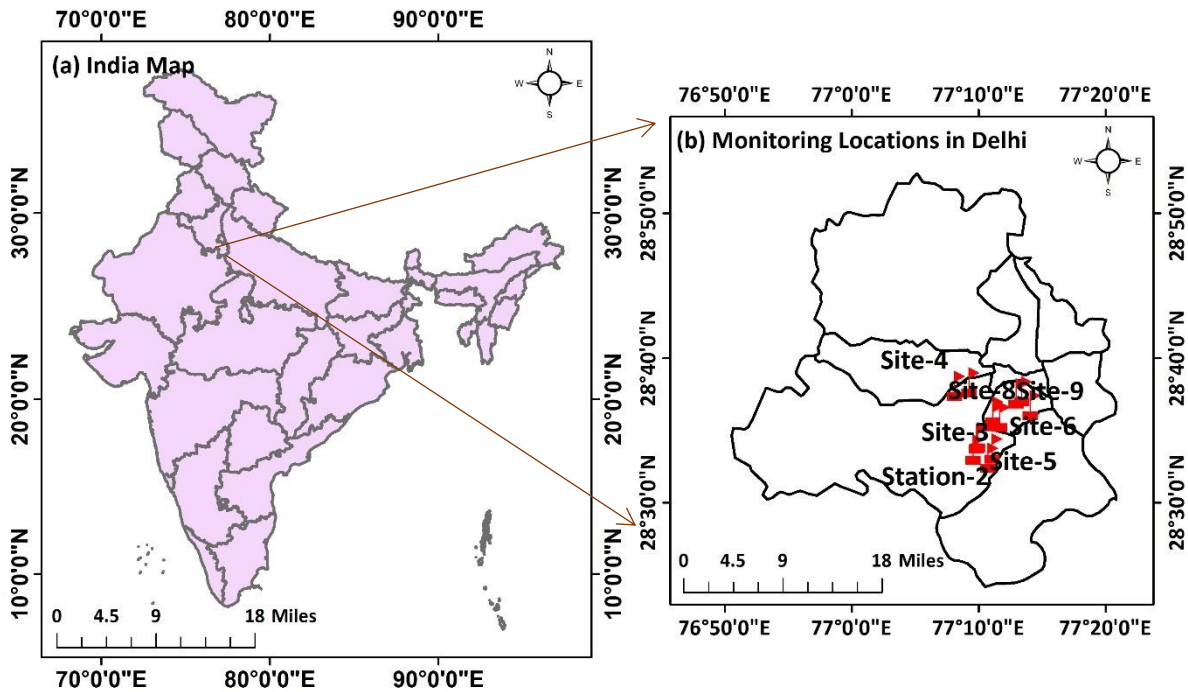


Figure.3.1 Location of the monitoring stations in Delhi.

Table.3.1 Latitude and Longitude of the Monitored Construction Sites

Location no	Latitude	Longitude
Site – I	28.575938	77.167812
Site – II	28.574438	77.166562
Site – III	28.551983	77.181062
Site – IV	28.63484	77.13757
Site – V	28.561731	77.1616297
Site – VI	28.60545	77.18763
Site – VII	28.62874	77.22552
Site – VIII	28.600187	77.188063

Site – IX	28.5991	77.1968
Site – X	28.260525	77.290094

Table.3.2 Total number of DPCC maintained CAAQMS monitoring stations in the study area

CAAQMS Station	Latitude	Longitude
National Stadium (Major Dhyan Chand Stadium)	28.612563	77.236812
RK Puram (KV Sector-2)	28.562688	77.186688
PUSA (New Delhi)	28.638750	77.156250

3.2 Parameters for Analysis

The parameters employed for evaluating the variations in air quality in this research include PM_{2.5} and PM₁₀, as these pollutants are essential and frequently monitored because of their considerable effects on human health and the environment.

3.3 Data Collection

In pursuance to the directions issued by CAQM dated 11.06.2021 and 20.12.2021, DPCC has developed an in-house online monitoring and enforcement mechanism through a web portal called "Dust Pollution Control Self-Assessment" (<https://dustcontroldpcc.delhi.gov.in/>) for self-assessment by construction agencies and project proponents with respect to dust pollution in their C&D sites.

It mandates that all the current or upcoming projects having plot area equal to or greater than 500 sq mtrs of C&D for civil structures under the territorial jurisdiction of Urban Local Bodies in the National Capital Region are required to mandatorily register themselves on the above-mentioned web portal. The project proponents are required to install reliable PM_{2.5} and PM₁₀ sensors at the

project site and data of PM_{2.5} and PM₁₀ is transmitted real time to DPCC Dust portal for purpose of monitoring by Officials.

The data gathered throughout the study consisted of one-hourly average concentrations of pollutants (PM_{2.5} and PM₁₀) from 10 different construction sites in New Delhi Revenue District. This information was divided into different stages that cover data from the year 2024 to 2025 as shown in Table 3.3. The sensor data was fetched from the C&D sites which was available on DPCC dust portal. All the 10 different construction sites are located in the New Delhi district. The data was collected before, during, and after the implementation of the various stages of the GRAP in Delhi.

Table.3.3. GRAP stages and their implementation dates in Phase 1

Stage	Implementation period	No. of days
Before GRAP	01/10/2024 to 14/10/2024	14
Stage I	15/10/2024 to 21/10/2024	7
Stage II	22/10/2024 to 14/11/2024	24
Stage III	15/11/2024 to 17/11/2024	3
Stage IV	18/11/2024 to 04/12/2024	17
Stage II	05/12/2024 to 15/12/2024	11
Stage IV	16/12/2024 to 23/12/2024	8
Stage III	24/12/2024 to 26/12/2024	3
Stage II	27/12/2024 to 02/01/2025	7
Stage III	03/01/2025 to 04/01/2025	2
Stage II	05/01/2025 to 08/01/2025	8
Stage III	09/01/2025 to 11/01/2025	3
Stage II	12/01/2025 to 14/02/2025	34

Stage IV	15/01/2025	1
Stage III	16/01/2025	1
Stage II	17/01/2025 to 28/01/2025	11
Stage III	29/01/2025 to 02/02/2025	5
Stage II	03/02/2025 to 23/03/2025	49
Stage I	24/02/2025 to 28/02/2025	5

3.4 Data Analysis

To investigate the changes in quality of air before, during, and after the implementation of the GRAP by zone area, the average pollutant concentrations from 10 monitored construction sites were computed and presented in graphs utilizing R Studio and Origin. These graphs illustrate the levels of pollutants in two distinct phases, alongside the periods before GRAP, during various stages, and following GRAP across five zones (North, South, East, West, Central). Moreover, the percentage changes were found to evaluate the differences in pollutant levels before, during, and after the implementation of GRAP. These changes are displayed as graphs that depict the percentage variations for all pollutant concentrations across different GRAP stages within each zone. In addition, a temporal analysis of pollutant levels across zones and GRAP stages was conducted, and a comparative analysis with pollutant concentrations relative to the NAAQS was performed. A table outlining the GRAP guidelines alongside the suggested recommendations from the study to improve its effectiveness was also included. The sensor data is verified using the nearest CAAQMS data which is located in the New Delhi District. The CAAQMS such as National Stadium (Major Dhyan Chand stadium), RK Puram and Pusa data were used for the nearest construction sites.

Chapter – 4

Results and Discussion

Both PM₁₀ and PM_{2.5} are harmful air pollutants, however PM_{2.5} poses a greater health risk due to its finer size. PM₁₀ particles, measuring ≤ 10 micrometres, can irritate the eyes, nose, and throat, leading to respiratory illness like asthma, bronchitis, and reduced lung function. They can also contribute to heart disease by inflaming blood vessels. PM_{2.5} particles, which are ≤ 2.5 micrometres, can penetrate much deeper into the pulmonary system and even enter the bloodstream, leading to more severe health problems. Long-term exposure to PM_{2.5} is linked to pulmonary diseases, heart disease, stroke, lung cancer, and premature death. Both types of particulate matter can worsen pre-existing conditions, with PM_{2.5} being particularly dangerous due to its ability to reach the most vulnerable parts of the respiratory system.

4.1 Temporal variation of PM_{2.5} and PM₁₀ at Construction Site-I

This site is a GCHB Society located at Plot No 44, Paschimi Marg, Vasant Vihar, New Delhi, a residential site having Plot Area of 679.34 square meters and BUA of 1528.51 square meters.

The calendar plot for the concentration of PM_{2.5} and PM₁₀ are shown in Figure 4.1 and 4.2. The maximum concentration of PM_{2.5} concentration was observed during November 18 which was around 400 $\mu\text{g}/\text{m}^3$. During October the concentration of PM_{2.5} was found to be less than 100 $\mu\text{g}/\text{m}^3$ (Fig. 4.1). The PM₁₀ concentration during November and December concentration were found to be in the range of 500 to 800 $\mu\text{g}/\text{m}^3$. In January and February, the concentration of PM₁₀ concentration was found to be in the range of 400 to 500 $\mu\text{g}/\text{m}^3$ (Fig. 4.2).

The temporal variation of $PM_{2.5}$ and PM_{10} concentration were compared with the CAAQMS. The trend in the concentration of $PM_{2.5}$ and PM_{10} concentration installed in the construction site is similar to the CAAQMS concentration. In the period before GRAP, the concentration was found to be $< 200 \mu\text{g}/\text{m}^3$. During the Stage IV the concentration of $PM_{2.5}$ and PM_{10} concentration was found to be the highest concentration (Fig 4.3). The construction site $PM_{2.5}$ and PM_{10} concentration was found to be the similar with the concentration trend of the CAAQMS. The results show that the usage of sensors at construction sites provides realistic data. During GRAP III and GRAP IV, the concentration of the pollution increases gradually due to the existing meteorological conditions, emissions sources. The implementation of the GRAP is based on the forecast in concentration of pollution which results in the shutting down of different sources. During GRAP III, the concentration of PM_{10} was found to be around $750 \mu\text{g}/\text{m}^3$ (Fig 4.4). The period late December to February, malfunctioning of sensors resulted in same concentration for some period. The concentration of the $PM_{2.5}$ and PM_{10} are compared with the previous phase of the GRAP.

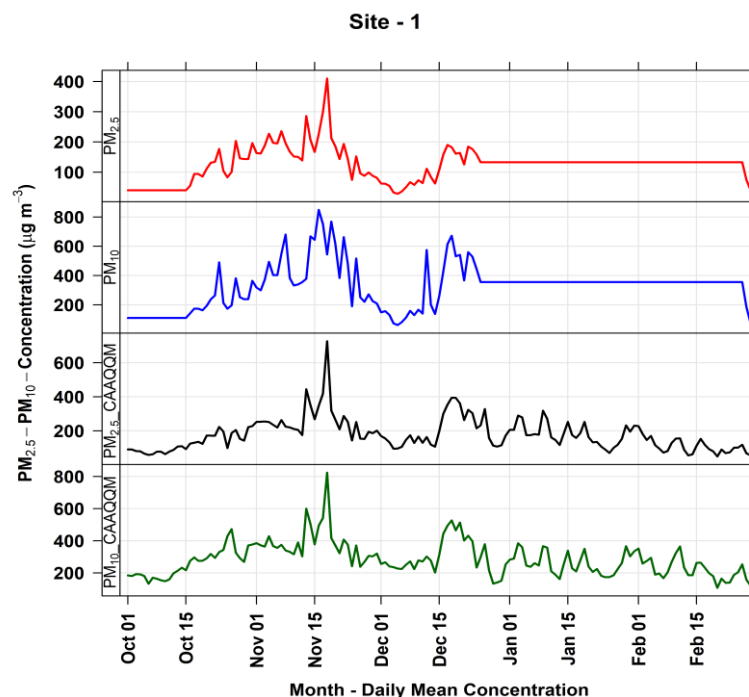


Figure 4.3 Temporal variation of $PM_{2.5}$ and PM_{10} concentrations in 44 GCHB Society Vasant Vihar (Site-I) with the CAAQMS.

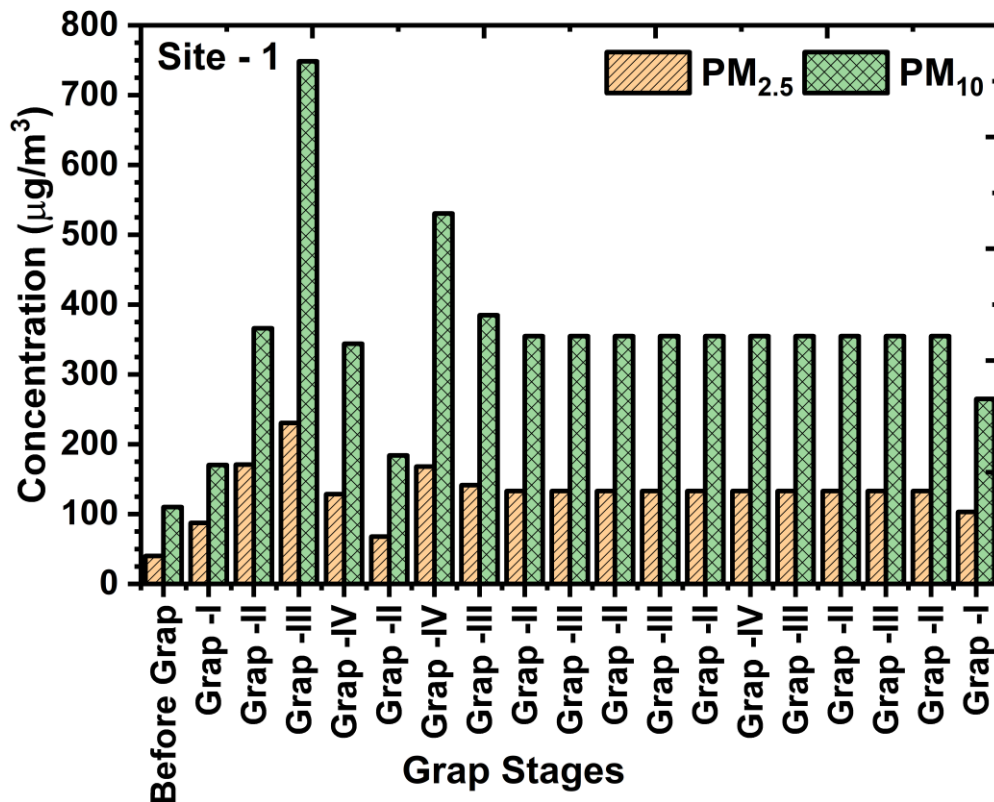


Figure 4.4 Bar Plot of PM_{2.5} and PM₁₀ during different stages of GRAP in Site-I

The percentage analysis reveals that the concentration of the PM_{2.5} and PM₁₀ got reduced during the Stage III to Stage IV and Stage IV to Stage II (Fig 4.5). The implementation of the GRAP stages during different periods is based on the existing concentration and the forecast in concentration of the locality. During Higher pollution concentration, GRAP IV was implemented to minimise the sources and during GRAP I, the sources were given some relaxation. When the concentration reaches back to normal level, the GRAP were relaxed.

