Report | December 2025

How Construction Activities Affect Urban Air Pollution

Insights from Air Quality Monitoring at a Construction Site in Gurugram

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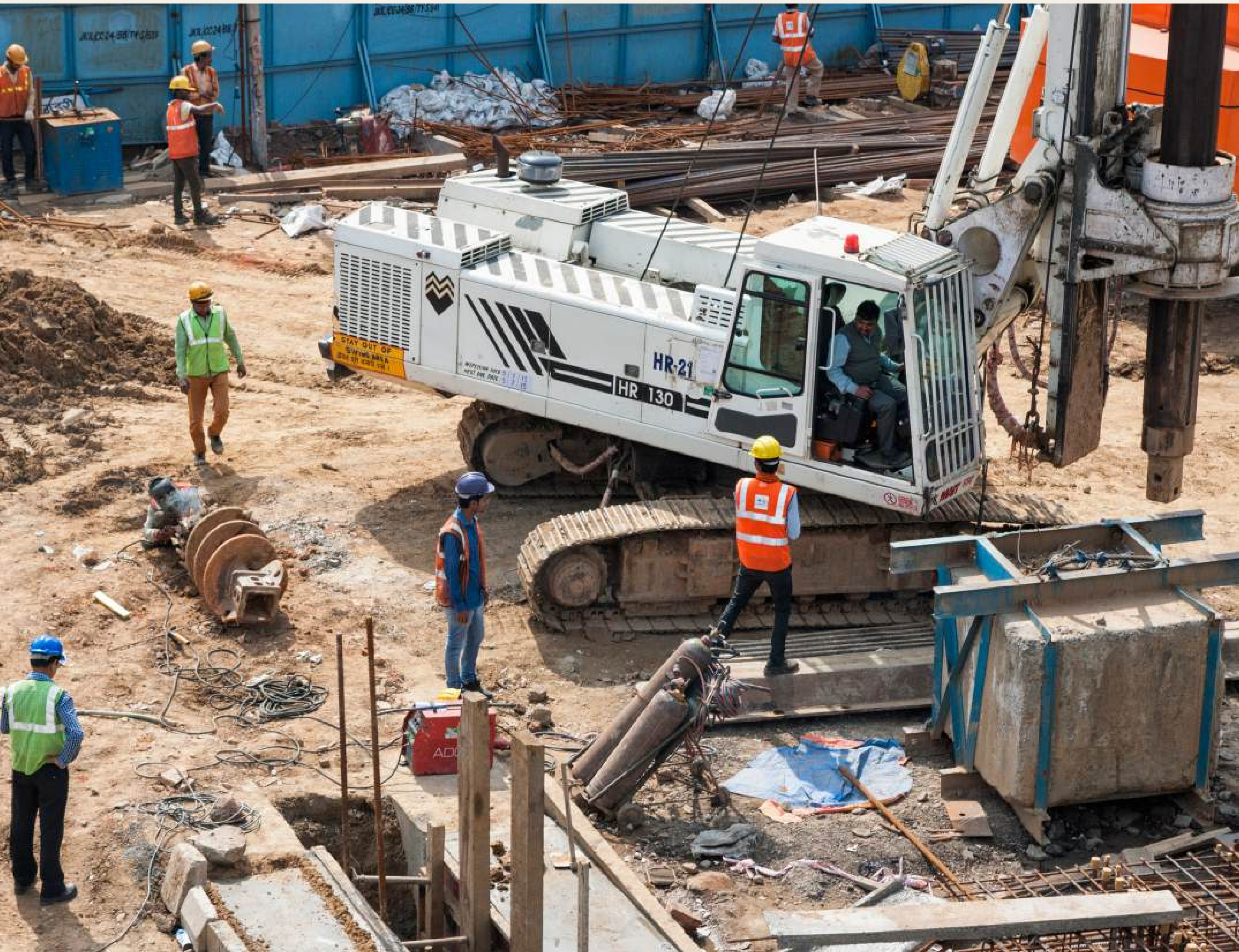

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2021 | Net Zero by 2070
2022 | Mission LiFE
2022 | National Bioenergy Programme
2022 | E-waste (Management) Rules
2023 | G20 Green Development Pact
2023 | National Green Hydrogen Mission
2024 | Green Steel Taxonomy
2024 | PM *Surya Ghar Yojana*
2025 | National Critical Mineral Mission
2025 | Rajya Sabha guidelines on crop residue burning
2025 | National Adaptation Plan

STATE

2022 | Rajasthan Organic Farming Mission
2022 | Jharkhand Solar Policy
2022 | Uttar Pradesh *Vidyut Sakhi* programme
2023 | Rajasthan Green Hydrogen Policy
2023 | Uttarakhand Solar Policy
2024 | Net-zero roadmaps for Bihar & Tamil Nadu
2025 | Green Odisha Initiative
2025 | Maharashtra Climate Action Plan 2.0
2025 | 50 Heat Action Plans (GJ, OD, MH, TN)
2025 | Delhi Clean Air Action Plan
2025 | Delhi EV Policy 2.0

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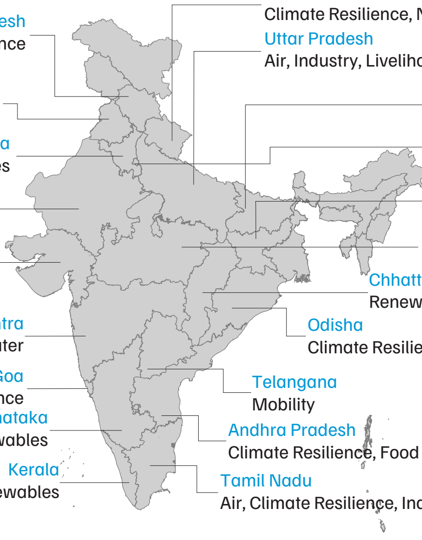

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Climate Resilience, Livelihoods, Net Zero

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Mobility

Andhra Pradesh
Climate Resilience, Food Systems

Tamil Nadu
Air, Climate Resilience, Industry, Net Zero, Water

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Contents

Executive summary

Construction activities contribute significantly to urban air pollution (Luo et al. 2021). According to the Delhi Pollution Control Committee, construction-related dust alone accounts for up to 30 per cent of the dust pollution in the city (DPCC 2023). With urban expansion, the number of construction and demolition sites in and around Delhi continues to grow (Realty Assistant 2025). Therefore, their impact on air quality is likely to rise sharply. What's urgently needed is a robust monitoring framework, stricter compliance protocols, and stronger actions for self-regulation at construction sites.

As things stand, cities have started restricting construction activities during high-pollution periods. Measures like blanket construction bans under the *Graded Response Action Plan* (GRAP) are meant to alleviate the air pollution situation in Delhi-NCR. However, these restrictions, often guided by a lack of on-site ground-level data, disproportionately affects daily-wage workers, contractors, and builders (Shukla 2024). Policymakers should instead consider identifying and assessing activities based on their actual pollution impact, and plan the mitigation measures accordingly. Such an approach will not only ease the economic burden but also allow project planners to devise air pollution-appropriate scheduling.

Recognising the need for evidence-based solutions, the Council on Energy, Environment and Water (CEEW), in partnership with the real estate company Signature Global (India) Limited, carried out a pilot at an active construction site. **CEEW deployed an air quality monitoring network in a concentric circle pattern with two key objectives: first, to assess the air quality impact of ongoing construction activities, and second, to measure the effectiveness of different dust mitigation strategies in real-time**. We use the findings to offer few recommendations on optimising pollution-control measures to balance environmental concerns with economic ones.

Image: Arvind Kumar/CEEW

Targeted regulations and smart scheduling can help reduce construction dust pollution without disrupting economic system and safeguarding livelihoods.

Approach and methodology

Nine air quality monitors and an automated weather station (AWS) were deployed at a large construction site (>20,000 square metres) in Gurugram, Haryana. Four of the air quality monitors were deployed in a shopping-cum-office (SCO) complex, and the other five in the residential (RES) area. These air quality monitors use low-cost air quality sensors (LCS), in line with the direction of the Commission on Air Quality Management (CAQM) in Delhi-NCR and adjoining areas. Over a period of 18 months starting July 2023, thirty-minute interval data of $PM_{2.5}$ concentration and met parameters (including relative humidity, temperature, wind speed, wind direction) were recorded.

Additionally, one air quality monitor of a similar grade was deployed at an ambient background site to record the simultaneous changes in the pollutant concentrations at the local level. The background location is at an aerial distance of ~1.5-2 km from the active construction site. The background site was situated far away from major roads or any other air pollution sources; therefore, the impact of other air pollution sources was minimised or eliminated.

To assess activity-specific levels of particulate matter (PM), simultaneous ongoing activity information was collected manually at the site. A trained technician was deployed at the site to record all the activities happening within a 50 m radius from each air quality monitor thrice a day. The start and end of dust mitigation measures, such as water sprinkling or anti-smog guns, were recorded as well to further assess the impacts of those measures on reducing air pollutants at the site.

Key findings

- Among the four phases of a typical construction project, **most of the air pollution happens during the first (product phase) and second (structural phase) phases of construction**. Typically, we observed during our pilot, these two phases lasted 18 months for residential towers and 15 months in the shopping/office buildings. The two phases primarily comprise activities such as **excavation, earthwork, roadwork, foundation and framework, brickwork, cement and concrete work**, and **vehicle movements**.
- Among all the construction activities carried out during these two phases, excavation, earthwork, roadwork, and vehicle movement are pollutant-intensive. **During these activities, $PM_{2.5}$ concentration increases by around ~1.8 times compared to the other activities**, like foundation and framework, brickwork, cement, and concrete work, which are non-pollutant-intensive or less polluting activities. Vehicular movement, which is independent of the construction phases, happens throughout the construction, and is most polluting activity (typically ~2.5 times higher than no-work levels) if the roads within the sites are not paved.
- Dust mitigation measures like water sprinkling can significantly reduce $PM_{2.5}$ levels at the construction site. **If the water sprinkler at the site is on for ~30–40 minutes, the PM levels can be reduced by ~45–70 per cent, with the impact of this intervention lasting ~3 hours**.

Key recommendations

- **Targeted regulation by activity type**: Regulations must differentiate construction activities based on their polluting intensity. Our data shows significant PM spikes during certain activities like excavation and earthwork, while some other activities create a lower impact. GRAP and similar policies should adopt an activity-specific framework, restricting pollution-intensive tasks while permitting less polluting ones with safeguards.
- **Smart scheduling by builders**: Builders must align construction timelines with pollution data. High-emission activities should be scheduled during months where the ambient PM levels are lower (outside the winter months) and paired with dust control measures (e.g., water sprinkling). The authorities can support this via forecast-based advisories. This approach ensures compliance, reduces pollution spikes, and protects worker productivity.