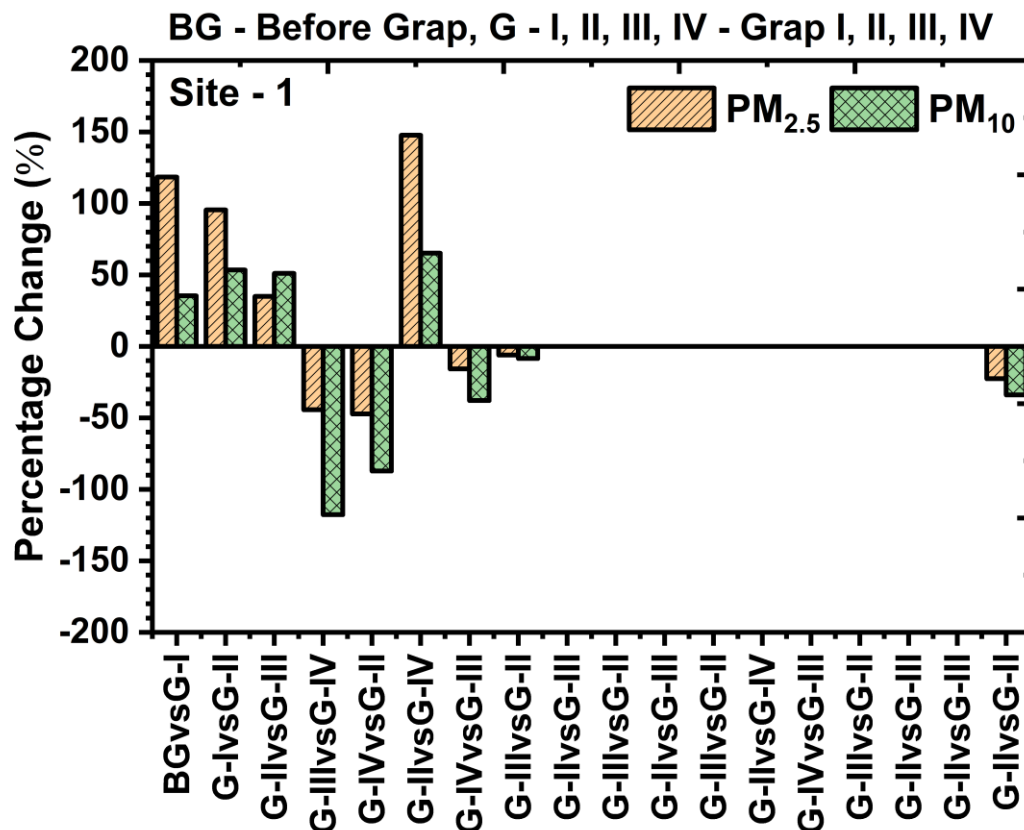


Figure 4.5 Percentage change in concentration during different stages of GRAP (Site-I)

4.2 PM_{2.5} and PM₁₀ Temporal distribution at Construction Site-II

Site II is a residential plot being constructed by Wealth smart Solutions LLP and is located at Vasant Vihar, New Delhi. The site has a plot area of 641.3 square meters and BUA of 2518.21 square meters.

Compared to Site-I, the PM_{2.5} and PM₁₀ concentration were found to be much higher (Fig 4.6, 4.7). The daily concentration of PM_{2.5} and PM₁₀ were found to be high during November compared to the Site-I. whereas during January the observed concentration was found to be less compared to the Site-I. In Site-II, the PM_{2.5} concentration ranged between 50 to 600 µg/m³.

Site - 2

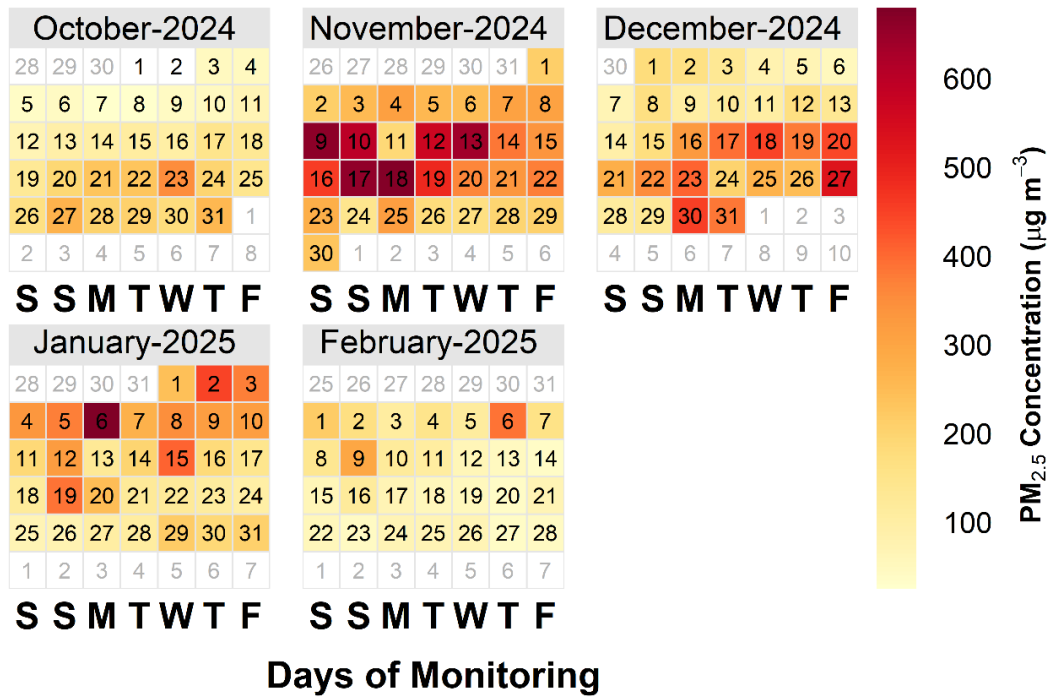


Figure 4.6 Calendar plot of PM_{2.5} concentrations at construction site-II

Site - 2

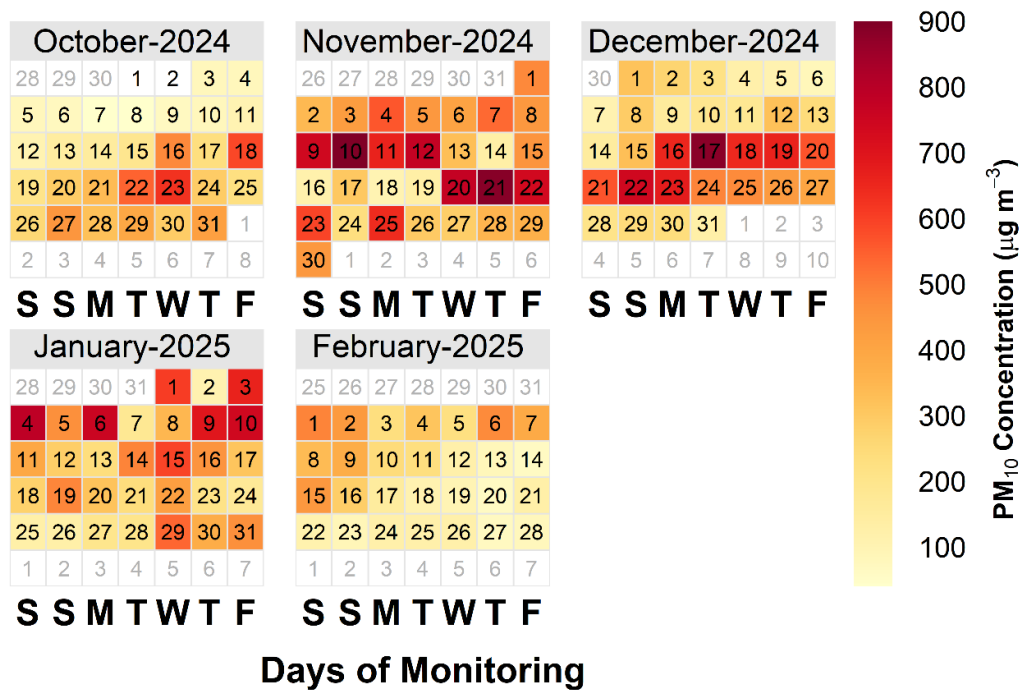


Figure 4.7 Calendar plot of PM₁₀ concentrations at construction site-II

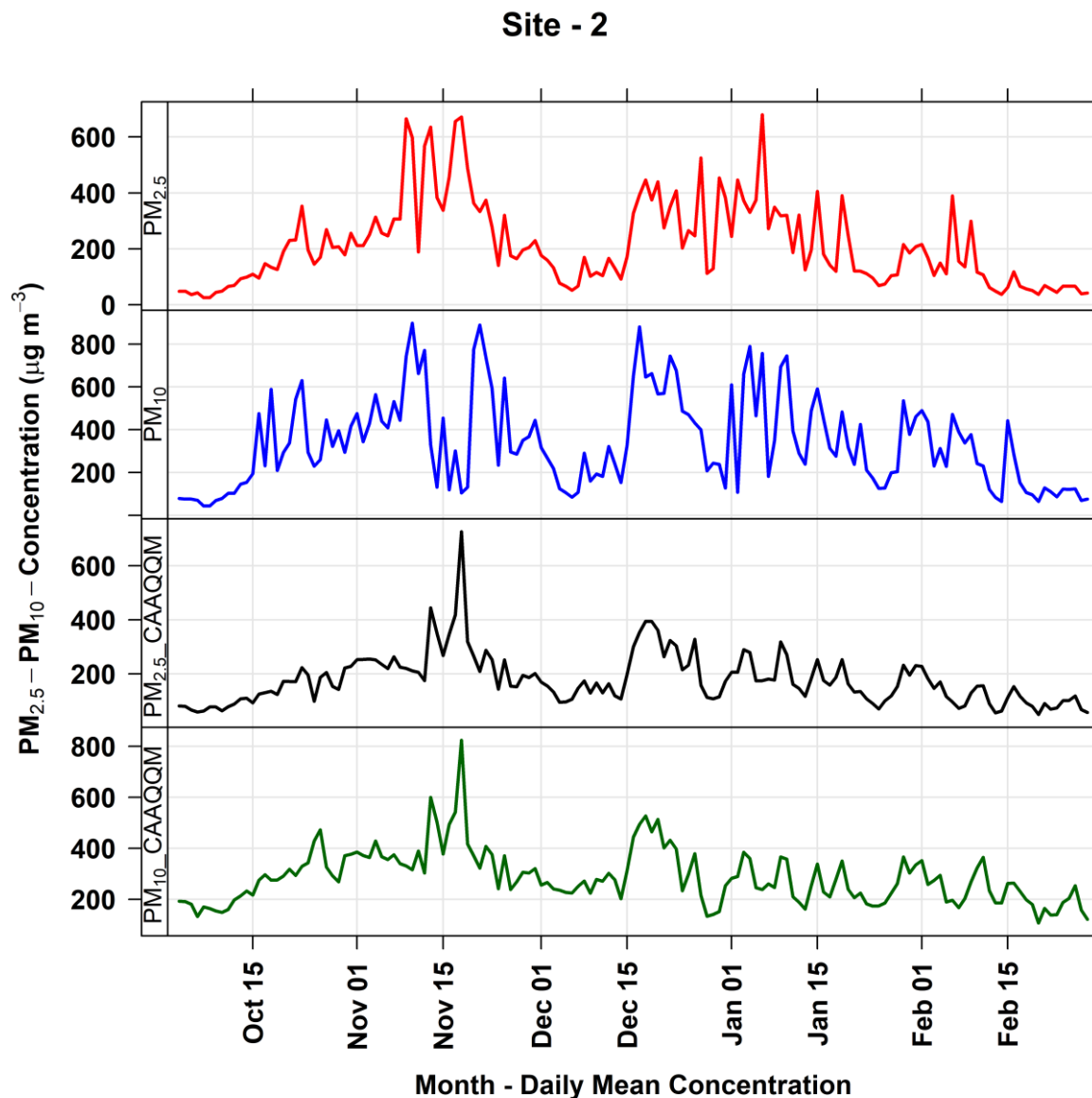


Figure 4.8 Temporal variation of $PM_{2.5}$ and PM_{10} concentrations at construction site-II with the CAAQMS

The temporal variation of the $PM_{2.5}$ and PM_{10} showed that the concentration in the construction site peaked during November and in January (Fig 4.8). During this period the GRAP III and GRAP IV were implemented in the region. Even though the construction activities were restricted during that period, the concentration increased due to the contribution from other sources. The concentration observed in the Site-II is majority of the time higher than 100 found to be less compared to the Site-I. In Site-II the $PM_{2.5}$ concentration ranged between 50 to 600 $\mu g/m^3$ (Fig 4.9).

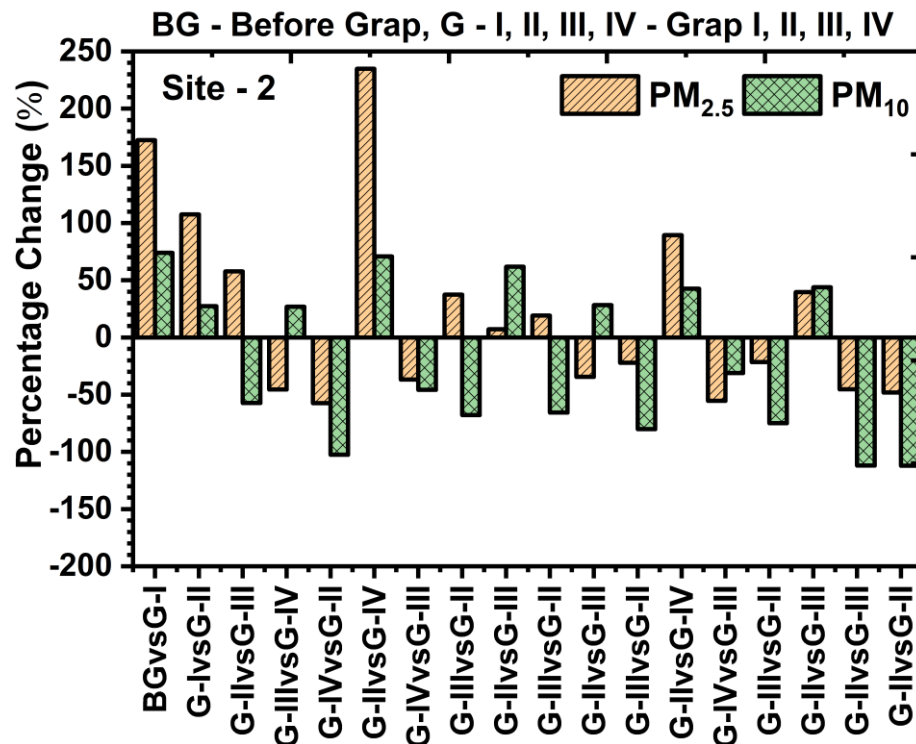


Figure 4.10 Percentage change in concentration during different stages of GRAP (Site-II)

4.3 Temporal behavior of PM_{2.5} and PM₁₀ at Construction Site-III

Construction site III is an Institutional Project undertaken by CPWD namely Construction of Integrated Facilities of Office Training Complex: ISTM at Old JNU Campus at Olof Palme Marg, Munirka RK Puram Sector-III, New Delhi. Site is having Plot Area of 24644 square meters and BUA of 37000 square meters.

The PM_{2.5} and PM₁₀ concentrations observed in Site-III is found to have much lesser concentrations of PM_{2.5} and PM₁₀ < 500 µg/m³. In Site- III also, the maximum concentration of PM_{2.5} and PM₁₀ were found during the month of November and December (Fig 4.11, 4.12). GRAP IV implementation came to effect from 18th November where the concentration reached a maximum and the highest concentration were found during that period at all the sites. In this Site III, the concentration found in the construction site was less than the concentrations found in CAAQMS. Similar to other sites the trend in concentration of PM_{2.5} and PM₁₀ were found to be

similar with the CAAQMS. However, the concentration of $PM_{2.5}$ in the CAAQMS were found to be ranged between 100 to 600 $\mu g/m^3$ and for PM_{10} it was 50 to 800 $\mu g/m^3$ (Fig 4.13).