> Data-driven, activity-specific regulation can cut construction dust emissions while protecting workers, communities, and maintaining project timelines.

- **Protecting workers and neighbourhoods**: PM emissions from construction pose direct health risks. Real-time air quality monitoring at sites must be mandatory. Workers need protective gear, regular health check-ups, and exposure limits. For the public, buffer zones, green belts, dust barriers, and alert systems should be standardised for construction sites. Health safeguards must become core to construction approvals.

Delhi's development cannot come at the cost of clean air and public health. Our study shows that pollution from construction is not uniform, and varies widely across activities and phases. A data-driven, activity-specific regulatory approach can balance environmental goals with economic continuity. By empowering builders to schedule smartly and mandating real-time monitoring, the authorities can move beyond reactive bans to proactive management. The path forward lies in coupling science with policy by using granular evidence to shape regulations.

1. Introduction and context

1.1 Air pollution and construction activities: a growing concern

Construction activities significantly contribute to urban air pollution and impact public health (Wieser et al. 2021; Luo et al. 2021). Among major Indian cities, this sector accounts for approximately 8 per cent of annual $PM_{2.5}$ and 21 per cent of PM_{10} concentrations in Delhi (TERI 2018) and around 9 per cent of total PM emissions in Mumbai (MPCB 2023). With the accelerating pace of urbanisation, this contribution is projected to increase substantially.

For instance, Delhi-NCR is witnessing a boom in construction activities due to rapid infrastructural development and rising demand for residential and commercial spaces (Cushman and Wakefield 2025; Bhavishya Nirman Developers 2024). Key hotspots include Gurugram, Noida, Greater Noida, and Faridabad; particularly areas along the Dwarka Expressway, Noida Extension, and the Yamuna Expressway corridor.

Several large-scale infrastructure projects are being executed, including two major highway projects in Delhi-NCR, estimated to cost a combined USD 1.2 billion (InfraJunction 2025). While these projects are expected to transform the urban landscape, improve connectivity, and enhance economic growth, they pose a grave pollution risk for the region.

Although policies aimed at mitigating construction-related air pollution exist, such as the Construction and Demolition Waste Management Rules (2016) and episodic bans under the Graded Response Action Plan (GRAP), their effectiveness remains uncertain. Table 1 reviews all the efforts by different states and city-level policymakers to restrict the impacts of construction activities in the urban areas.

> Rapid urban expansion is driving construction-related pollution to intensifying levels, demanding stricter, more effective mitigation strategies.

Table 1. City-level actions and mandates on clean construction often lack self-compliance and self-regulation

Region	Details
Delhi's recent plans (Shakshi 2025; DoE 2025; PTI 2024; Ahmed et al. 2024)	• The 2025 mitigation plan & annual winter action plans expand routine dust suppression to a year-round exercise, relying on anti-smog guns, mandatory water sprinkling, & 14-point construction guidelines (including real-time online registration for all sites larger than 500 sq m). • Blanket bans on construction and demolition work during peak pollution episodes (under GRAP) have become common, suspended only for critical infrastructure or public health projects.
Gurugram and other NCR cities (UNDP 2024; CAQM 2025)	• Multi-sectoral action plans address construction dust as a major local contributor. • Increased site inspections and enforcement of NGT/CPCB directions, and digital monitoring portals have been rolled out since 2022.

State/Cities	Details
Maharashtra/ Mumbai (MMRDA 2025; MPCB 2023)	• The Mumbai Metropolitan Region Development Authority (MMRDA) has launched decisive campaigns to monitor construction dust sources and issue penalties, using a dedicated action plan for construction and demolition (C&D) dust as part of its broader Clean Air Action Plan. • Regular inspections and surprise audits target high-risk locations, with corrective actions such as site shutdowns and penalties.
Gujarat/ Ahmedabad, Surat, Vadodara, Rajkot (CAG 2022; Shakshi 2025)	• Gujarat's state pollution control board has developed source apportionment studies to guide interventions. • City action plans focus on enforcing dust controls, managing unscientific disposal of solid and demolition waste, and addressing fugitive emissions from construction and hot-mix plants.
Karnataka/ Bengaluru (Kulkarni 2025; NGT 2022; CPCB 2020)	• The *State Action Plan on Air Pollution for Karnataka* (2025) emphasises stricter enforcement of dust suppression measures at construction sites and roadside dust controls, in addition to industrial and vehicular interventions.
Howrah (WBPCB 2020)	• The *Clean Air Action Plan*, Howrah mandates rigorous implementation of dust control measures, including water sprinkling, barriers, windbreaks, and dust suppression equipment, with steep penalties for non-compliance. • Builders with projects measuring over 20,000 sq m are categorised as 'orange industry', needing special scrutiny and air pollution control, with all construction activities restricted during high pollution episodes (GRAP triggers).

State/Cities	Details
Pune (CPCB 2025)	• Strict dust suppression at all sites (mandatory water sprinkling, ready mix concrete), covered transport of building materials, and compliance checks by Pune Municipal Corporation (PMC). • Guidelines exist for 'green building', with a 10 per cent property tax rebate for sustainable practices; as of 2017, 57,000 properties had benefited
Other cities/ states (PIB 2025; Ganguly et al. 2020; Chowdhury and Kumari 2024)	• Several other cities across Rajasthan, Uttar Pradesh, and the Indo-Gangetic plain, identified as non-attainment cities for failing to meet the National Ambient Air Quality Standards (NAAQS), have adopted similar measures (C&D waste management, ban on dust-causing works during adverse weather, heavy penalties for violations), in line with National Clean Air Programme (NCAP) mandates.

Source: Authors' analysis

However, most of these action plans are reactive in nature, and the temporary bans imposed during high-pollution episodes are often insufficiently targeted and face implementation challenges due to economic disruptions. The current mandate to suspend all construction activities during such periods, therefore, requires a more nuanced and evidence-based approach.

1.2 Necessity of activity-specific information for dust mitigation planning

As a measure under GRAP in Delhi-NCR, the Commission for Air Quality Management (CAQM) mandates banning all construction activities to reduce air pollution(Khan et al. 2022). These interventions primarily aim to reduce particulate matter. However, such measures are typically enforced without sufficient ground-level data to identify which specific construction activities are the most polluting. As a result, blanket bans are often imposed across the sector, regardless of the emission intensity of different activities, or the phase a construction project is in (Sharma 2024).

For example, in 2023 and 2024 alone, construction activities in Delhi-NCR were halted for a cumulative total of **78 days** under GRAP (CAQM 2025), causing significant economic repercussions in terms of delaying project timelines, increasing project costs, disrupting infrastructure development, and causing reputational and financial damage to project proponents (REIAS 2024). Daily-wage construction workers are particularly vulnerable to the impact of such bans, as sudden work stoppages result in loss of income, food insecurity, and forced migration due to financial distress (Shukla 2024).

This gap necessitates generating evidence to categorise the different activities within construction as more and less polluting (Patra and Ahmed 2025). In the absence of such a differentiation, policymakers and project proponents are unable to implement targeted dust mitigation strategies. This lack of nuance results in overly broad restrictions may inadvertently stall non-critical, low-impact activities, potentially leading to unintended economic and social consequences.

1.3 Research gap and objectives of the study

In this study, we have tried to address the following research questions

- How do emissions vary across different types of construction activities? Which specific activities generate the highest levels of dust?
- To what extent are dust control measures effective in reducing air pollutant concentrations? Over what duration do these measures remain impactful?

In response to these gaps, the study is guided by two core objectives:

1. To distinguish between more- and less-polluting construction activities, thereby enabling better targeted and proportionate regulatory interventions.
2. To evaluate the actual impact of commonly adopted mitigation practices on reducing pollutant levels at construction sites.

2. Approach and methodology

2.1 Study design

To generate data on activity-specific dust emissions, and evaluate the effectiveness of mitigation measures, an air quality monitoring network was deployed at a large construction site (> 20,000 sq m) in Gurugram, India. The network comprised nine low-cost air quality sensors installed across the site along with an automated weather station (AWS) to capture relevant meteorological parameters. This enabled high-resolution, real-time monitoring of $PM_{2.5}$ and PM_{10}.

Pollutant concentration data were continuously recorded for a duration of approximately 18 months. Each monitored activity was documented and temporally aligned with corresponding pollutant readings to facilitate activity-wise profiling. To assess the effectiveness of dust mitigation strategies, pollutant levels were measured across three distinct timeframes: before, during, and after the intervention.

2.2 Site description

The pilot was undertaken at an active construction site at Gurugram (28°25′ N and 76°57′ E, Figure 1). The city is located in the south-eastern part of Haryana and forms part of the National Capital Region (NCR) of India. Its climate is tropical and semi-arid. The annual temperature ranges from 5°C to 40°C with mostly westerly winds.

Figure 1. Map of study area

Source: Authors' analysis and Google maps

The pilot study was conducted by the Council on Energy, Environment and Water (CEEW). The pilot is part of an MoU between real estate company Signature Global Limited and CEEW to collaborate on finding solutions to reduce air pollution from construction activities. Signature Global (India) Ltd. is one of India's leading real estate companies, and provided one of their ongoing construction sites (Signature Global Imperial) to carry out the study. The construction plot covers an area of ~35,000 sq m, and is organised into two sections: (a) residential area (RES), where eight residential building towers are being constructed, and (b) shopping-cum-office area (SCO), where commercial complexes are being developed.

2.3 Monitoring approach

To deploy the air quality monitoring network at the pilot site, a series of preliminary assessments were carried out. These include a detailed review of the site layout, review of the scheduling of construction activities, and the surrounding land use and land cover. Subsequently, the monitors were deployed based on the concentric-circle approach to estimate the potential air quality impacts of different construction activities. Based on these insights, we developed and deployed a first-of-its-kind monitoring network comprising nine low-cost air quality monitors strategically placed across the pilot site in Gurugram (Patra et al. 2025). The monitor placement was done according to the project plan, prevailing wind directions, and to ensure representative data collection. The configuration of the monitoring network is illustrated in Figure 2.

2.4 Data collection and analysis

The pilot study's sampling involved cumulating continuous real-time pollutant and meteorological data, and manual monitoring of activities at the construction site. Of the data collected, we focused our analysis on a period of one year, from July 2023 to June 2024, covering all seasons. The details of data collection and analysis are discussed further in the following sections. For statistical analysis, Microsoft Excel and R statistical computing and graphical software were used. The data visualisation was carried out using Flourish Studio.

Figure 2. A representative visual of the monitoring network showing the placement of the nine low-cost sensors and the automated weather station arranged in a concentric circle pattern

Source: Authors' analysis

Pollutant data

Particulate matter ($PM_{2.5}$ and PM_{10}) concentrations were measured using low-cost air quality sensors (LCS). The specifications of the sensors are provided in Annexure I. The sensors were installed at an average height of ~2.5-3.5 metres above surface level. Nine LCSs were installed at the study site: five in the RES area, and four in the SCO area. Concurrent PM measurements were also recorded at another location, which is around ~4 km away from the construction site and is primarily a green surrounding devoid of any severe pollution-causing activities. This location was considered a background site to obtain baseline PM data for comparison. Continuous real-time $PM_{2.5}$ and PM_{10} concentration data were collected at 30-minute time intervals, and processed. The PM data was analysed primarily for the working hours of the construction site, i.e., from 7 a.m. to 7 p.m. The $PM_{2.5}$ data was taken into consideration for evaluation due to its higher reliability compared to PM_{10} measured by the sensors. Additionally, prescribed quality control and quality assurance steps were followed for PM measurements before deploying the sensors at the site.

Meteorological data

When monitoring air quality levels at a construction site, meteorological (Yan et al. 2019) parameters play a significant role in determining the concentration of particulate matter. Accurately assessing these factors is crucial for evaluating how they affect the distribution of construction dust. To map the meteorological conditions during the study, several parameters—namely temperature, relative humidity, wind direction, and wind speed—were measured by the automatic weather station (AWS) deployed at the site. Annexure II shows the monthly wind roses of the prevailing wind speeds and directions at the study site.

> A first-of-its-kind sensor network enabled real-time, activity-specific tracking of dust emissions at an active construction site in India.

Data on ongoing activity

Any type of construction activity occurring within a ~50 m radius of each sensor was documented manually. Activity-wise information was recorded thrice a day for all nine sensors deployed at the site. Mostly, a single activity (e.g., excavation) was found to occur throughout the day, and the daily average pollutant concentration during working hours was attributed to that activity. However, on a few occasions, multiple activities were observed to be taking place in the vicinity of a sensor during the day where two visits observed a same activity (e.g., excavation), while the third showed a different activity (e.g., foundation). In such cases, we recorded the common activity observed during the two visits and attributed that to the daily average pollutant concentration. Similarly, the mitigation measures within the site, such as water sprinkling and the use of anti-smog guns, were also recorded with proper start and end timings.

2.5 Quality assurance and quality control

PM data, meteorological parameters, and activity updates were carried out with utmost precaution, and by maintaining standard operating protocols like installation, maintenance schedules, data collection intervals, power supply, and backup. The LCS was selected by carrying out a series of performance tests to evaluate six different models. The LCSs were explored and compared in terms of the technology, performance, data quality, data accuracy, uptime, usability, and maintenance costs. The selected LCS was further collocated and calibrated with a reference grade monitor for data reliability (Annexure III). To assess the representability of the data, the LCS data were also compared with four of the nearest Continuous Ambient Air Quality Monitoring (CAAQM) stations. The comparisons are shown in Annexure IV; it was found that $PM_{2.5}$ concentrations followed a similar diurnal trend; however, the concentration levels varied depending on the land use and land cover of the CAAQMS. Each of the deployed LCSs was supported by routine checks, cleaning, calibration, and periodic servicing once/twice a week based on the dust load. Data screening was regularly carried out through a backend dashboard to identify sensor malfunctions, data spikes, or extreme values.

3. Key findings

A typical construction project involves multiple phases that are strategically scheduled with different construction activities (Luo et al. 2021). Different activities are carried out at different phases of construction, like excavation, road clearing, framework, and material transportation, to finishing-stage activities like plumbing or painting. Each type of activity is responsible for generating different levels of dust emissions into the surroundings with varying intensity (Wieser et al., 2021). Air pollution characteristics of the construction sector can vary based on several factors, including the type of construction activity, the project's scale, the schedules and duration of the activities, and the prevailing environmental conditions (Owolabi et al. 2024). A work breakdown structure (WBS) is generally used by most construction companies to develop a working schedule and estimate the costs and duration of each related activity (Cerezo-Narváez et al. 2020). A basic breakdown of the different phases involved in a construction schedule is discussed below-

- The first or initial phase of a construction project is the **product phase**, where site clearing, and raw materials processing, transport, or manufacturing are carried out, and which can significantly contribute to air pollution. Emissions from vehicles used to transport raw materials from mining to production sites play a crucial role in this regard (Kumar et al. 2025). Additionally, the methods used to extract raw materials and the types of transport vehicles can further impact the level of air pollution (Wieser et al. 2021).

- The next phase is the **structural or construction process phase**. The major construction activities, such as excavation, earth filling and levelling, foundation laying and building of infrastructure, and finishing works are carried out during this phase. This stage also involves vehicular transportation and traffic on the site. This is one of the most crucial phases in any construction project, and its activities contribute significantly to the air pollution levels. During this phase, both construction workers and individuals living in the vicinity are continuously exposed to the emissions, leading to severe health impacts (Araújo et al. 2014).

- The third phase is the **use phase**, during which pollutant emissions are generally generated by energy consumption from the constructed structures and users' activities. Emissions from cooling and heating appliances, along with ventilation, play a crucial role in this phase, significantly impacting indoor air pollution. In this phase, factors such as indoor airflows, outdoor pollution levels, and indoor emission sources also contribute to overall air quality.

- The last phase of any construction project is the **end-of-life phase**, where building materials are demolished, recycled, and reused for a second life cycle once the building structures have completed their use phase. During the demolition or deconstruction of buildings and infrastructure, significant amounts of dust and pollutant particles are released into the atmosphere, degrading the local air quality. Furthermore, the transportation of materials, machinery, and equipment used for demolition can also contribute to the overall pollution inputs.

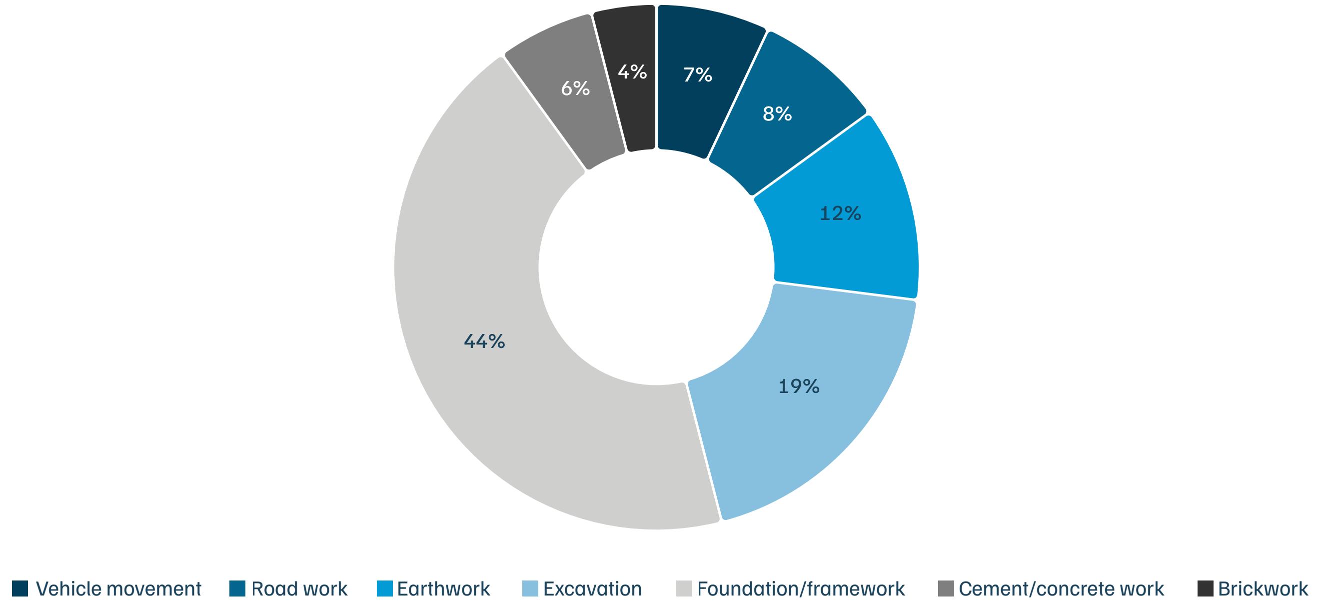
> Real-time monitoring shows only a few construction activities cause major dust emissions, enabling targeted and effective regulation.

Figure 3. Photos of some on-ground activities taking place at the construction site during the monitoring period

Source: Authors' analysis

Our pilot study was mainly carried out during the 1st and 2nd phases of the project, which were operative during the one-year time period. The activities noted to be occurring were excavation, earthwork (land filling, land levelling, relocation of loose soil), roadwork (construction of onsite roads, walkways, driveways, parking areas, garden areas by clearing, levelling, filling, and paving of unpaved surfaces), foundation/framework (shuttering, column, beam, slab construction, iron and aluminium framing, binding of tower structures, construction of gates, staircases, elevator shafts), brickwork (construction of internal and boundary walls, block pavements), cement/concrete work (masonry work, pouring of concrete, plastering, flooring), and vehicle movements (transport of construction materials through trucks and light motor vehicles, movement of water tankers, tractors, and heavy-duty vehicles (HDV) such as earthmovers, ready-mix cement trucks). A few on-ground photos of the mentioned activities are shown in Figure 3. These activities were carried out throughout the study duration at different paces and at different locations with respect to the deployed LCS. The Figure 4 presents the percentage distribution of data corresponding to different construction activities recorded throughout the entire study period. It shows that nearly half of the total observations correspond to foundation and framework work (44 per cent), followed by excavation (19 per cent) and earthwork (12 per cent).