Site - 3

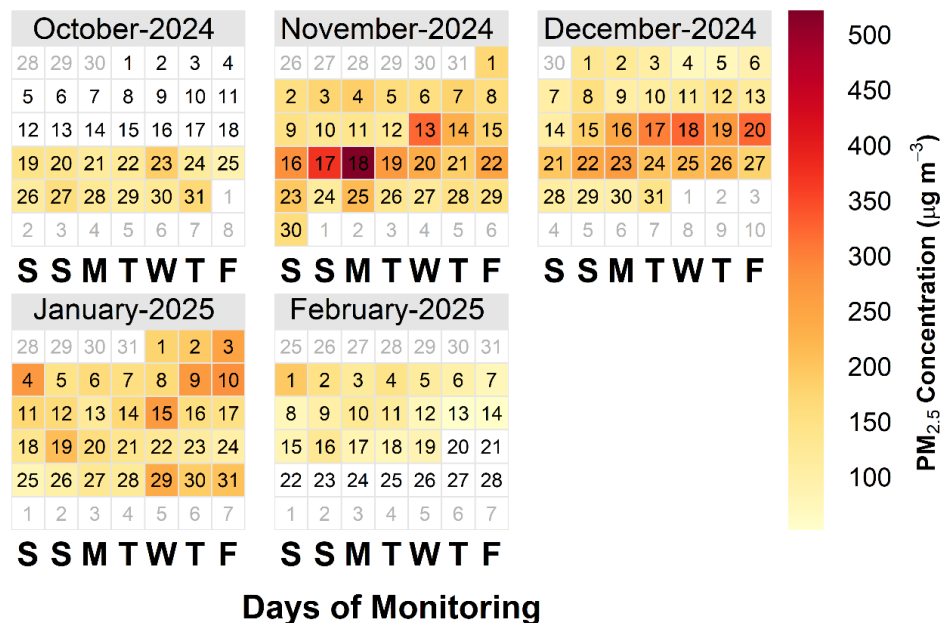


Figure 4.11 Calendar plot of $PM_{2.5}$ concentrations in ISTM JNU Campus (Site-III)

Site - 3

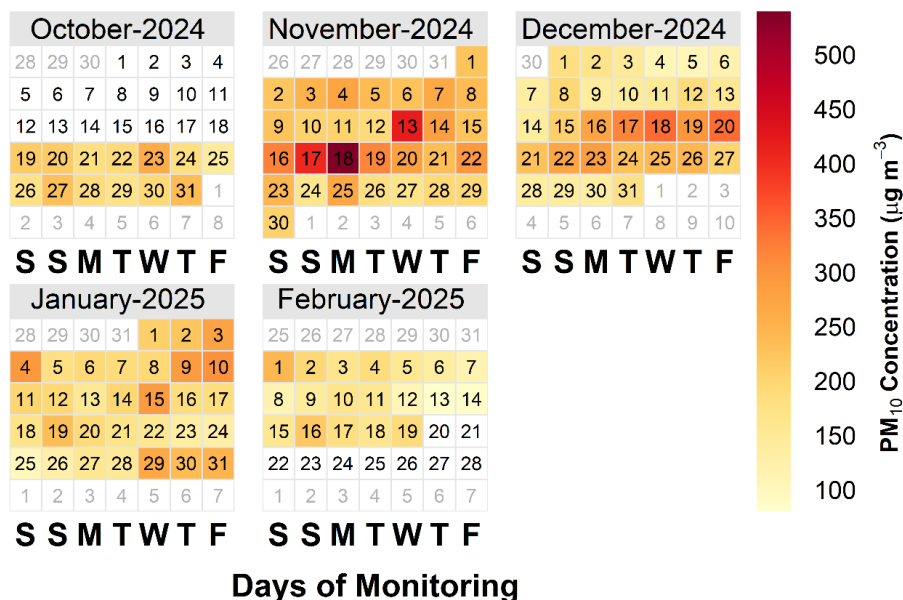


Figure 4.12 Calendar plot of PM_{10} concentrations in ISTM JNU Campus (Site-III)

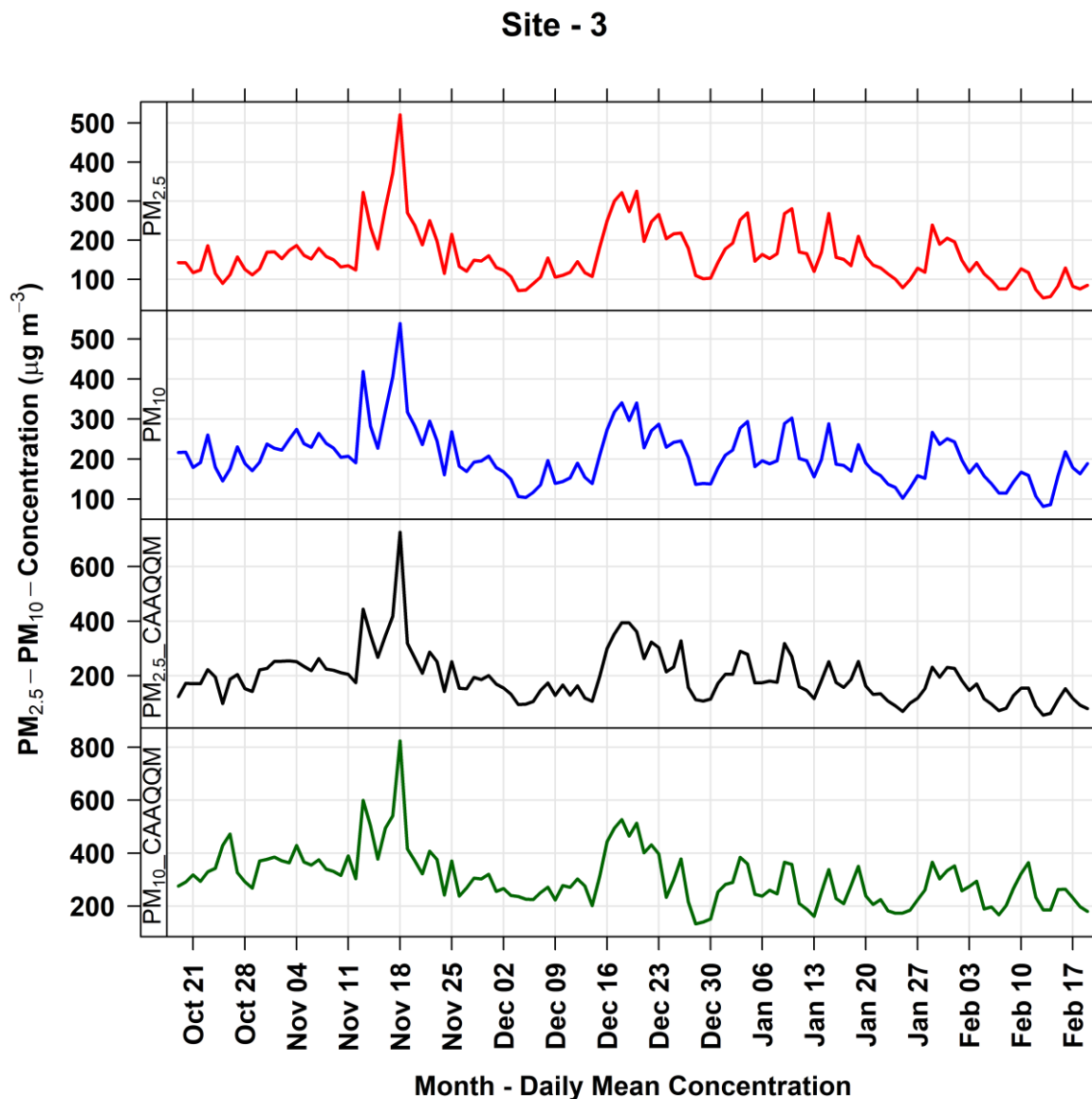


Figure 4.13 Temporal variation of $PM_{2.5}$ and PM_{10} concentrations in ISTM JNU Campus (Site-III) with the CAAQMS

In Site-III, the contribution of $PM_{2.5}$ to PM_{10} was found to be more than any other stations. The $PM_{2.5}$ concentration was found to have 90% of the PM_{10} concentrations throughout the GRAP period (Fig 4.13). The percentage of concentration during different phases of the GRAP revealed that the concentration of $PM_{2.5}$ increased during majority of the period. The reduction in concentration in $PM_{2.5}$ and PM_{10} were found during the GRAP III and GRAP IV implementation (Fig 4.14).

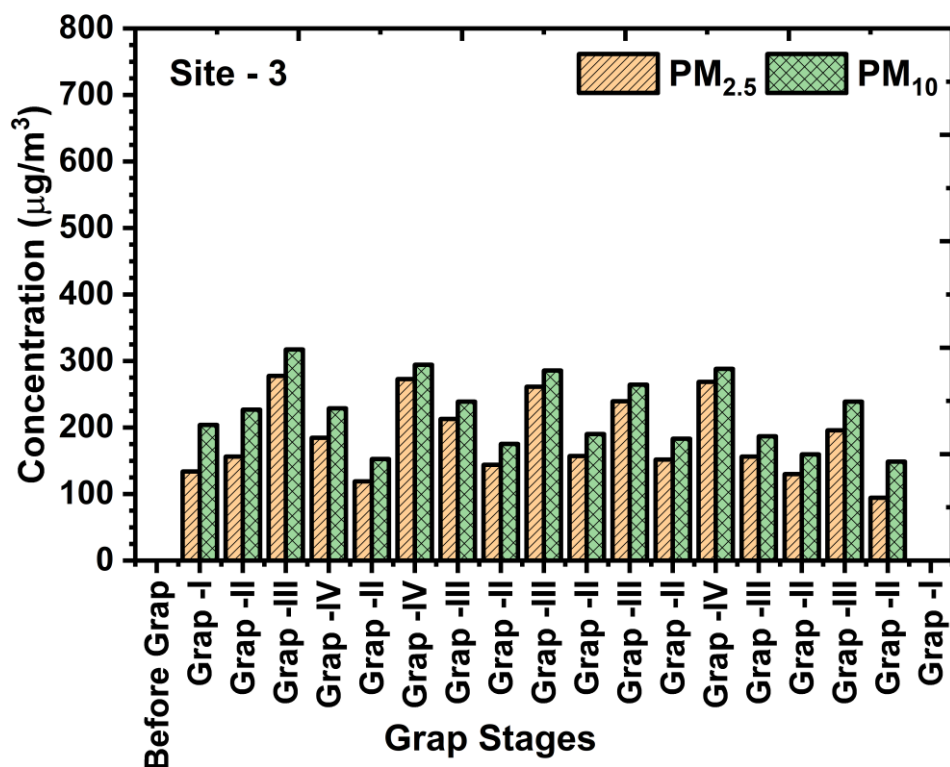


Figure 4.14 Bar Plot of PM_{2.5} and PM₁₀ during different stages of GRAP in Site-III

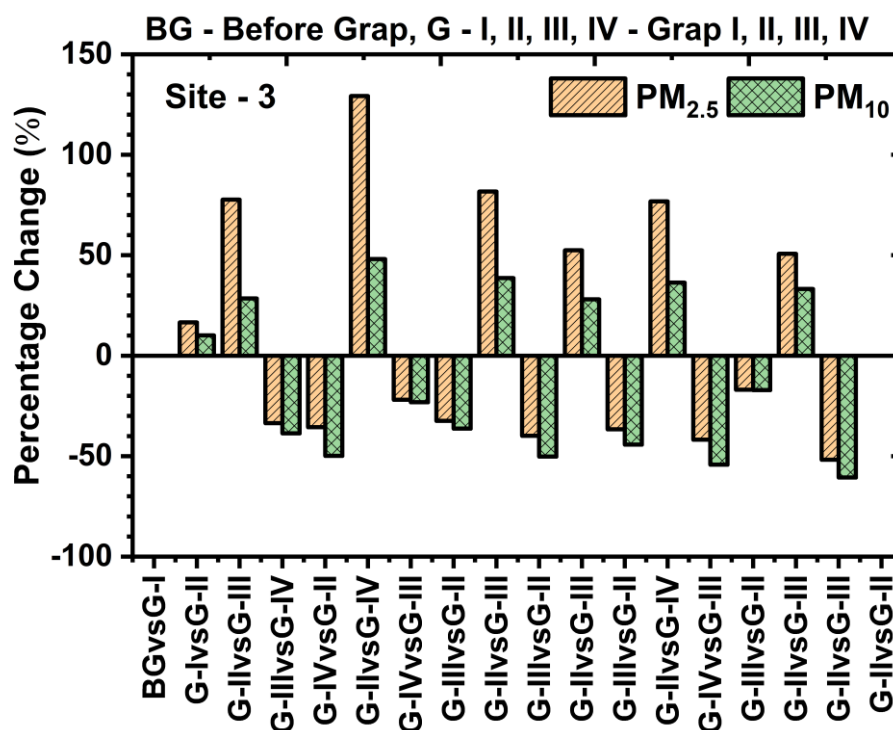


Figure 4.15 Percentage change in concentration during different stages of GRAP (Stage-III)

4.4 Construction site-IV temporal trends of PM_{2.5} and PM₁₀

This site comes under Industrial Site, located in Naraina Industrial Area, Phase-I, New Delhi. It falls under Delhi Cantonment Sub-Division of New Delhi District having Plot Area of 1200 square meters and BUA of 3004.74 square meters.

The PM_{2.5} and PM₁₀ concentrations at this site were found to be higher than the nearby CAAQMS. This showed that the construction sites concentration was the dominating source in Site-IV and the influence of other sources are found to be less in this region. Like all other previous sites, the higher concentration (PM_{2.5} and PM₁₀) was found during November, December and January (Fig 4.16, 4.17).

Site - 4

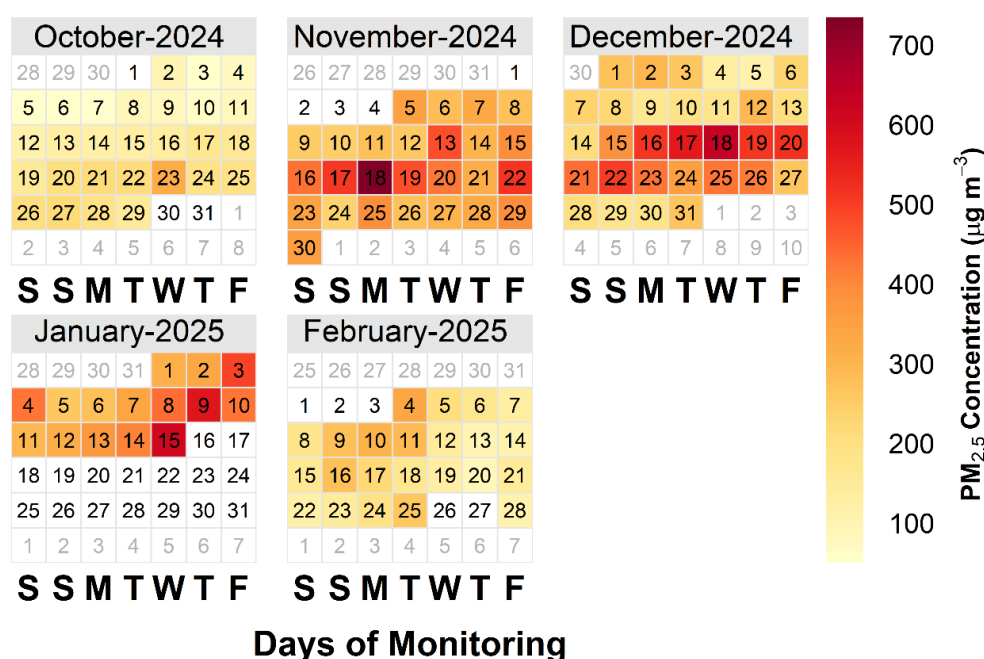


Figure 4.16 Calendar plot of PM_{2.5} concentrations in A-37 NIA-1 (Site-IV)

At construction site the PM_{2.5} concentration ranged between 50 to 600 µg/m³ and at the nearest CAAQMS it ranged between 100 to 500 µg/m³ (Fig 4.18). Similarly, for PM₁₀ concentration, it ranged between 50 to 800 µg/m³ and in CAAQMS ranged between 100 to 700 µg/m³. The concentration data was not available from 15th January to 1st February. The temporal variation of

the concentration of PM_{2.5} and PM₁₀ revealed that in PM₁₀ concentration PM_{2.5} contributes for more proportion. GRAP III and GRAP IV period were found to have higher concentration of the particulate matter compared to other periods.