Figure 4. Foundation/framework activities accounted for the highest share of observed work during the study period



Source: Authors' analysis

3.1 Identifying pollutant-intensive and non-pollutant-intensive activities

During periods of severe air pollution, restrictions are put in place limiting or halting construction activities due to their dust emission impacts (Gerrard 2024). These restrictions apply to all activities regardless of their contribution to pollution. As part of the pilot study, we monitored the real-time PM levels during each of the construction activities through the AQ monitoring network deployed at the site. We evaluated the $PM_{2.5}$ concentration levels associated with a defined set of activities for one year, and found that excavation, road work, earthwork, and vehicle movement generate a higher amount of dust emissions in their vicinity in comparison to foundation/framework, cement/concrete work, and brickwork. Further, during the monitoring period, we observed holidays, Sundays (week off), or days when there were statutory restrictions on carrying out construction activities. We also found days when there was no ongoing activity near some or all of the deployed LCSs. Such occasions, where no activity was observed to occur for any particular LCS, were considered as no-work days for the study. The average concentrations on no- work days during the monitoring period were considered as the site's background levels, as they reflect conditions within the site without the occurrence of any on-site activity inputs. Also, the sensor placed at a distance from the site did not capture site-specific conditions. Therefore, using the no-work day data as the background was considered more appropriate for comparison.

Table 2. Different types of construction activities generate varying levels of $PM_{2.5}$ concentration

Activity	Total number of recorded activities	$PM_{2.5}$ concentration range ($\mu g/m^3$)	Average±SE	Median	25th percentile	75th percentile
No-work	609	10-362	63±2	40	25	97
Brickwork	66	16-264	46±6	31	23	49
Cement/concrete work	113	16-246	63±6	39	25	78
Foundation/framework	754	9-492	71±3	38	26	97
Excavation	338	25-474	85±4	50	35	106
Earthwork	209	25-357	91±6	47	43	125
Road work	136	13-454	112±8	72	42	182
Vehicle movement	125	61-395	140±8	98	79	179

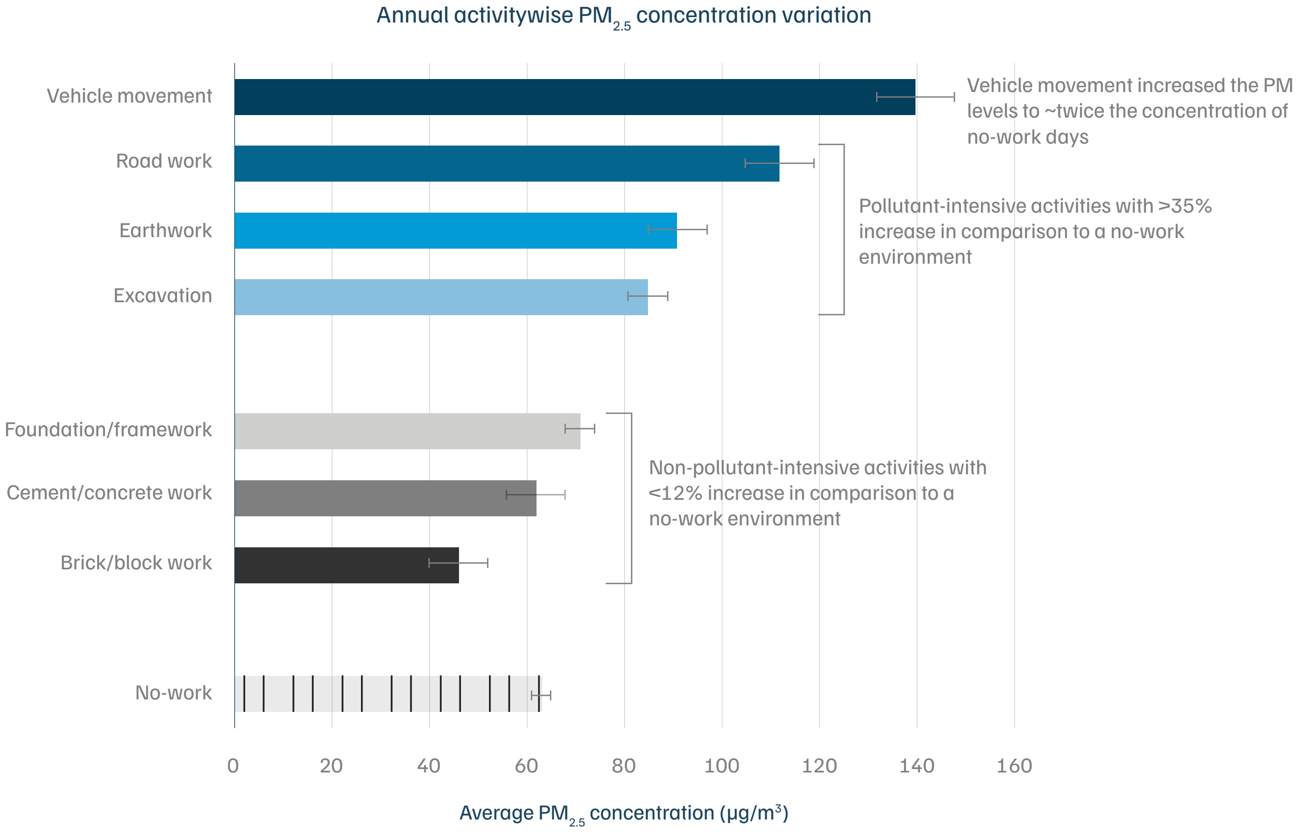
Source: Authors' analysis

Note: SE - standard error

Table 2 shows the average $PM_{2.5}$ concentration levels associated with each activity, along with their median, ranges, quartiles, and the diurnal counts of recorded activities as per each sensor. Considering the median $PM_{2.5}$ concentration of each activity, we found that activities like brickwork, cement/concrete work, and foundation/framework generated less than ~40 $\mu g/m^3$ each, similar to the no-work median concentration. However, activities such as earthwork, excavation, and road work were found to have higher median concentrations of 47 $\mu g/m^3$, 50 $\mu g/m^3$, and 72 $\mu g/m^3$, respectively. Additionally, the median for $PM_{2.5}$ concentration during vehicle movements was 98 $\mu g/m^3$, which is around 2.5 times higher than no-work-day levels. Thus, it is observed that each type of activity generates different levels of dust pollution in its vicinity, and can be categorised into pollutant-intensive and non-pollutant-intensive activities. It was also observed that ~600 instances of 'no work' were captured during the whole study duration. Depending on the variable meteorological conditions and seasonal variability, the overall $PM_{2.5}$ concentration during no work ranged from 10-362 $\mu g/m^3$ with an average of 63.4±2.12 $\mu g/m^3$.

We conducted non-parametric tests, like the Wilcoxon signed-rank and the Sign test, to statistically assess the variations in $PM_{2.5}$ concentration levels recorded during various construction activities in comparison to no-work conditions. The test statistics are provided in Annexure V. It was observed that activities such as vehicle movement, road work, earthwork, and excavation showed statistically significant differences ($p < 0.05$) under both tests, indicating higher PM levels compared to no-work conditions. In contrast, foundation/framework and cement/concrete work showed no significant differences ($p > 0.05$), suggesting relatively lower incremental dust generation. Interestingly, for brickwork, both tests indicated a significant difference ($p < 0.05$); however, in this case, the dust levels were lower than those during the no-work condition.

Figure 5. Why vehicle movement is more pollutant-intensive than brickwork



Source: Authors' analysis

Note: The slightly lower $PM_{2.5}$ levels observed during brickwork is due to fewer data points and the inherently less dust-intensive nature of the activity

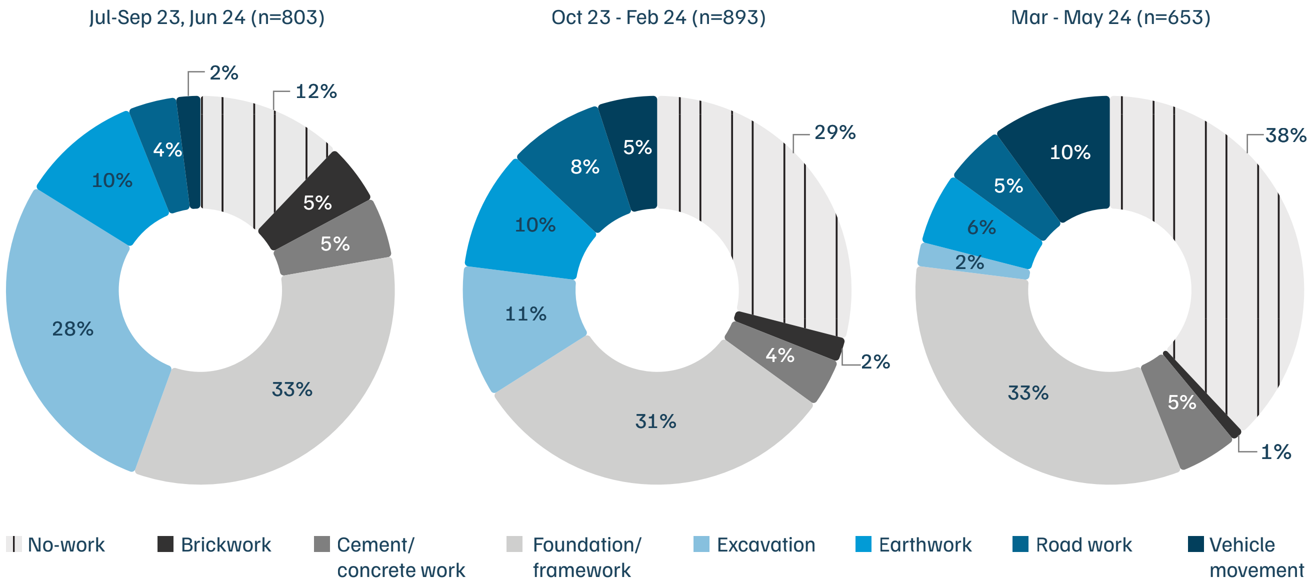
Subsequently, we compared the average $PM_{2.5}$ concentration levels of the defined construction activities to those observed during no-work conditions. Figure 5 shows that the pollutant-intensive activities exhibit a significant increase in $PM_{2.5}$ concentration levels, with excavation causing a ~35 per cent spurt, earthwork ~44 per cent, roadwork ~78 per cent, and vehicular movement a significant increase of ~122 per cent. The non-pollutant-intensive activities, meanwhile, showed low intensity in terms of $PM_{2.5}$ concentration, exhibiting less than ~12 per cent increase from no-work concentrations. Moreover, the $PM_{2.5}$ concentrations of the pollutant-intensive activities (excavation, earthwork, and road work) were found to be ~60 per cent higher than those of the non-pollutant-intensive activities. Further, the resuspension of dust by vehicular movements increased the concentration levels by ~135 per cent in comparison to the combined average concentration of the non-pollutant-intensive activities (i.e., 60 μg/m^3). The $PM_{2.5}$ levels recorded during brickwork activities were found to be slightly lower than those observed during the no-work period. This variation is likely due to the smaller number of data points available for brickwork compared to no-work conditions, which may have affected the overall average. Moreover, brickwork generally involves limited dust-generating activity and usually takes place after the more pollutant-intensive phases, such as excavation or earthwork. As a result, the surrounding dust levels during brickwork tend to remain relatively low.

3.2 Seasonal variations among the $PM_{2.5}$ contribution of different activities

The NCR experiences vast variations in weather conditions, from extreme winter between December and February, to extreme summer from May–August. The meteorological conditions prevailing in these seasons also vary drastically, with differences in not just temperature, but also humidity, wind speed, and wind direction. The monsoon, from late June to September, brings heavy rains that help settle dust particles and wash away pollutants, often resulting in temporarily improved air quality during this period. Occasional dust storms are also a common phenomenon during the pre-monsoon season, spanning from April to June, in the NCR. These dust storms are marked by strong, dusty winds, which significantly reduce air quality and visibility (Gandhiok 2025). Also, several other factors escalate during this period, including transboundary dispersion of air pollutants from crop residue burning, bursting of crackers during festivities, smog formation, and temperature inversions. Thus, a combined effect of these factors produces severe air pollution episodes in the region during the post-monsoon and winter months, extending from October to February.

Due to these factors, the construction activities also vary seasonally and are scheduled accordingly, aligned with the phases of construction. The seasonal variation in the total count of occurrences per activity is shown in Figure 6. It is evident from the figure that not all the activities have the same span of occurrences during all the seasons; we found that 803 instances of activities were recorded during the monsoon (June to September), 897 during the post-monsoon and winter season (October to February), and 653 during the pre-monsoon period (March to May). The foundation or framing work was found to be happening at the same rate throughout all the seasons, accounting for 31 to 33 per cent of the total occurrences. However, during the monsoon season, excavation activities accounted for 28 per cent of all activity occurrences; this percentage eventually decreased to 11 per cent during the post-monsoon and winter seasons, and just 2 per cent during the pre-monsoon season. Instances of no work also varied between the seasons, with 12 per cent during the monsoon season and 38 per cent during the pre-monsoon season.

Figure 6. From low of 2% during pre-monsoon, excavation activities rise to 11% during post-monsoon & winter seasons



Source: Authors' analysis

We observed that during the pre-monsoon season, pollutant-intensive activities have a lower occurrence in comparison to the other seasons; rather, the opposite case should have been more appropriate. The pre-monsoon period witnesses more favourable meteorological conditions, and thus scheduling pollutant-intensive activities during this season is more logical. Restrictions on construction activities or complete bans are often witnessed during the winter months due to severe pollution episodes. Scheduling pollutant-intensive activities during those months may lead to more dust emissions and, consequently, delays when the higher pollution levels trigger blanket bans. That's why the planning and execution of construction activities need to be well-designed and scheduled in such a way that the pollutant-intensive activities are carried out in periods with favourable conditions, accompanied by proper dust mitigation measures.

An earlier CEEW study suggested that better all-year planning can prove a proactive approach to minimise losses from regulatory bans (Ahmed et al. 2024). The study recommended incorporating dust mitigation plans into the construction schedules as sub-tasks from the get-go, and regulating them throughout the year. Dust mitigation plans include various measures like using anti-smog guns, green covering, high barriers surrounding the work site, and sprinkling water on a regular basis (Omega Environmental 2023).

We further evaluated the changes in $PM_{2.5}$ concentration levels of the defined activities during different seasons. Figures 7a and 7b illustrate the variations in the PM contribution of each activity during different seasons, and also compare those to the no-work concentration levels. Annexure VI presents the total count of days for each type of activity recorded during different months, along with the corresponding meteorological parameters prevailing during those periods. It also shows the monthly average temperature and relative humidity, providing insight into the influence of meteorological conditions on $PM_{2.5}$ concentrations across various construction activities during different months.

Figure 7A. PM contribution of pollutant-intensive activities surged 84% over no-work levels in post-monsoon & winter months

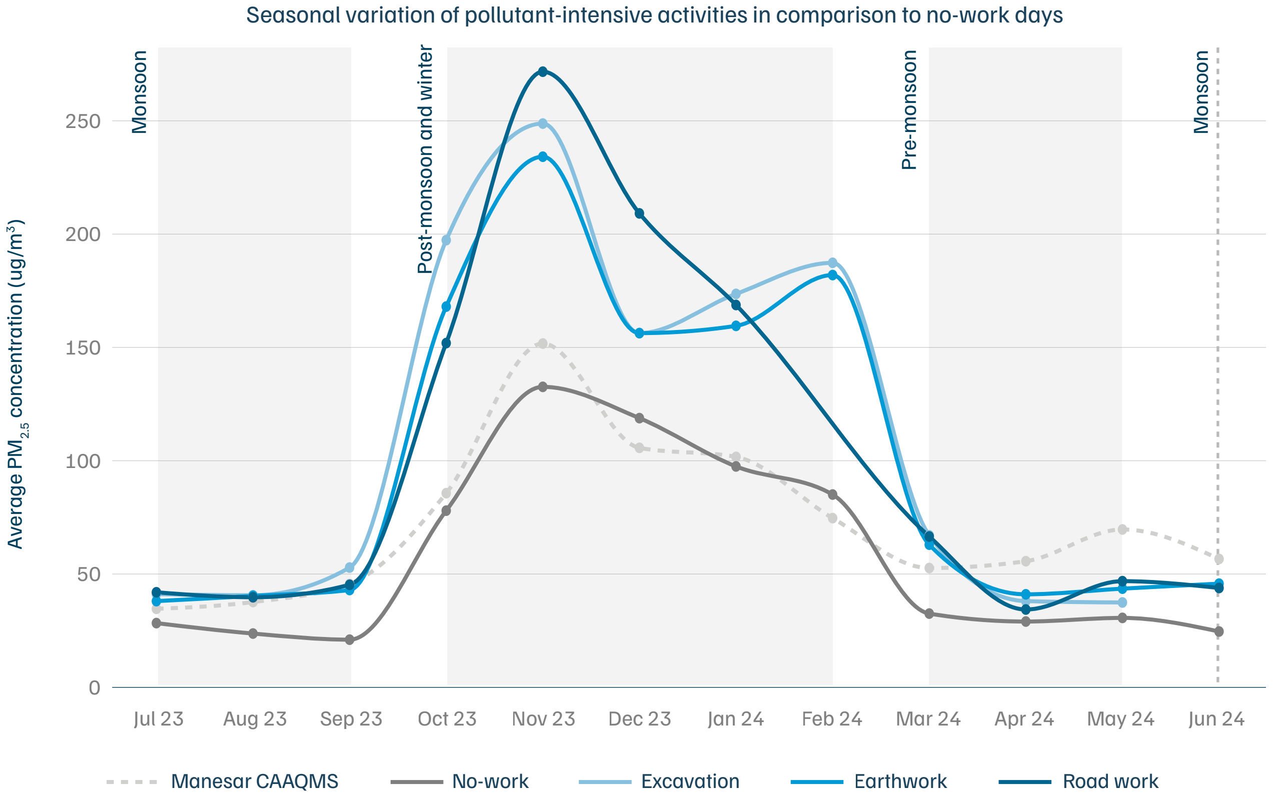
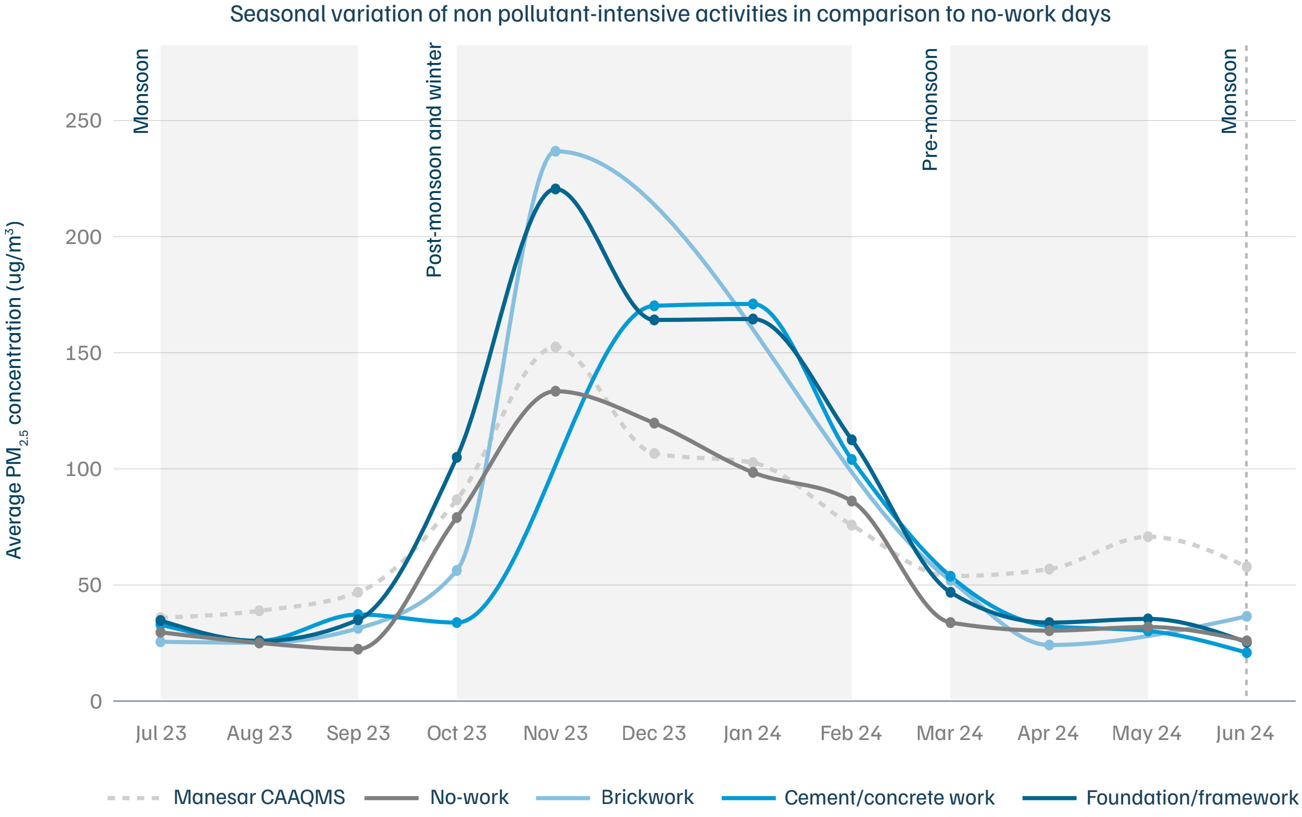


Figure 7B. For non-pollutant-intensive activities, average $PM_{2.5}$ concentrations rose by up to 72% in winter



Source: Authors' analysis

The figures above show that the $PM_{2.5}$ concentrations were significantly higher during the post-monsoon and winter seasons than the pre-monsoon and monsoon seasons. The PM concentration levels of pollutant-intensive activities registered a nearly fourfold increase during the post-monsoon and winter seasons in comparison to the monsoon season. Additionally, when the concentration levels of pollutant-intensive activities were compared to the no-work concentration levels, a ~65 per cent increase was registered during the pre-monsoon and monsoon seasons, and ~84 per cent during the post-monsoon and winter seasons.