Site - 4

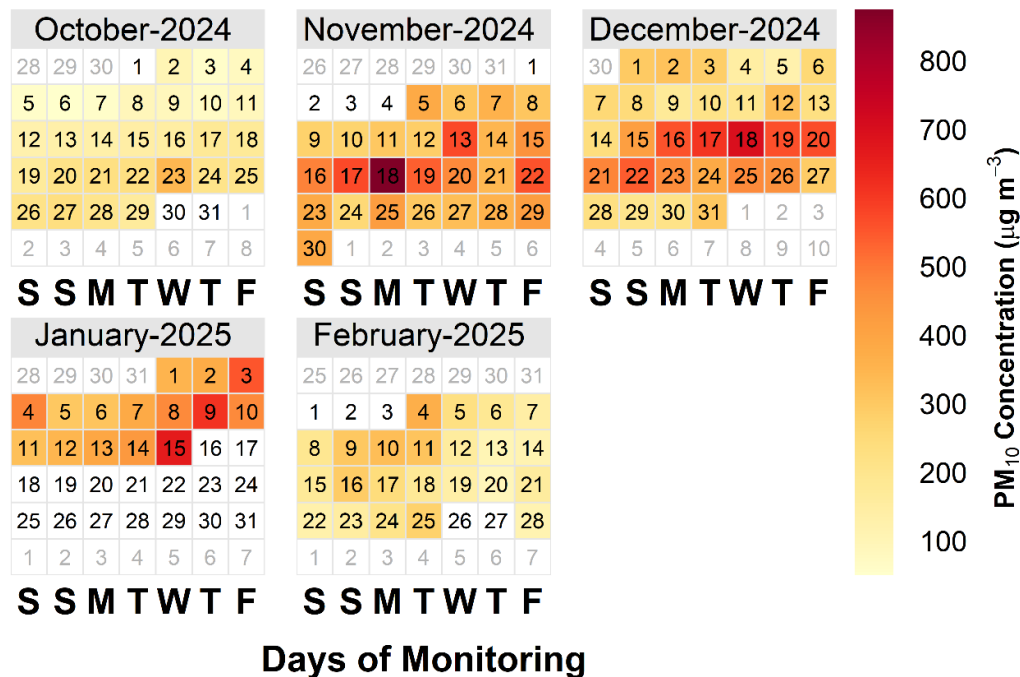


Figure 4.17 Calendar plot of PM₁₀ concentrations in A-37 NIA-1 (Site-IV)

During GRAP I period, PM_{2.5} and PM₁₀ were observed to have concentration $< 200 \mu\text{g m}^{-3}$ (Fig 4.19). The concentration of PM_{2.5} and PM₁₀ in Site-IV was having multiple higher concentrations compares to other sites. The concentration trend of PM_{2.5} and PM₁₀ at Site-IV and CAAQMS station were similar and revealed that the concentration found at the construction site was higher than the ambient air quality monitoring station.

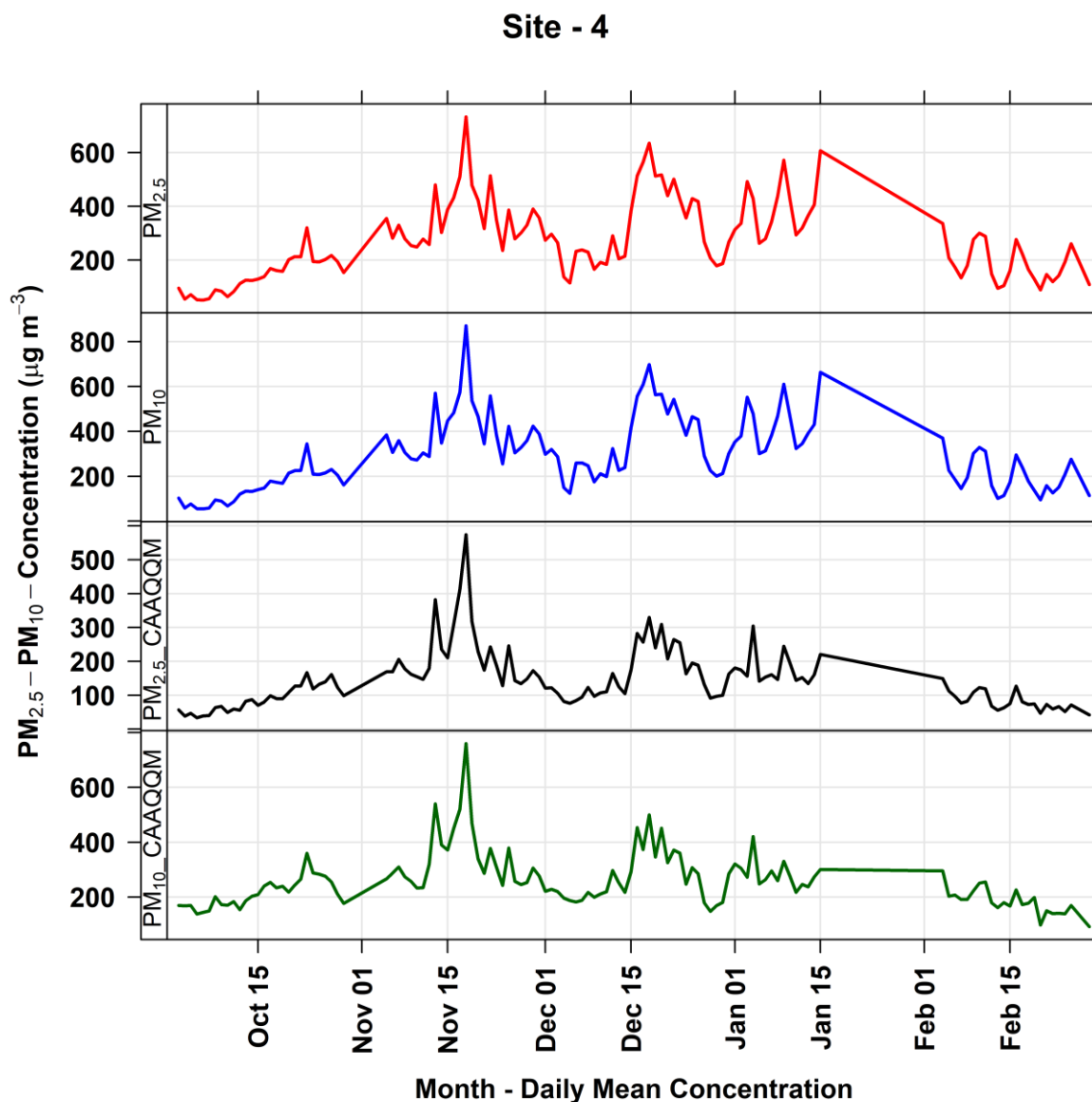


Figure 4.18 Temporal variation of $PM_{2.5}$ and PM_{10} concentrations in A-37 NIA-1 (Site-IV) with the CAAQMS

The percentage change in concentration of the $PM_{2.5}$ and PM_{10} revealed that the reduction in concentration was seen more in the PM_{10} concentration whereas the increase in concentration was found to be more in $PM_{2.5}$ (Fig 4.20). The GRAP reduction was seen more when the GRAP IV or GRAP III was returned back to GRAP II, whereas, the higher concentrations were also found during GRAP IV.

4.5 Temporal variation of PM_{2.5} and PM₁₀ at construction Site-V

This site was located at Vasant Marg, Vasant Vihar, New Delhi and covered under a Residential Site, having Plot Area of 634.28 square meters and BUA of 1036.79 square meters. The concentrations observed at the construction Site V was observed with concentration which was gradually increasing from GRAP I to GRAP IV and it decreases gradually (Fig 4.21, 4.21). The higher concentrations were found during the November to December period (Fig 4.23). The concentration was found higher than other periods (Fig 4.24). This period was found to have higher polluted days in almost at all the construction sites. The reduction in concentration of pollutants was found more in PM₁₀ concentration and the increase in concentration was found more in PM_{2.5} (Fig 4.25).

Site - 5

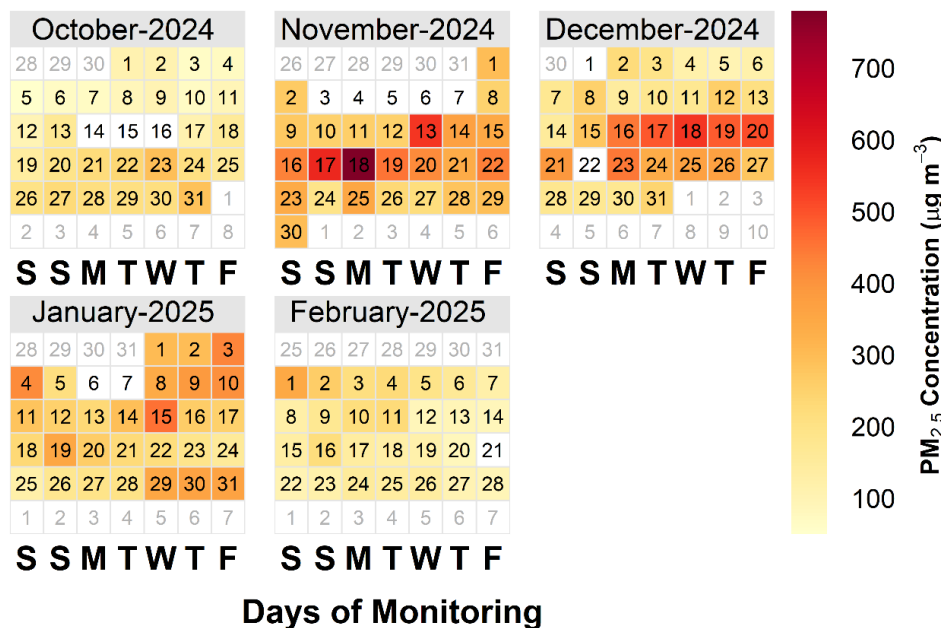


Figure 4.21 Calendar plot of PM_{2.5} concentrations in E-63 Vasant Vihar (Site-V)

Site - 5

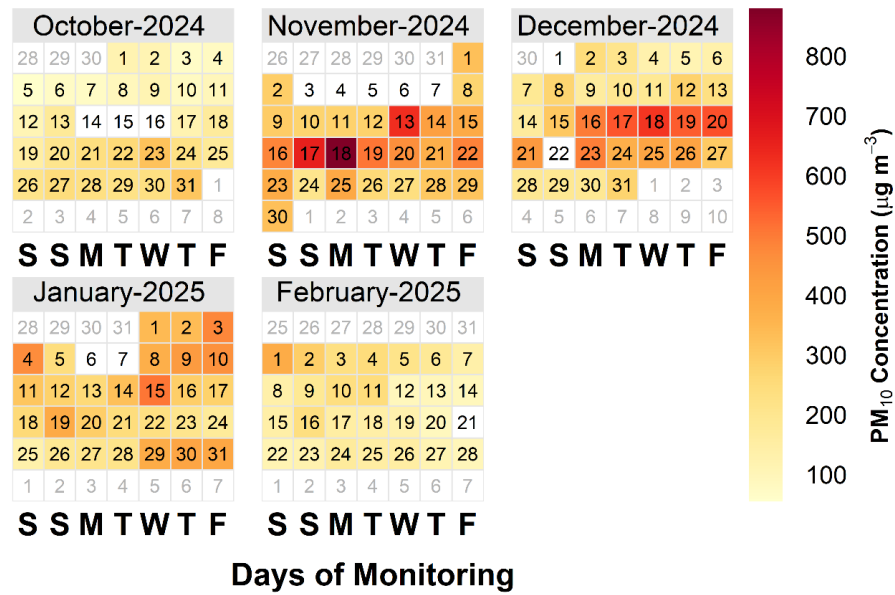


Figure 4.22 Calendar plot of PM₁₀ concentrations in E-63 Vasant Vihar (Site-V)

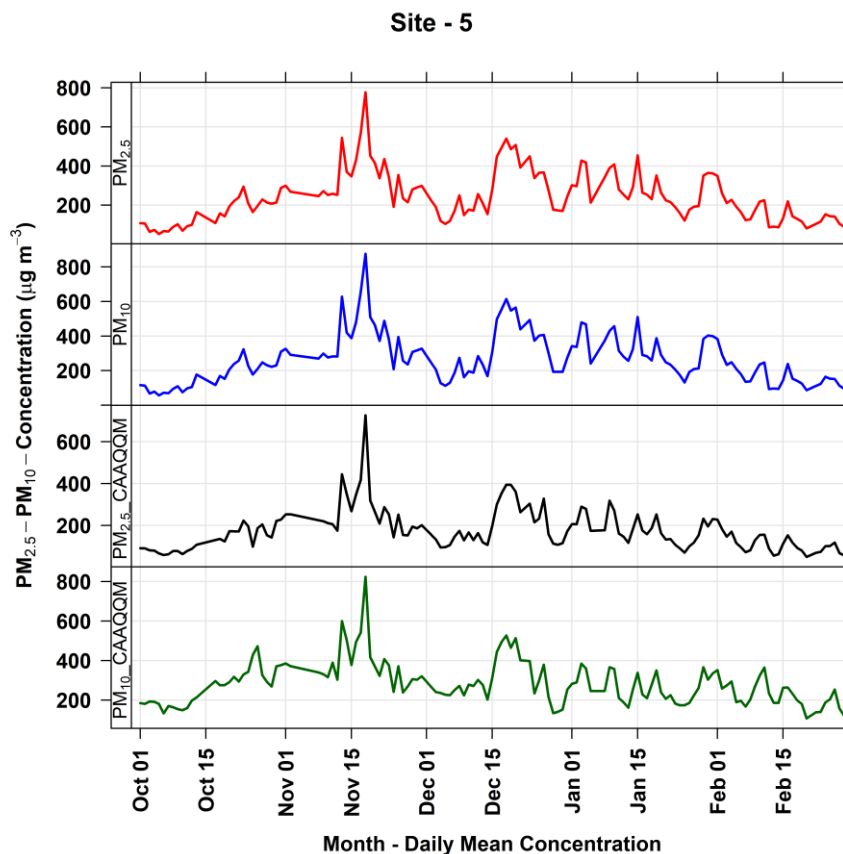


Figure 4.23 Temporal variation of PM_{2.5} and PM₁₀ concentrations in E-63 Vasant Vihar (Site-V) with CAAQMS

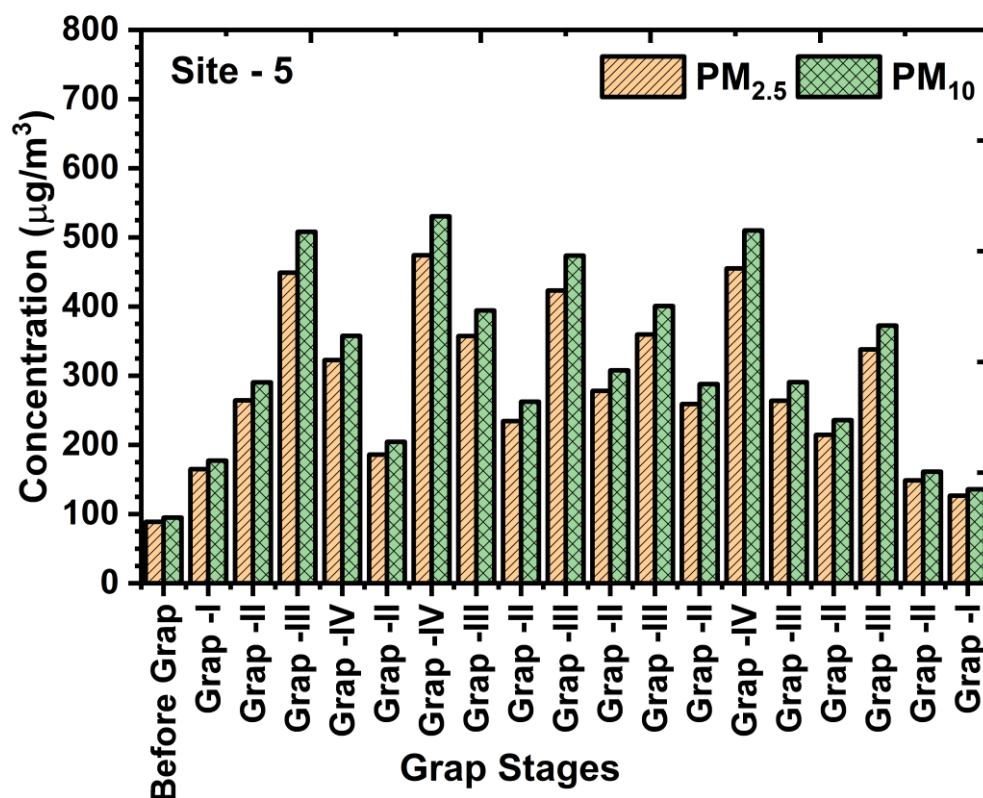


Figure 4.24 Bar Plot of PM_{2.5} and PM₁₀ during different stages of GRAP in Site-V