In case of the non-pollutant-intensive activities, no increase in pollutant levels was observed during the monsoon and pre-monsoon seasons. However, during the post-monsoon and winter seasons, mainly during the months of November, December, and January, the average $PM_{2.5}$ concentrations were found to increase by ~72 per cent, ~42 per cent, and ~71 per cent, respectively, in comparison to no work.

Between November and January, air pollution levels remain consistently high, with most days falling into the “poor” to “severe” air quality categories. During this period, the ambient levels of PM are already elevated to such an extent that it becomes challenging to differentiate and assess the additional contribution of outdoor construction activities. The background pollution essentially interferes with the PM emissions generated by these activities, making it difficult to draw clear distinctions. Despite these limitations, we made an effort to differentiate between pollutant-intensive and non-pollutant-intensive construction activities. Even in the midst of high ambient pollution, the data showed that pollutant-intensive activities still tended to contribute higher PM concentrations compared to non-pollutant-intensive activities or no work. Annexure VII represents box plots comparing $PM_{2.5}$ levels across different activity types and the no-work baseline. However, due to the already elevated ambient pollution levels during the winter season, the variation in PM concentrations across activity types is less comparable, making it difficult to observe a significant difference visually in the plots.

Box 1. *Graded Response Action Plan* (GRAP) mandates

Interestingly, during the post-monsoon and winter periods, the average monthly $PM_{2.5}$ concentrations were significantly higher for all activities. However, during this period, the GRAP restrictions were also implemented from 6 October 2023 to 27 February 2024.

So, were construction activities still being carried out during the officially mandated restriction periods?

The answer is NO.

The mandates under GRAP are generally implemented in four stages in response to the prevailing category (poor, very poor, severe, severe plus) of the Air Quality Index (AQI). The government may implement or withdraw the guidelines on any day and for any period, depending on the AQI levels. However, construction activities are restricted mainly during the III and IV stages of GRAP. At the time of our study period, the dates of implementation and the revocation of the actions under GRAP stage III and IV are mentioned in the table below -

GRAP stage	Implementation date	Revocation date	Total number of days
GRAP III	2 November 2023	28 November 2023	26
GRAP IV	5 November 2023	18 November 2023	13
GRAP III	22 December 2023	01 January 2024	10
GRAP III	14 January 2024	18 January 2024	04

Between October 2023 and February 2024, there were 152 days in total, out of which 40 days were under restrictions or a complete ban on construction activities in line with GRAP guidelines. Our analysis shows that construction activities were only carried out on non-GRAP days, i.e., days when restrictions were not implemented. However, even on these non-restricted days, the daily average ambient $PM_{2.5}$ levels ranged between 28 and 166 $\mu g/m^3$ (according to Manesar CAAQMS, nearest to the site), suggesting that while construction was compliant with the GRAP mandates, operating activities on the non-GRAP days also contributed to the overall deterioration of air quality, further elevating $PM_{2.5}$ concentrations during an already polluted period.

Source: Authors' analysis

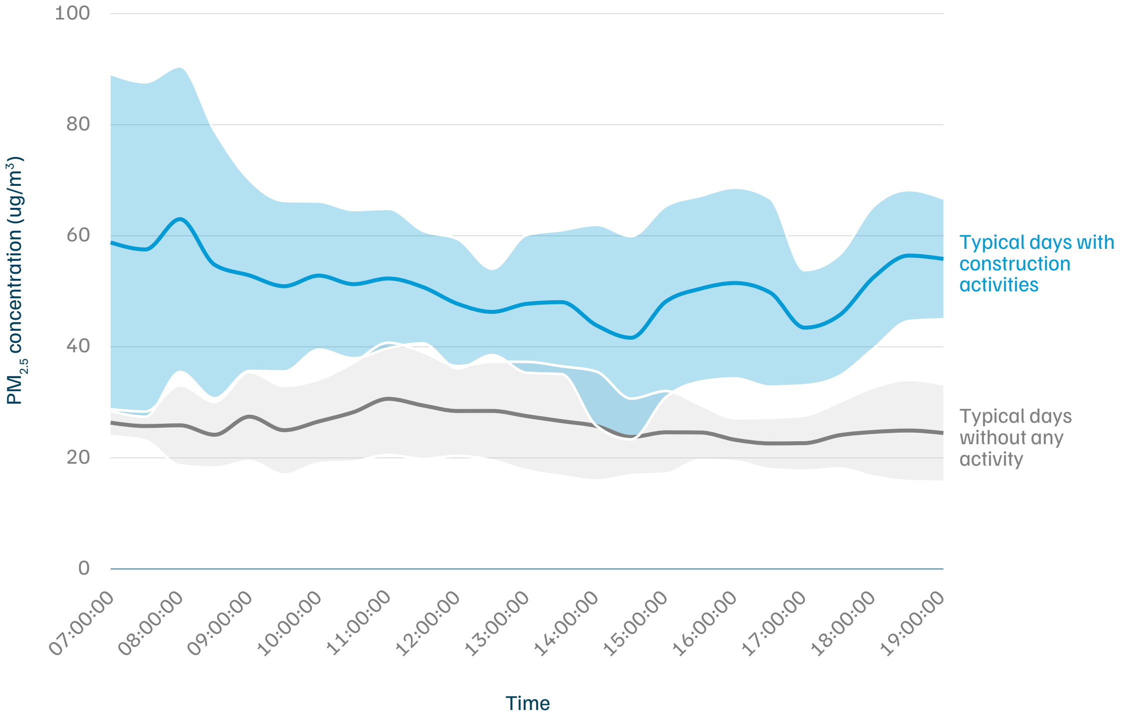
3.3 Assessing the effectiveness of dust mitigation strategies

Several mitigation measures are mandated by the regulatory authorities (CAQM 2021) to be carried out at construction sites within Delhi and the NCR, in order to reduce the on-site PM levels raised by different construction activities. Water sprinkling, use of anti-smog guns, dust suppressants, wind barriers, etc., are some of the recommended dust mitigating measures that need to be deployed at construction sites for proper dust compliance. However, these measures are mostly deployed at construction sites by their proponents, mainly during the GRAP period or when any restrictive guidelines are in force during severe pollution episodes. These mitigation measures are mandated by law for dust compliance. When implemented, they essentially reduce the dust pollution levels in the vicinity to an extent (GORD 2023), although their overall effectiveness is still not well evaluated.

We were well aware that sprinkling water can effectively reduce dust levels in a dry dust-dominant area and its surroundings, *but how long is it effective? What is the per cent reduction in terms of PM levels*? Through our pilot study, we tried to find out the answers to these questions and assess the effectiveness of a mitigation measure, i.e., water sprinkling, in reducing dust pollution levels within the construction site. Figures 8 and 9 show the difference made by deploying water sprinklers within the construction site during ongoing activities. This is again based on a comparison between $PM_{2.5}$ concentration levels during typical no-work days and those recorded while excavation was being carried out. (Figure 8).

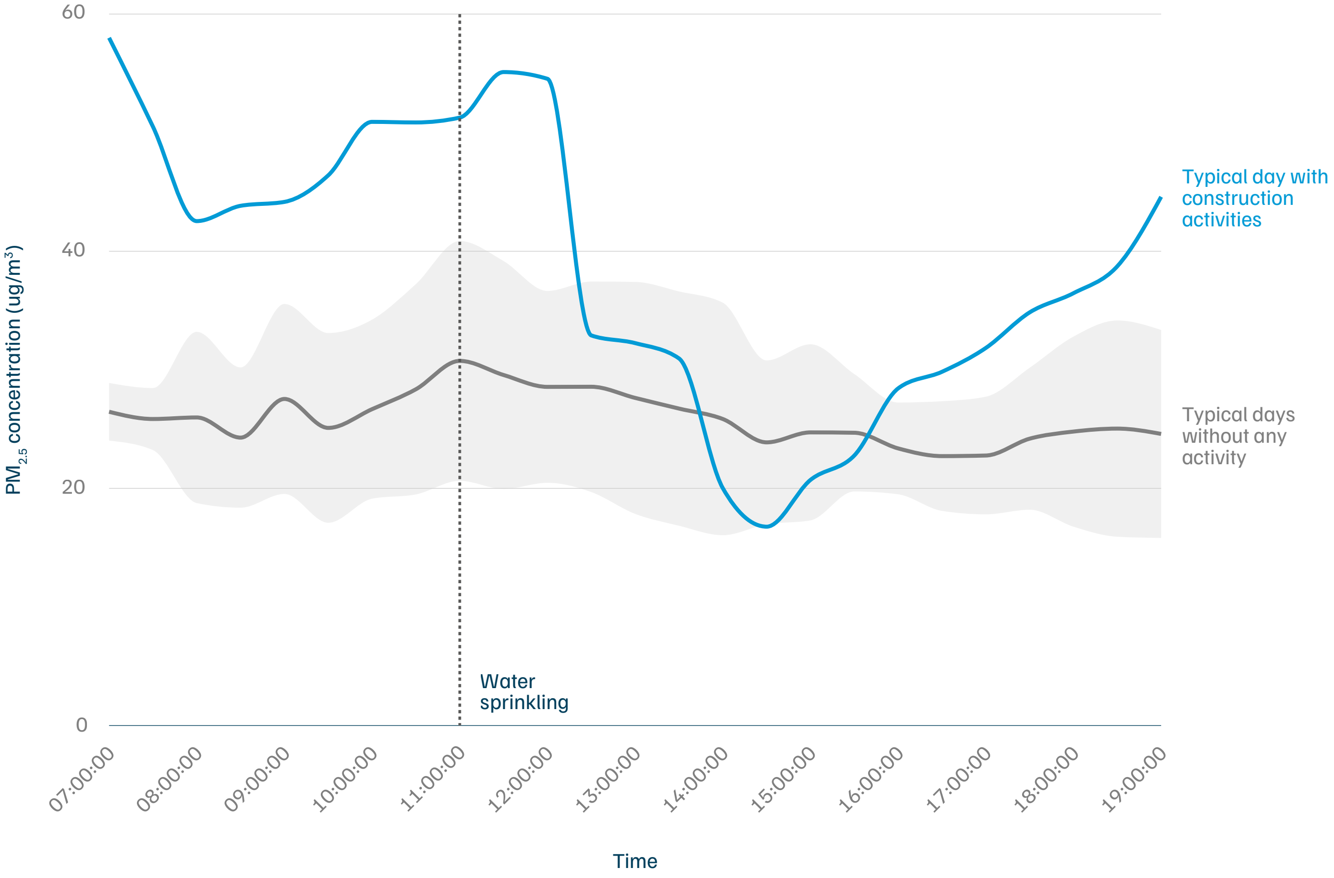
It was observed that $PM_{2.5}$ concentration levels increased by ~3 times the no-work levels during the pollutant-intensive activity in the absence of water sprinkling or any other dust mitigation measures. When water sprinkling (Figure 9) was deployed, we found that while $PM_{2.5}$ concentration levels were initially high during the pollutant-intensive activity, they gradually started decreasing. When water sprinkling was carried out near the activity area for ~30-40 minutes, the $PM_{2.5}$ levels came down by ~45-70 per cent, and the measure remained effective for nearly 3-4 hours. After 3 hours, the $PM_{2.5}$ levels again started to increase gradually as the activity continued.

Figure 8. $PM_{2.5}$ concentration during excavation increased ~3 times the no-work levels in the absence of water sprinkling



Source: Authors' analysis

Figure 9. Water sprinkling cut excavation emissions by ~45-70% for 3-4 hours

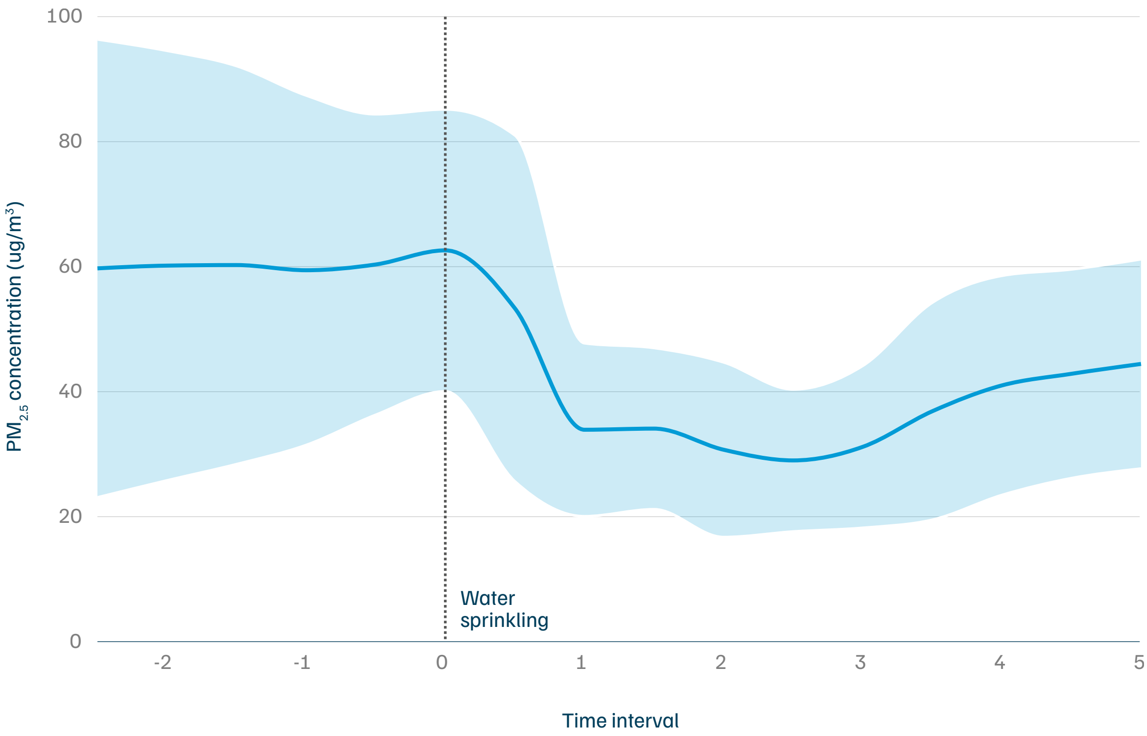


Source: Authors' analysis

Figure 10 shows the trend of $PM_{2.5}$ concentrations when water sprinkling was carried out at the construction site. Data from selected days between July and October 2023—when water sprinkling was implemented to control high dust levels—were analysed. Sprinkling was carried out at different times on different days: for analytical consistency, the start time of each event was aligned to zero on the `x-axis. It was observed during the study that $PM_{2.5}$ concentrations dropped noticeably following the initiation of sprinkling, with the reduction effect lasting for nearly 3 to 4 hours regardless of when the sprinkling was carried out. Detailed information on the specific dates of observation and corresponding meteorological conditions is provided in Annexure VIII. This consistent trend signifies the reliability and temporal effectiveness of water sprinkling as a short-term dust mitigation measure at construction sites.

Our analysis proves that dust mitigation measures like water sprinkling can significantly reduce the pollutant levels at construction sites. Therefore, integrating a well-structured dust mitigation plan into overall project schedules should be mandated at construction sites, particularly during pollutant-intensive activities like excavation. As highlighted in the previous section, implementing water sprinkling at regular intervals of 3 to 4 hours, i.e., approximately three times a day, can effectively reduce the PM levels and minimise the exposure risks of the residents living nearby.

Figure 10. Consistent fall in pollution levels signifies reliability of water sprinkling as a short-term dust mitigation measure



Source: Authors' analysis

However, the degree of effectiveness of these measures is not uniform. It can be influenced by the nature of the on-site activities, such as excavation, material handling, or transportation, which generate varying levels of dust. Additionally, the prevailing meteorological conditions like wind speed, humidity, and temperature may affect the effectiveness duration. Soil characteristics also play an important role, as fine-grained soil or loose, dry surfaces tend to release more dust compared to compact or cohesive soil types. Therefore, for optimal results, dust suppression strategies should be tailored to site-specific conditions, ensuring that both environmental and operational factors are considered, and resources used optimally.

3.4 Limitations of the study

While this study provides valuable insights into activity-specific dust emissions and the effectiveness of mitigation measures at a construction site, certain limitations must be acknowledged. These limitations also highlight areas for future research and potential methodological enhancements:

1. **Focus limited to outdoor construction activities**
   The monitoring network and data collection efforts were focused exclusively on outdoor construction activities such as excavation, earthwork, foundation, and material handling. Indoor or semi-enclosed construction phases—such as interior finishing, plumbing, or electrical installation—had not started during the study duration and hence were not monitored. As a result, the study does not capture the full spectrum of dust-generating activities that occur throughout the construction lifecycle. Future studies can benefit from incorporating both indoor and outdoor monitoring to provide a more comprehensive emissions profile across all construction phases.

2. **Lack of weathering assessment**
   The study did not incorporate the impact of natural weathering processes—such as resuspension of settled dust, rainfall wash-off, and surface erosion—on measured particulate concentrations. These factors can significantly influence ambient pollutant levels, and the apparent effectiveness of mitigation strategies. Due to site-level constraints and the complexity of isolating weather-related effects, this

dimension could not be accurately assessed. Future research should explore integrated meteorological-dust models and longer-term datasets that can differentiate between emissions from construction activities and those driven by weathering or seasonal variability.

3. **Site-specific construction type**
   The study was conducted at a single construction site in Gurugram, focused on a specific type of mixed-use, residential, high-rise development, which is more frequent in cities these days. Consequently, the findings may not be fully generalisable to other constructions such as low-rise residential buildings, infrastructure projects (e.g., roads, flyovers), or industrial developments, each of which may have distinct emission profiles and mitigation challenges. Expanding the research to include a diverse range of construction types across different geographic and climatic regions will provide a broader evidence base for developing universally applicable regulatory guidelines.

4. Recommendations

Based on the findings and limitations of this study, several key recommendations are proposed to support better targeted, evidence-based, and health-conscious air quality management within the construction sector:

A. Policy modifications for activity-specific regulation of PM emissions

- Current regulatory frameworks, such as GRAP, often rely on blanket bans that do not distinguish between high-polluting and less-polluting construction activities. This study highlights the need for a policy modification that enables activity-wise mitigation measures for all construction activities.

- Standardised emission profiles for common construction activities should be developed by the authorities, such as CAQM, based on empirical on-ground data. These profiles should subsequently be adopted and disseminated by regulatory authorities such as the state pollution control boards (SPCBs) to guide construction firms in implementing activity-specific emission-control measures.

- Instead of issuing indiscriminate bans, policies should classify activities into pollutant-intensive and non-pollutant-intensive categories. This will enable the authorities to impose targeted regulation and enforcement during high-pollution periods.

- Robust policies should be formulated, incorporating comprehensive protocols with clearly defined thresholds for monitoring, reporting, and enforcement of activity-specific dust-control measures.

B. Builders' responsibility towards clean construction practices

- Builders should integrate air quality information while scheduling construction projects. Construction firms and contractors should be mandated and supported to integrate dust mitigation into their planning, and include dust mitigation plans as sub-tasks in project timelines.

- Builders should strategically schedule high-polluting activities, such as excavation and demolition, during periods of lower ambient pollution and favourable meteorological conditions.

- Less-polluting or indoor activities can be prioritised during peak pollution episodes, ensuring that construction timelines are not entirely disrupted, while minimising environmental impact.

- Project management systems should integrate environmental parameters to enable real-time adjustments in activity schedules based on air quality forecasts. Builders should deploy digital monitoring tools such as on-site display dashboards to present real-time air quality data and associated control measures. This will strengthen compliance with dust emission standards and ensure the timely implementation of appropriate mitigation strategies.

> Activity-specific policies, smarter scheduling, and stronger safeguards can significantly reduce construction dust and protect public health.

C. Strengthening occupational and public health safeguards against exposure to construction dust

- Occupational health standards should be strengthened, requiring employers to provide personal protective equipment (PPE), regular health screenings, and training for workers involved in high-dust emitting activities.

- Urban planning must account for the public health implications of construction-related emissions, particularly in densely populated or vulnerable neighbourhoods.