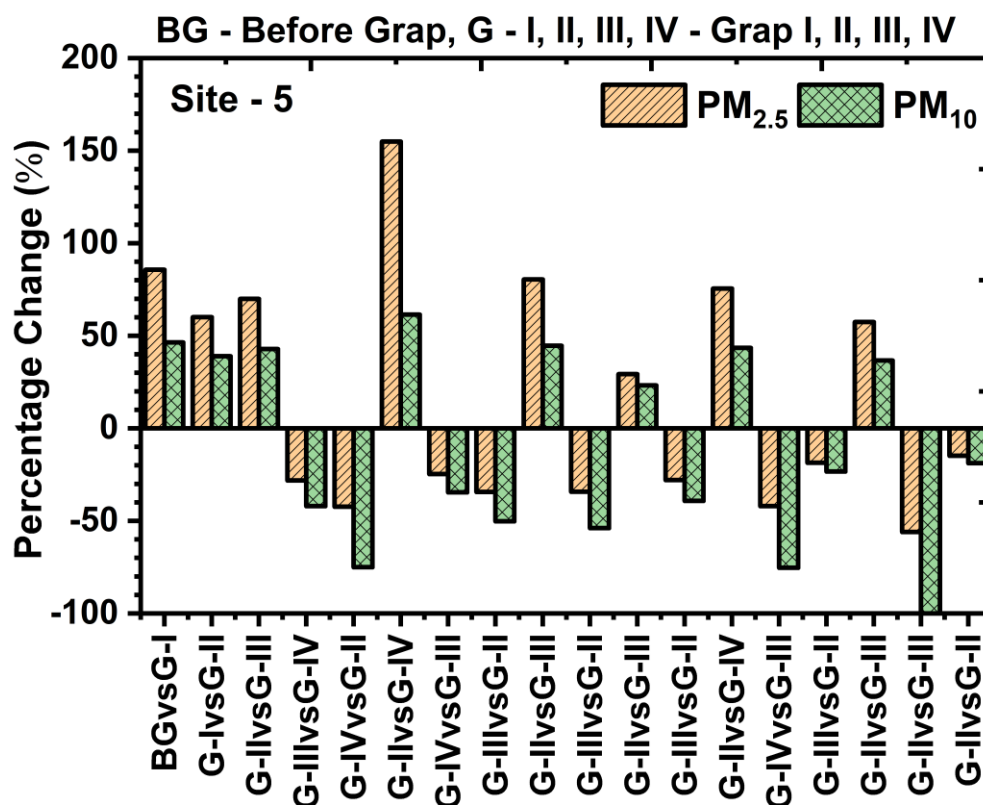


Figure 4.25 Percentage change in concentration during different stages of GRAP (Site-V)

4.6 PM_{2.5} and PM₁₀ time-series analysis at construction site -VI

Site-IV is a Government Project namely Assam Bhawan being undertaken by Assam PWD and is located at Sardar Patel Marg, New Delhi. The site is in Chanakyapuri Sub-Division of New Delhi District having Plot Area of 2115.6 square meters and BUA of 7291.84 square meters.

The PM₁₀ concentrations in Site VI is found to have higher concentration ranged from 700 to 800 µg/m³ in November to February.

Site - 6

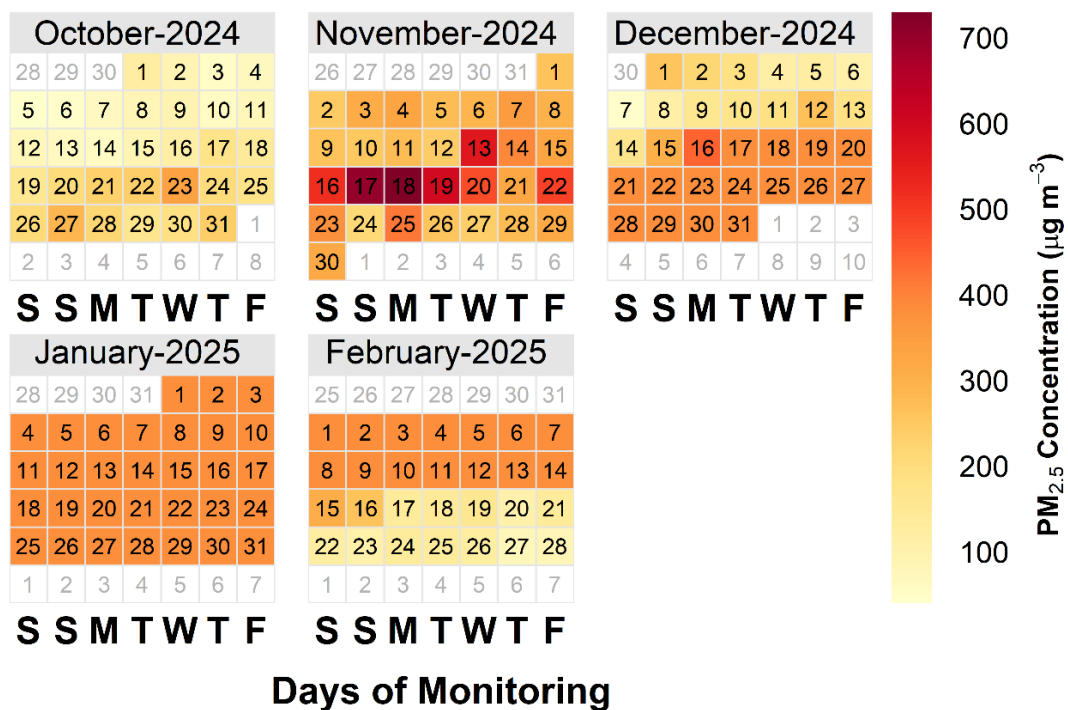


Figure 4.26 Calendar plot of PM_{2.5} concentrations at Sardar Patel Marg Assam Bhawan (Site-VI)

Site - 6

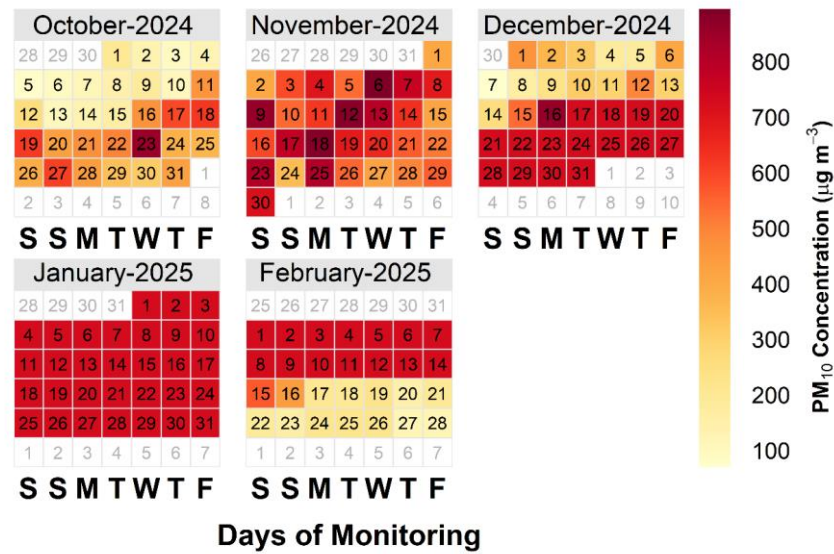


Figure 4.27 Calendar plot of PM₁₀ concentrations at Sardar Patel Marg Assam Bhawan (Site-VI)

Site - 6

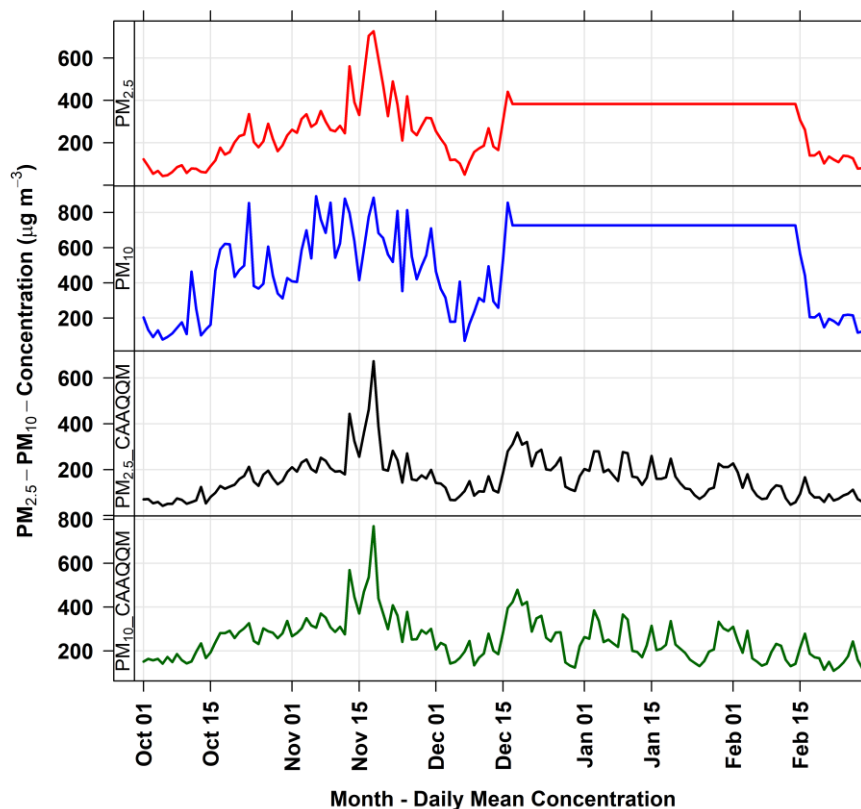


Figure 4.28 Temporal variation of PM_{2.5} and PM₁₀ concentrations at Sardar Patel Marg Assam Bhawan (Site-VI) with the CAAQMS

Higher concentration of PM₁₀ was found at Site-VI (Fig 4.26 to 4.27). The sensor data was not available for a period of two months i.e. from December 15 to February 15 (Fig 4.28). Similar trend of PM_{2.5} was also found at the site (Fig 4.29). The concentration ranged between 100 to 800 µg/m³ for the PM_{2.5} and PM₁₀ concentration (Fig 4.30).

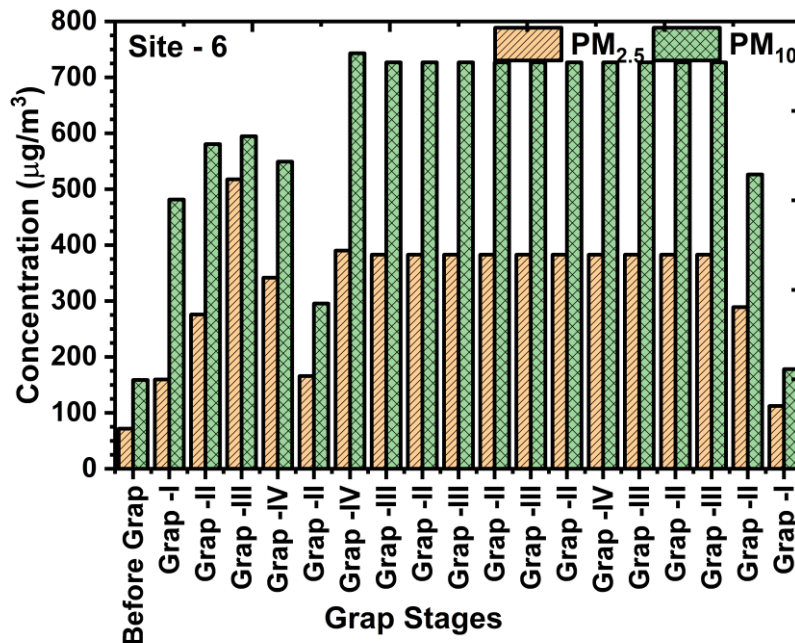


Figure 4.29 Bar Plot of PM_{2.5} and PM₁₀ during different stages of GRAP at Site-VI

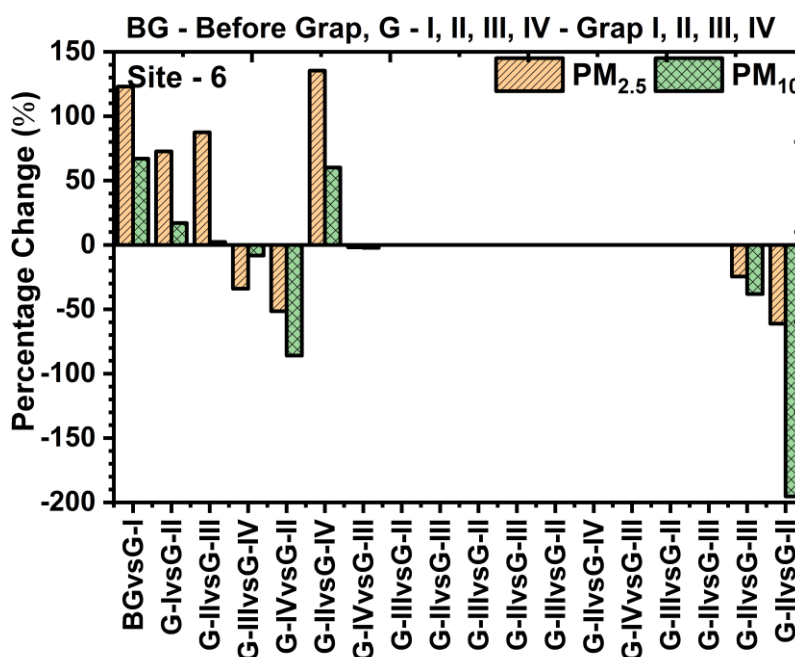


Figure 4.30 Percentage change in concentration during different stages of GRAP (Site-VI)

4.7 Temporal behavior of PM_{2.5} and PM₁₀ at construction site-VII

It is a Commercial Renovation Project of Amba Deep Building located at Kasturba Gandhi Marg, New Delhi. It comes in Chanakyapuri Sub-Division of New Delhi District having Plot Area of 5342 square meters and BUA of 24178 square meters.

Site - 7

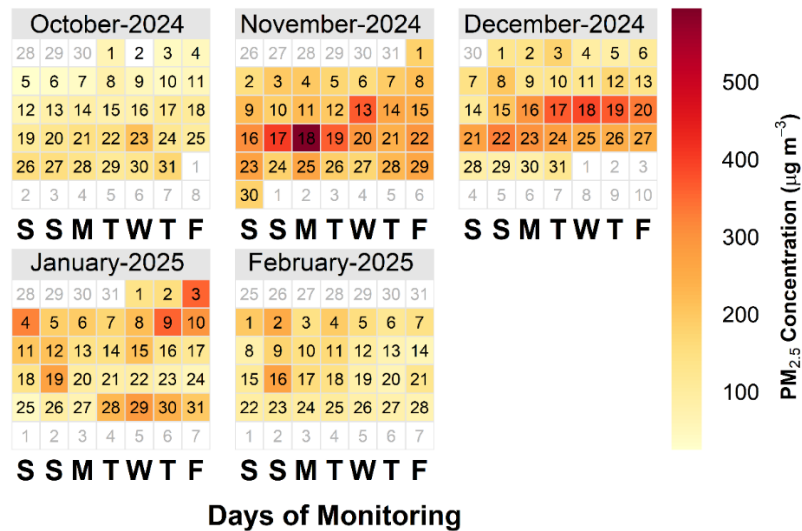
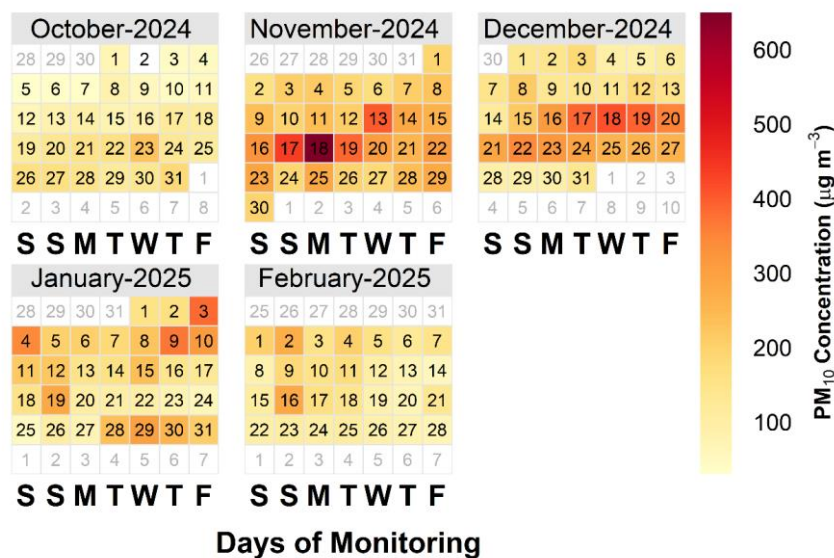


Figure 4.31 Calendar plot of PM_{2.5} concentrations in Ambadeep Building (Site-VII)

Site - 7



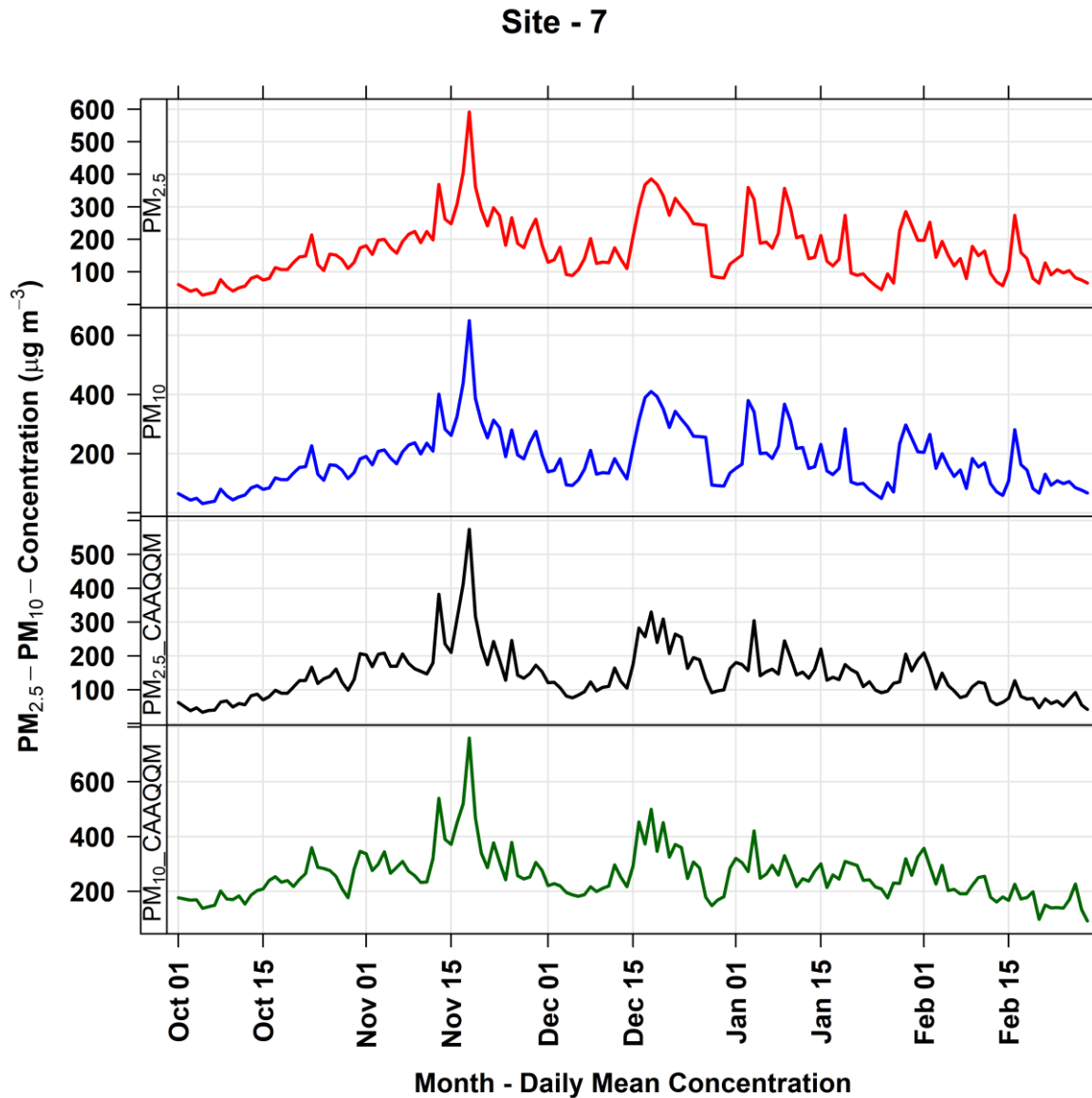


Figure 4.33 Temporal behaviour of $PM_{2.5}$ and PM_{10} concentrations in Amba deep Building (Site-VII) with CAAQMS

The Site-VII concentrations were found similar to the Site-II concentration. At almost all the sites from I to VII, the concentrations of $PM_{2.5}$ and PM_{10} at construction site were found to be in the similar range of 100 to 600 $\mu g/m^3$ (Fig 4.31,4.32). At Site-VII, the data of $PM_{2.5}$ and PM_{10} concentrations were available throughout the monitoring period (Fig 4.33). During different stages of GRAP, the concentration was found $< 400 \mu g/m^3$ for both $PM_{2.5}$ and PM_{10} concentrations (Fig

4.34). The concentration changes that observed during different phase of the GRAP ranged in both reduction and increase (Fig. 4.35).

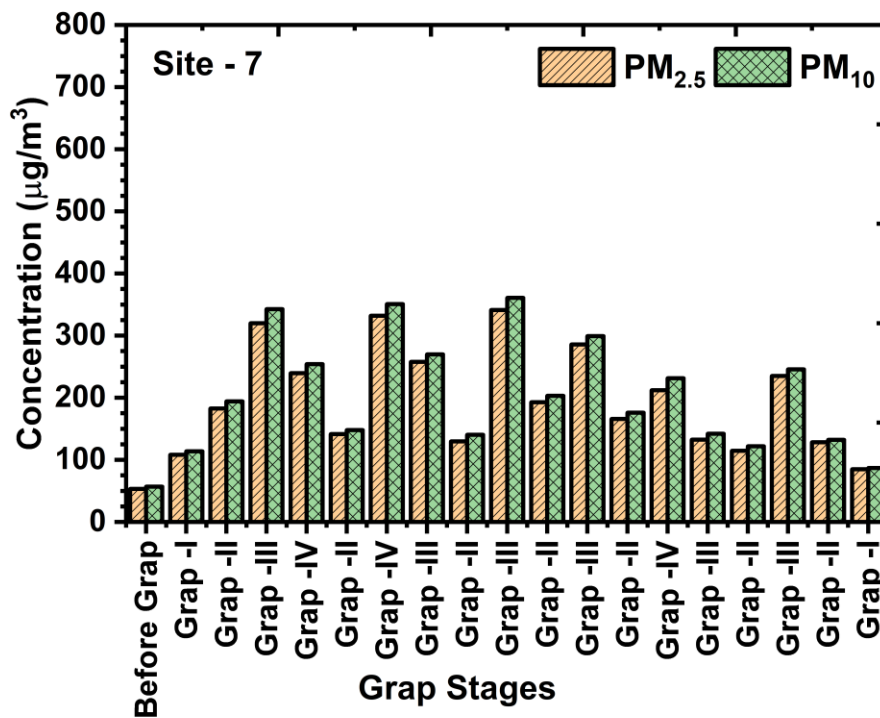


Figure 4.34 Bar Plot of PM_{2.5} and PM₁₀ during different stages of GRAP at Site-VII

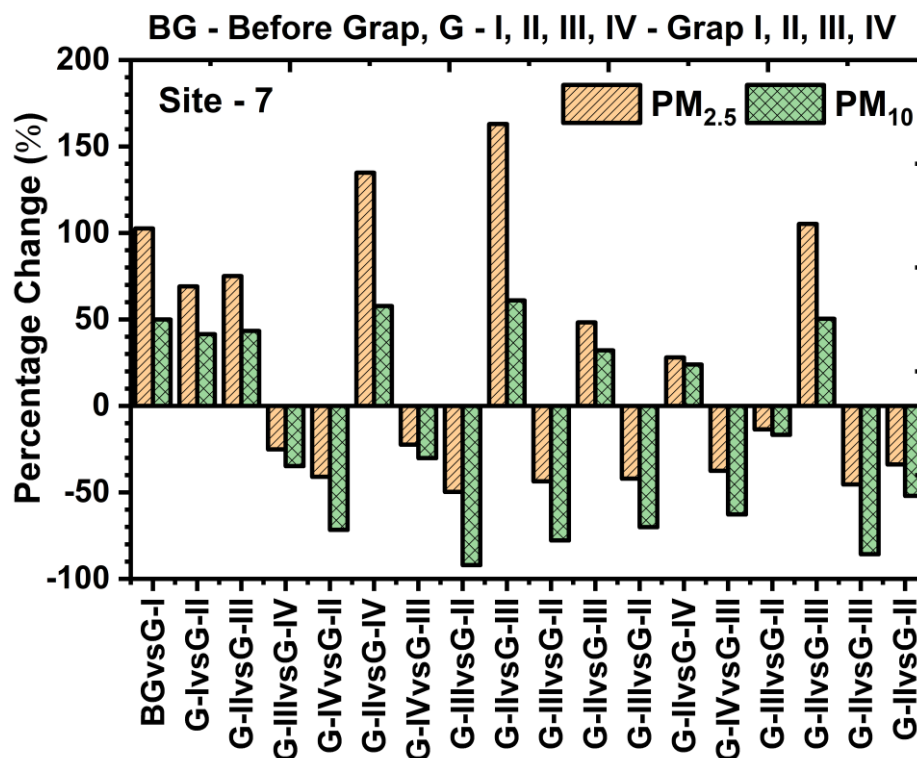


Figure 4.35 Percentage change in concentration during different stages of GRAP (Site-VII)

4.8 Construction site temporal trends of PM_{2.5} and PM₁₀ concentration

Site-VIII is an Institutional Project namely Institute of Constitutional and Parliamentary Studies (ICPS) being constructed by GSBA Builders Pvt Ltd. The site is located at Nyaya Marg, Chanakypuri, Delhi, having Plot Area of 4596.47 square meters and BUA of 20314 square meters.

The construction site (Site VIII) is found to have lowest concentration of PM_{2.5} and PM₁₀ in the New Delhi District as compared to all other sites, except few days. The concentration of the PM_{2.5} and PM₁₀ at the construction Site VIII did not exceed 200 µg/m³ (Fig 4.36 , 4.37).

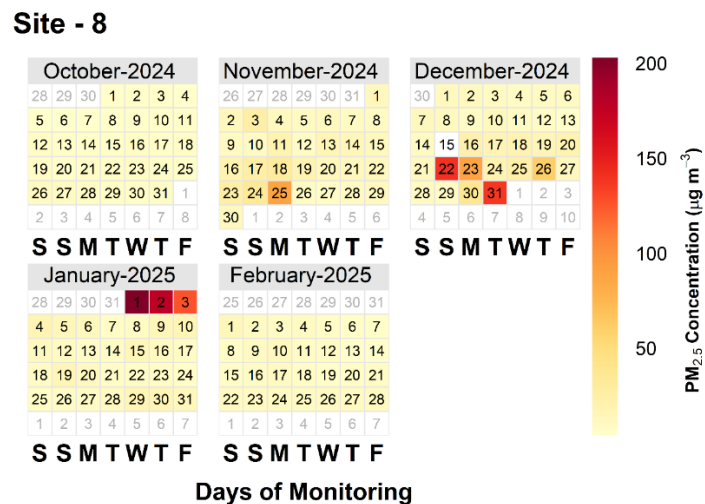


Figure 4.36 Calendar plot of PM_{2.5} concentrations in ICPS (Site-VIII)

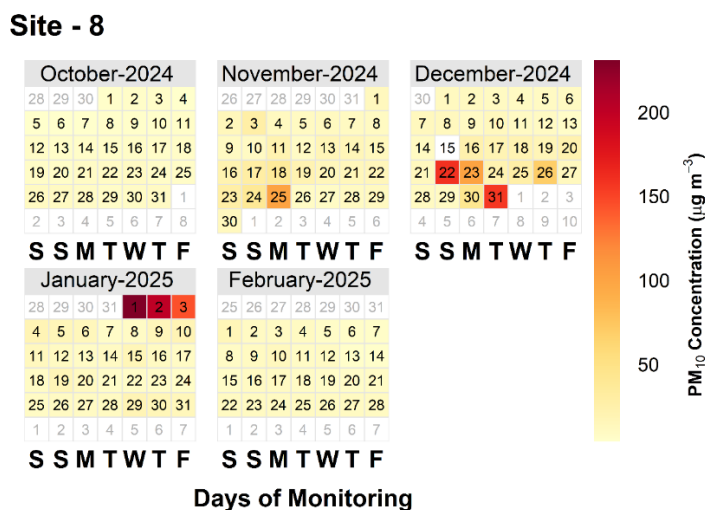


Figure 4.37 Calendar plot of PM₁₀ concentrations in ICPS (Site-VIII)

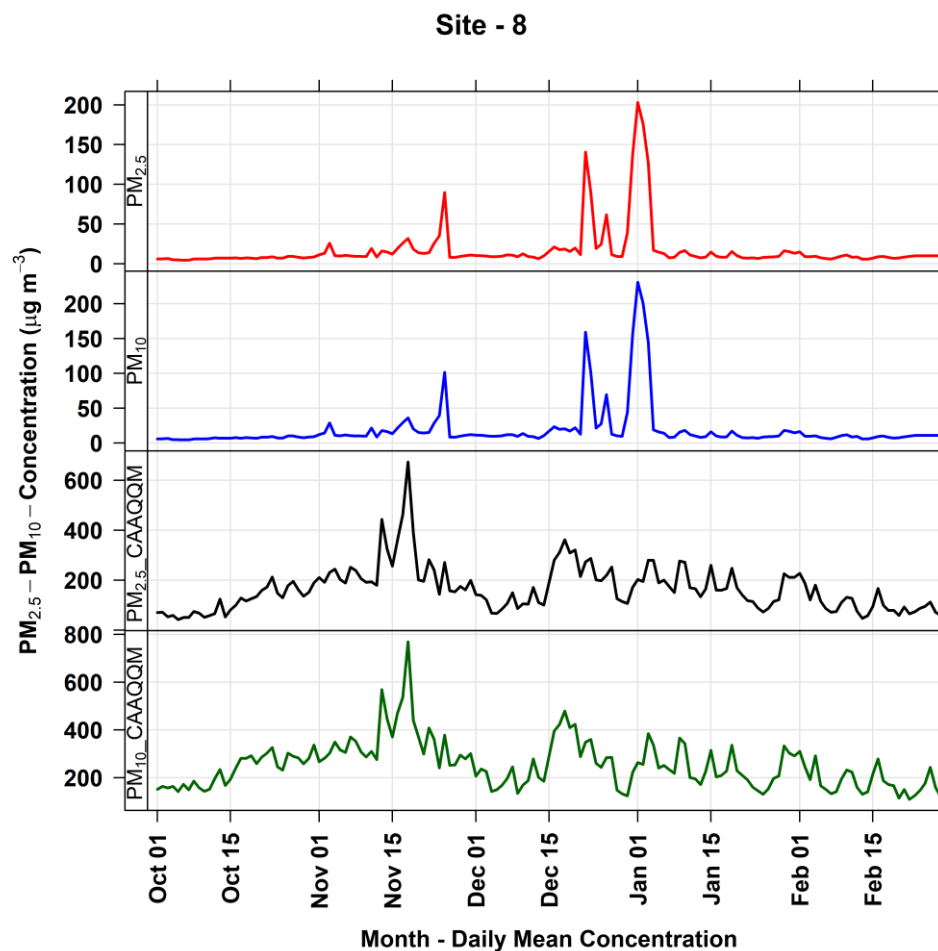


Figure 4.38 Temporal variation of $PM_{2.5}$ and PM_{10} concentrations in ICPS with CAAQMS (Site-VIII)

The temporal variation of the $PM_{2.5}$ and PM_{10} revealed that the concentration of $PM_{2.5}$ ranged ~ 50 to $200 \mu\text{g}/\text{m}^3$ majority of the monitoring period and similarly for PM_{10} at the construction site, whereas the CAAQMS data in the nearby construction site showed a variation of 50 to $600 \mu\text{g}/\text{m}^3$ for $PM_{2.5}$ concentration and for PM_{10} the concentrations were in the range of 50 to $800 \mu\text{g}/\text{m}^3$ during different phases of the GRAP implementation (Fig 4.38).

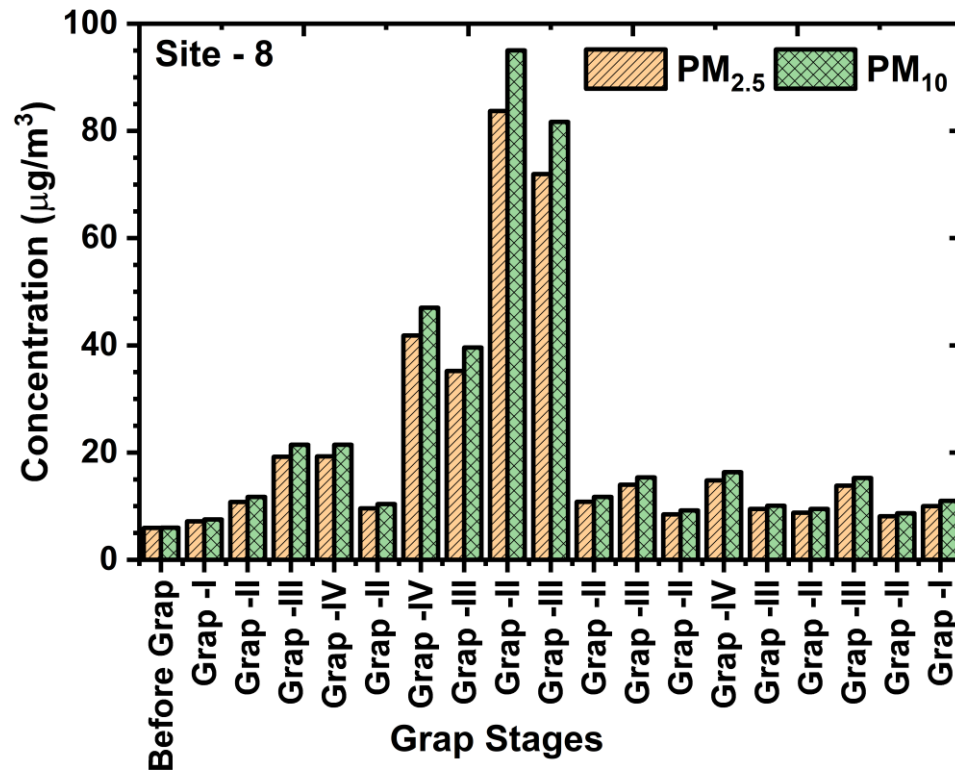


Figure 4.39 Bar Plot of PM_{2.5} and PM₁₀ during different stages of GRAP at Site-VIII

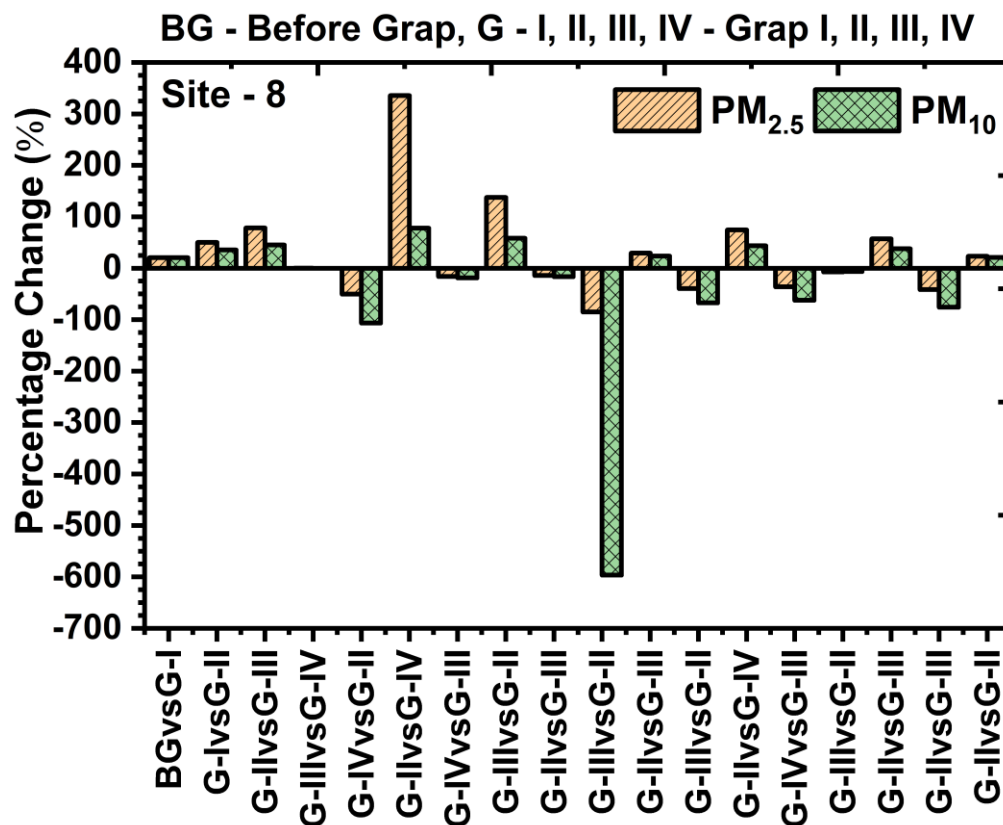


Figure 4.40 Percentage change in concentration during different stages of GRAP (Site-VIII)

The GRAP phase wise analysis for the daily average concentration at Site VIII was found to have less concentration among all the other construction sites. The concentration of PM_{2.5} and PM₁₀ ranged < 100 µg/m³. The percentage change in concentration during the different phases of the GRAP revealed that the concentration changes between one phase of GRAP to another phase of GRAP was not significant except few events. Rest of the period, the concentration variation was minimal (Fig 4.40).

4.9 PM_{2.5} and PM₁₀ time-series analysis at construction site-IX

It is a Government Institutional Project namely New Karnataka Bhawan-I (Cauvery) located at Kautilya Marg, Chanakyapuri, New Delhi, constructed by M/s Balajikrupa Projects Pvt Ltd, having Plot Area of 5638 square meters and BUA of 3420 square meters. The concentrations observed at this site was similar to the other sites. The daily average concentration ranged < 400 µg/m³ for PM_{2.5} (Fig 4.41) and for PM₁₀ it was < 500 µg/m³ (Fig 4.42). The observation data of this site was not available for a period of 17 days in the November month. Other construction sites were observed with higher PM concentrations in November month.

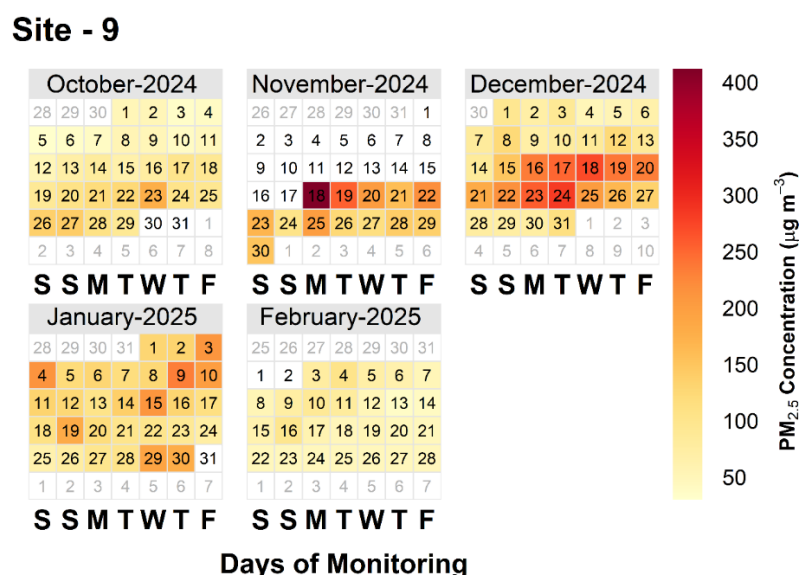


Figure 4.41 Calendar plot of PM_{2.5} concentrations in New Karnataka Bhawan (Site-IX)

Site - 9

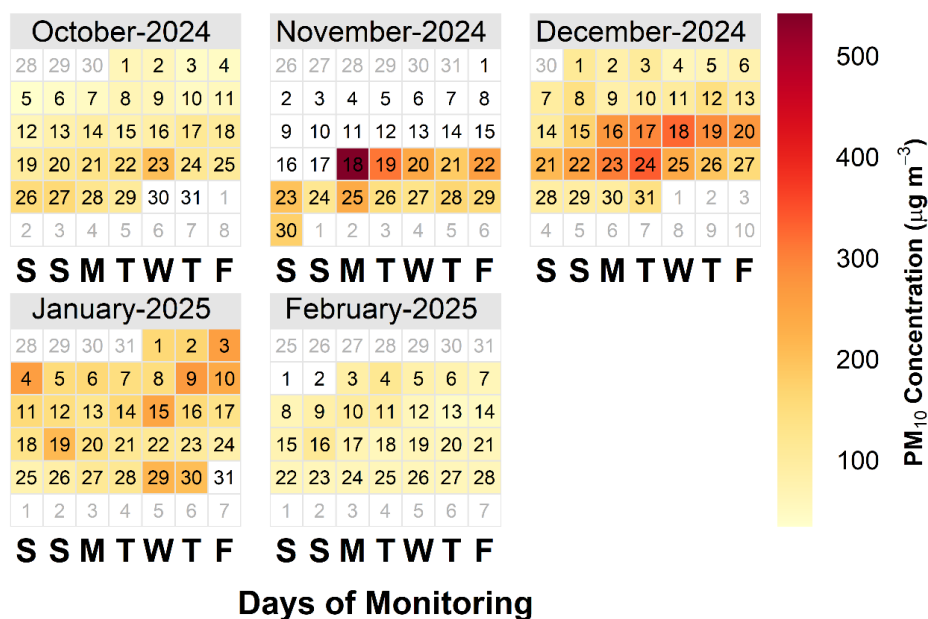


Figure 4.42 Calendar plot of PM₁₀ concentrations in New Karnataka Bhawan (Site-IX)

The hourly average temporal variation of the PM_{2.5} and PM₁₀ concentrations were found to be higher in the CAAQMS and lesser at the construction site. The PM₁₀ concentration in the CAAQMS reached up to 800 $\mu\text{g/m}^3$ (Fig 4.43) Like other construction sites the PM concentrations increased during GRAP IV and during before and after GRAP phases, the concentrations were found to be less. The daily average concentration during different phases of GRAP concentrations were found to be 300 $\mu\text{g/m}^3$. GRAP III and GRAP IV stages were found to have higher concentrations of particulate matter compared to other phases of GRAP (Fig 4.44).

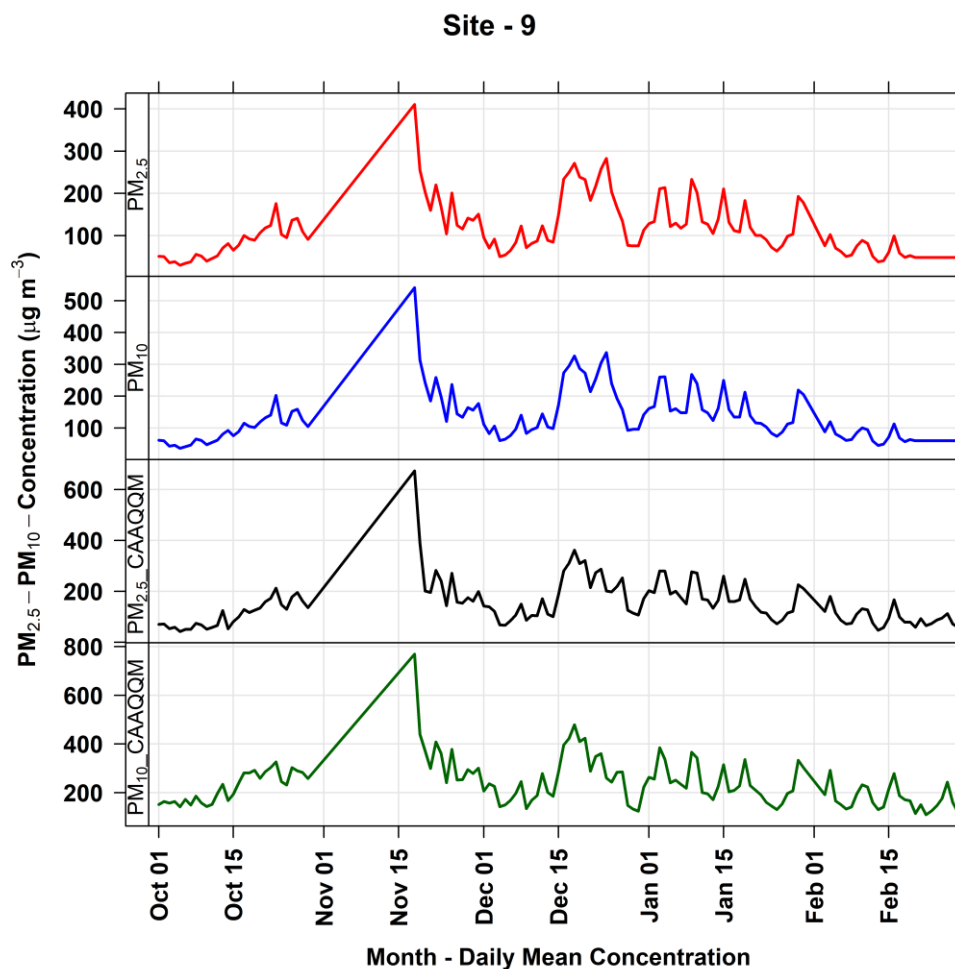


Figure 4.43 Temporal variation of $PM_{2.5}$ and PM_{10} concentrations in New Karnataka Bhawan (Site-IX) with CAAQMS

The percentage change in $PM_{2.5}$ and PM_{10} concentration during different phases of GRAP revealed that during GRAP II to GRAP III implementation on 28th January to 2nd February, the maximum reduction in PM_{10} concentration was found. $PM_{2.5}$ concentration increases during different period of GRAP compared to PM_{10} (Fig 4.45).

4.10 Temporal distribution of PM_{2.5} and PM₁₀ at construction site-X

This site is a Commercial Residential Project namely Godrej Connaught One, located at Lady Hardinge Road, Connaught Place, New Delhi. The project is being constructed by M/s Godrej Projects North LLP, having Plot Area of 3541 square meters and BUA of 18222 square meters.

At this site, the PM_{2.5} concentration was found below the range of 300 µg/m³. Similar to other sites, the higher concentration of the particles was found during November. The peak concentration of both PM_{2.5} and PM₁₀ were found during the same period. The concentration in October and February were found to < 150 µg/m³ (Fig 4.46).

Site - 10

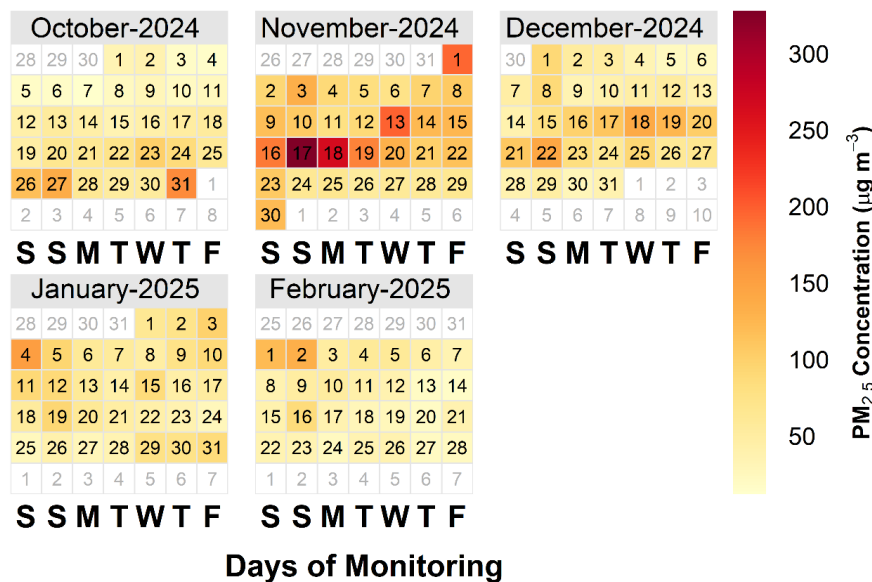


Figure 4.46 Calendar plot of PM_{2.5} concentrations in Godrej Connaught One (Site-X)

The PM₁₀ concentration was also found in the range of < 350 µg/m³ throughout the different phases of GRAP. Except for few days in GRAP IV period, the concentration found at the construction site was < 200 µg/m³ (Fig 4.47). The temporal variation of the construction site PM_{2.5} and PM₁₀ concentration were similar to the trend observed through the CAAQMS (Fig 4.48).

Site - 10

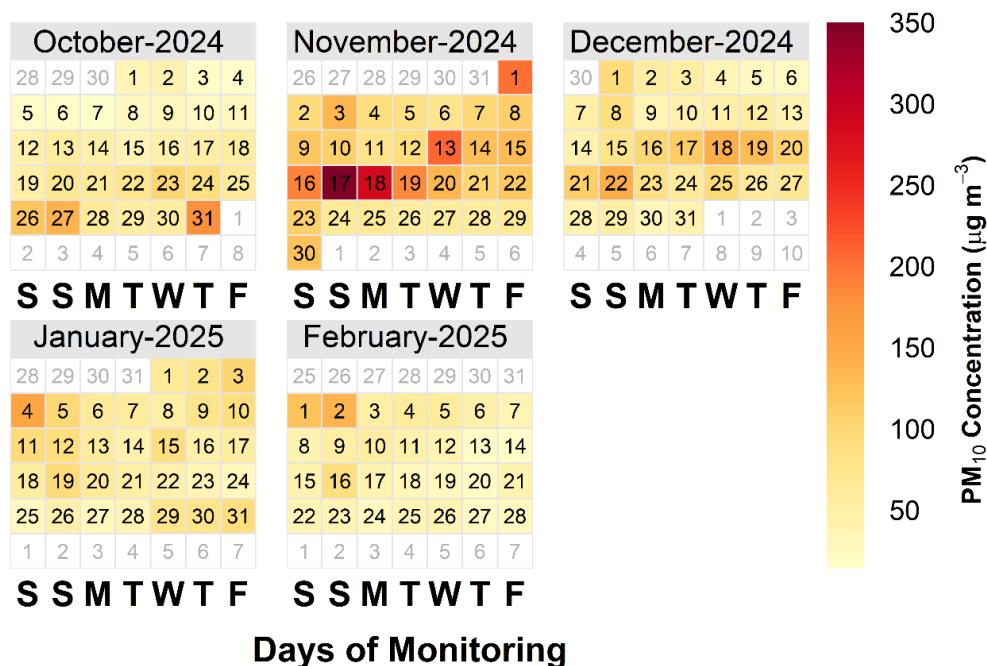


Figure 4.47 Calendar plot of PM₁₀ concentrations in Godrej Connaught One (Site-X)

The phase wise daily average concentration of GRAP revealed that during GRAP III, the observed concentration were found to be $> 200 \mu\text{g/m}^3$ whereas during other phases of GRAP, the concentration found at the construction site was $< 150 \mu\text{g/m}^3$ (Fig 4.48). Before and after GRAP period, the PM_{2.5} and PM₁₀ concentration were found to be $< 25 \mu\text{g/m}^3$ (Fig 4.49). The percentage change in concentration of PM_{2.5} and PM₁₀ during different phases of GRAP revealed that the concentration of PM changes during different phases.

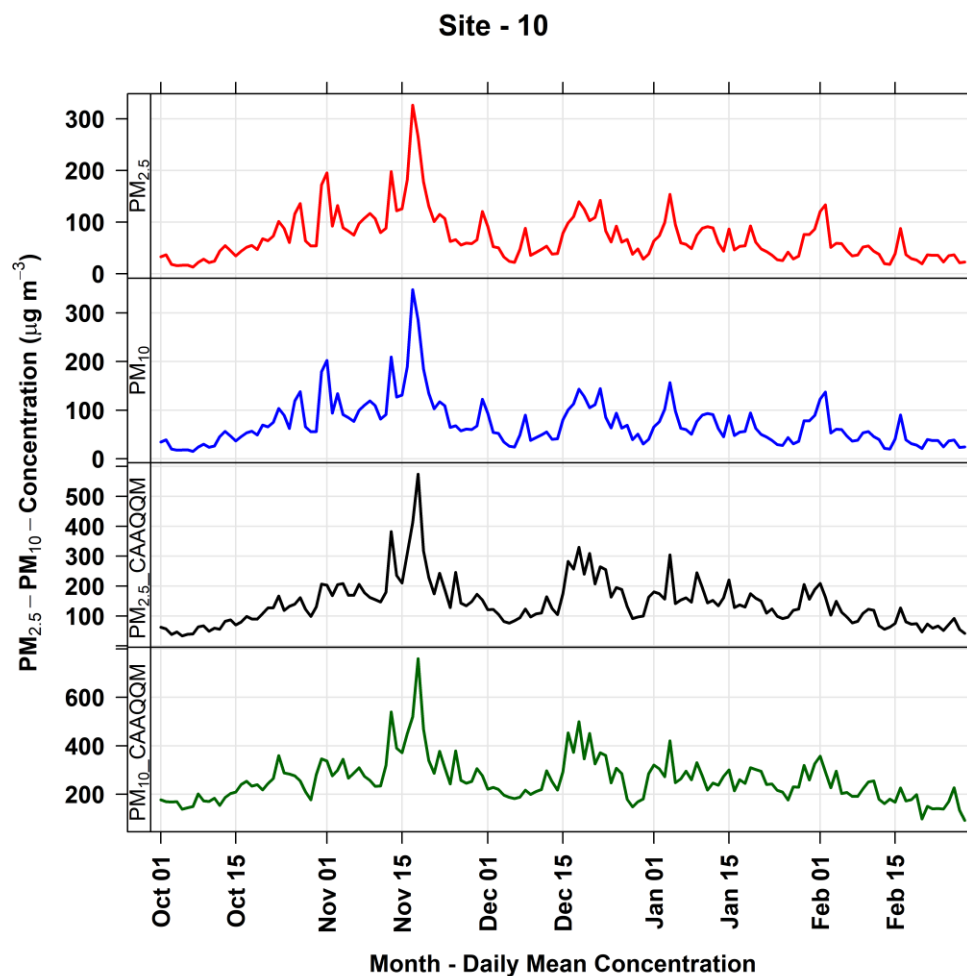


Figure 4.48 Temporal distribution of $PM_{2.5}$ and PM_{10} concentrations in Godrej Connaught One with CAAQMS

Sometimes the concentration was high during GRAP IV which leads to increase in concentrations. However, when the GRAP IV was implemented, the concentrations were reduced consequently based on the improvement in air quality (Fig 4.50).

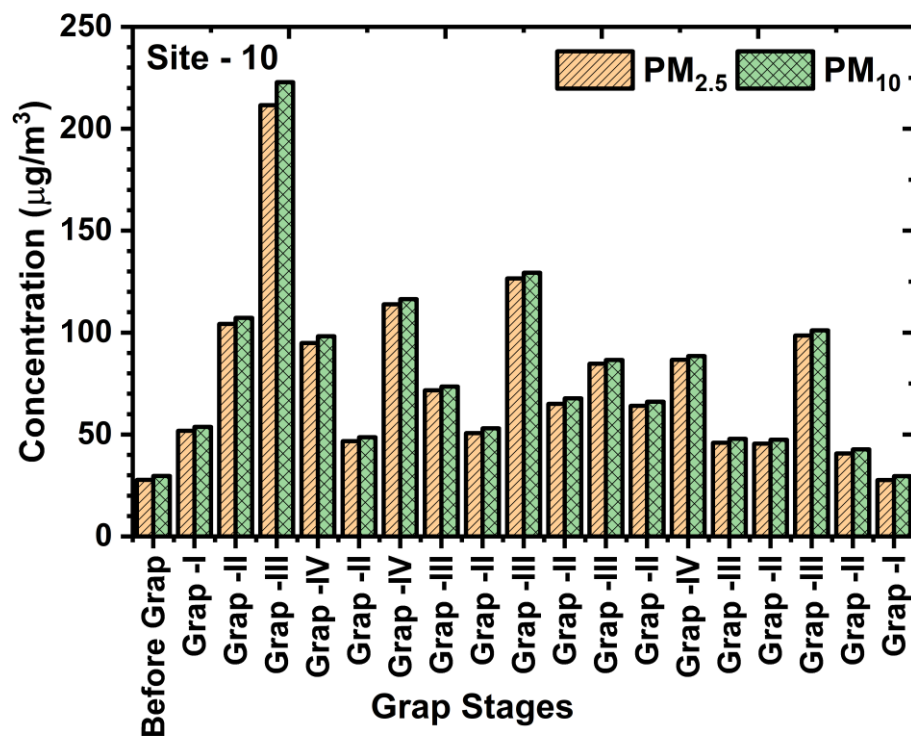


Figure 4.49 Bar Plot of PM_{2.5} and PM₁₀ during different stages of GRAP at Site-X

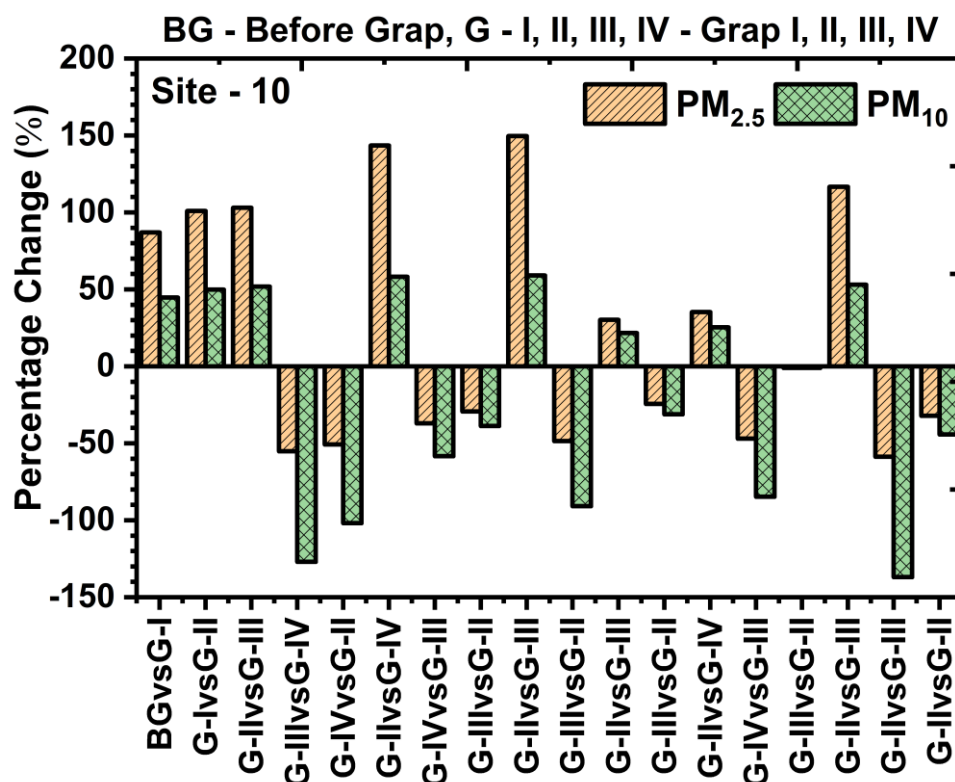


Figure 4.50 Percentage change in concentration during different stages of GRAP (Site-X)

5. Conclusions

The National Capital of India i.e. New Delhi, is one of the globally known city with higher levels of PM pollution. The concentrations found in the city is higher than many global cities. To reduce air quality in Delhi, several initiatives have been taken by the government including different short term to long term interventions. The GRAP is one of the major initiative taken by the CAQM in Delhi and NCR districts, one of the government body dedicatedly works for improving air quality in Delhi NCR region. The commission came up with an initiative called GRAP. The GRAP has four different stages and the restriction were imposed based on the stage implemented by the commission. As per the government mandate, the sensors for detecting air quality need to be installed at the construction sites, having plot area greater than or equal to 500 m². The study analysed the concentration of PM_{2.5} and PM₁₀ concentrations at 10 different C&D sites located in the New Delhi district in the city. The nearest CAAQMS data were also compared and analysed for detecting the concentration at construction sites and the CAAQMS. The results revealed that the PM₁₀ and PM_{2.5} concentration at the different construction sites ranged upto 800 µg/m³ and 600 µg/m³ respectively. The analysis revealed that at some construction sites, the concentration of PM_{2.5} and PM₁₀ was less than the CAAQMS and vice versa. The phase wise GRAP analysis revealed the higher concentration of particulates during GRAP III and IV implementation. The analysis also revealed that the concentration after GRAP IV implementation, consequently leads to decrease in concentration, showed that the GRAP policy helped in improving the city air quality.

5.1 Applications of the Study

The dust control and GRAP strategies play a very crucial role in achieving various SDGs by reducing air pollution, improving public health, and contributing to sustainable urban and industrial practices.

Table 5.1 Role of the current study in different SDGs

SDG	Goal Description	Dust Control & GRAP Contribution
 SDG 3: Good Health and Well-being	Ensure healthy life and promote well-being for each one across all ages.	Dust control reduces particulate pollution that can cause respiratory and cardiovascular diseases. GRAP measures minimize exposure to air pollutants.
 SDG 6: Clean Water and Sanitation	Ensure availability of clean water and sanitation for all.	Dust control prevents contamination of water sources by airborne particulates, ensuring cleaner water.
SDG 7: Affordable and Clean Energy	Ensure access to affordable, reliable, sustainable, and modern energy for all.	Dust control technologies can be powered by renewable energy sources, supporting energy sustainability.
 SDG 9: Industry, Innovation, and Infrastructure	Resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovative industrialization.	Dust control and GRAP promote cleaner industrial practices, reducing environmental harm. Innovations in dust control align with sustainable industry goals.
 SDG 11: Sustainable Cities and Communities	Make cities and human settlements inclusive, resilient, and sustainable.	Dust control contributes to healthier urban spaces by reducing air pollution, enhancing the quality of life. GRAP helps manage urban

SDG	Goal Description	Dust Control & GRAP Contribution
		pollution.
11 SDG 12: Responsible Consumption and Production	Ensure sustainable consumption and production patterns.	Dust control reduces the environmental impact of industries and helps ensure sustainable production. GRAP encourages responsible pollution management.
10 SDG 13: Climate Action	Take urgent corrective action to combat climate change and its impacts.	Dust storms and particulate pollution can affect global weather patterns; controlling dust contributes to climate mitigation.
14 SDG 15: Life on Land	Protect, restore, and promote sustainable use of terrestrial ecosystems.	Dust control prevents soil erosion, reduces land degradation, and protects biodiversity. GRAP helps reduce pollution's impact on ecosystems.