- Establishing minimum buffer zones between active construction zones and sensitive land uses (e.g., schools, hospitals) can help reduce exposure risks. Green belts or plantation areas should be established between project sites and surrounding areas to capture the dispersed fugitive emissions and mitigate air pollution.

- Awareness campaigns and community engagement should be incorporated into large-scale construction projects to ensure transparency and promote public accountability.

These recommendations, if implemented in coordination with empirical monitoring and enforcement, can help transition the construction sector towards sustainable, health-conscious development, balancing the dual imperatives of urban growth and environmental protection.

Image: iStock

Sustainable clean construction practices can enhance in balancing the dual imperatives of urban growth and environmental protection.

Annexures

Annexure 1

The following table outlines the technical specifications and performance criteria of the low-cost PM sensors deployed for the study

Table A1. Table showing the specifications of the deployed low-cost sensors

Parameter	Measurement Range	Unit
PM ($PM_{2.5}$ and PM_{10})	Effective Range: 0–500 (as per NAAQS for $PM_{2.5}$ and PM_{10})	µg/m^3
Accuracy (reproducibility)	±10	%
Minimum range **Range of measurement**	< 0.3 1.0~2.5 ; 2.5~10	µm
Counting efficiency	50%@0.3µm ; 98%@>=0.5µm	-
Response time: **Single response time** **Total response time**	 <1 <10	second(s)
Resolution	1	µg/m^3
DC power supply	Min:4.5 Max: 5.5	Volt (V)
Operating condition: temperature range	5 - 45	°C
Operating condition: relative humidity range	40 - 80	%
Minimum sampling interval	5	min
Sensor/device certification	µm MCERTS (mandate)	
Evaluation metric **- Correlation factor (R2)** **- Maximum deviation (RMSE)**	 - > 0.75 across all seasons - Up to 35 ug/m^3 across all seasons	
Calibration certificate	Certificate of tested and calibrated against beta attenuation monitor(BAM)	

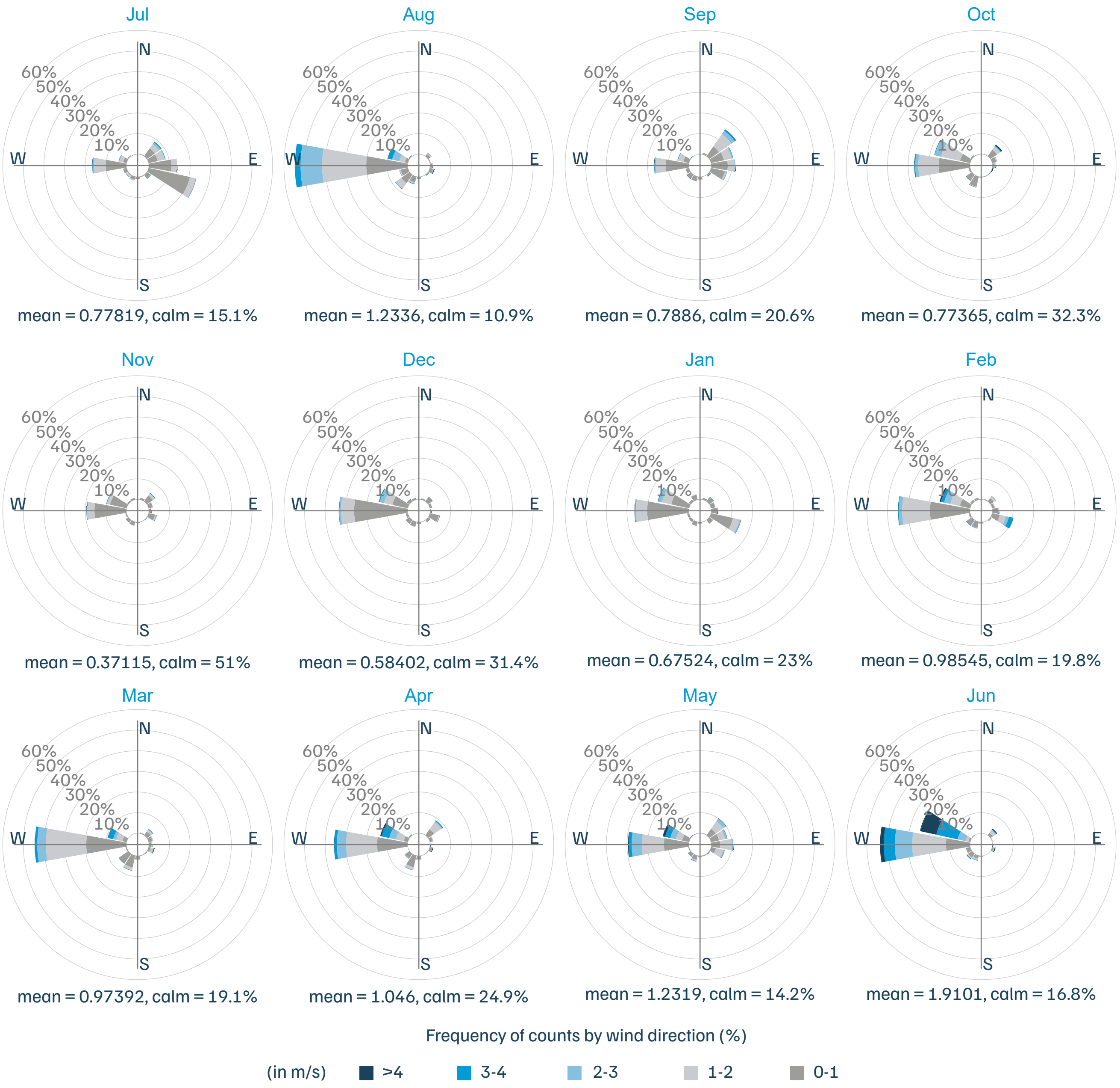
Source: Authors' analysis

Note: NAAQS- National Ambient Air Quality Standards (CPCB 2019); MCERTS- Monitoring Certification Scheme (EA 2017)

Annexure 2

The monthly windrose plots show the distribution of wind direction and wind speed at the study site from July 2023 to June 2024. The radial bars indicate the frequency of winds from each direction, while the colour scale represents wind speed ranges in m/s. The highest wind frequencies occur predominantly from the west and east, with notable seasonal variation. Mean wind speeds vary across months, with peak values in June (1.91 m/s) and lower speeds in November (0.37 m/s). Calm conditions are more frequent in the winter months, reaching over 51% in November.

Figure A1. Monthly windrose plots illustrating the prevailing wind direction and wind speed distribution at the study site

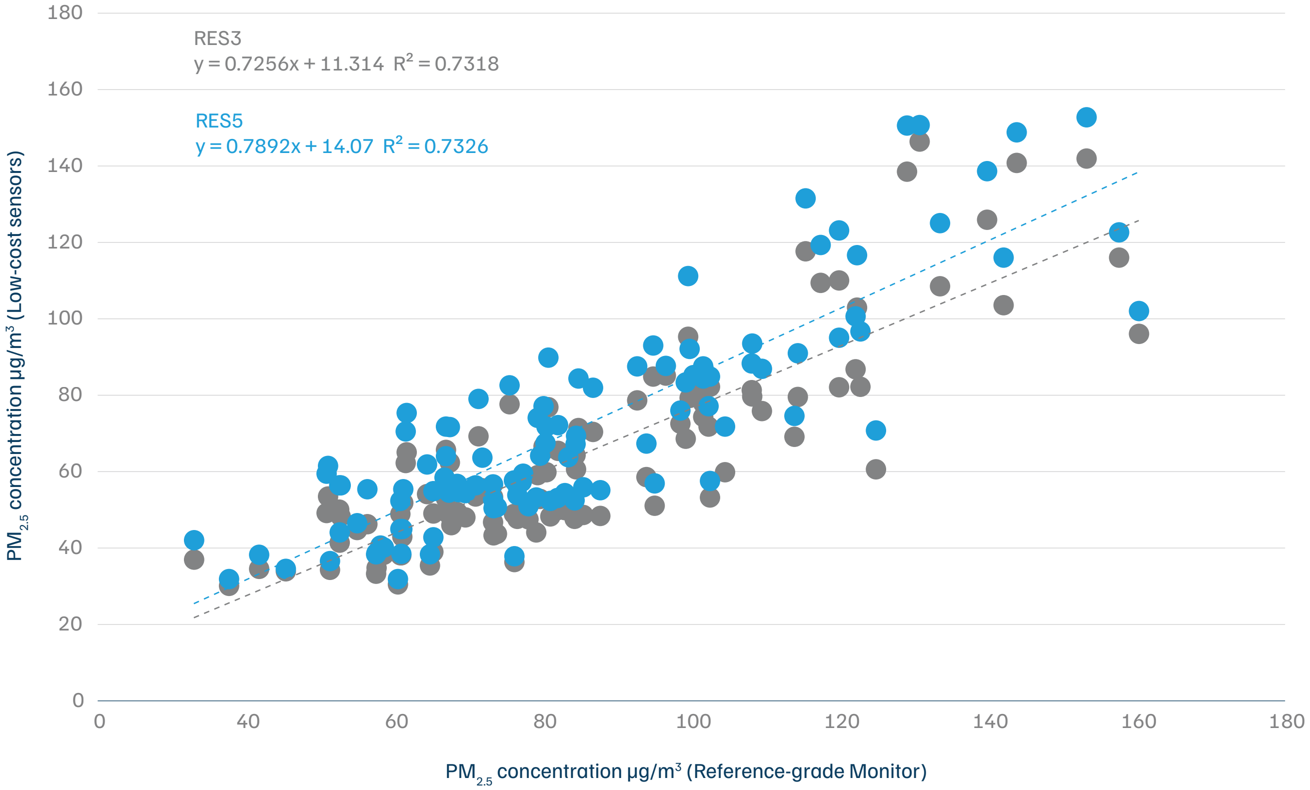


Source: Authors' analysis

Annexure III

The following scatter plot shows the collocation analysis where $PM_{2.5}$ concentrations measured by two low-cost sensors (RES3 and RES5) are compared against a reference-grade monitor. Both sensors show strong positive correlations with the reference data, with R^2 values of 0.7318 (RES3) and 0.7326 (RES5). The regression slopes (0.7256 for RES3 and 0.7892 for RES5) indicate that both sensors slightly underestimate concentrations compared to the reference-grade monitor. However, the close agreement between the two datasets suggests reliable sensor performance.

Figure A2. Scatter plot showing the relationship between $PM_{2.5}$ concentrations of two low-cost sensors (RES3 and RES5) and a reference-grade monitor

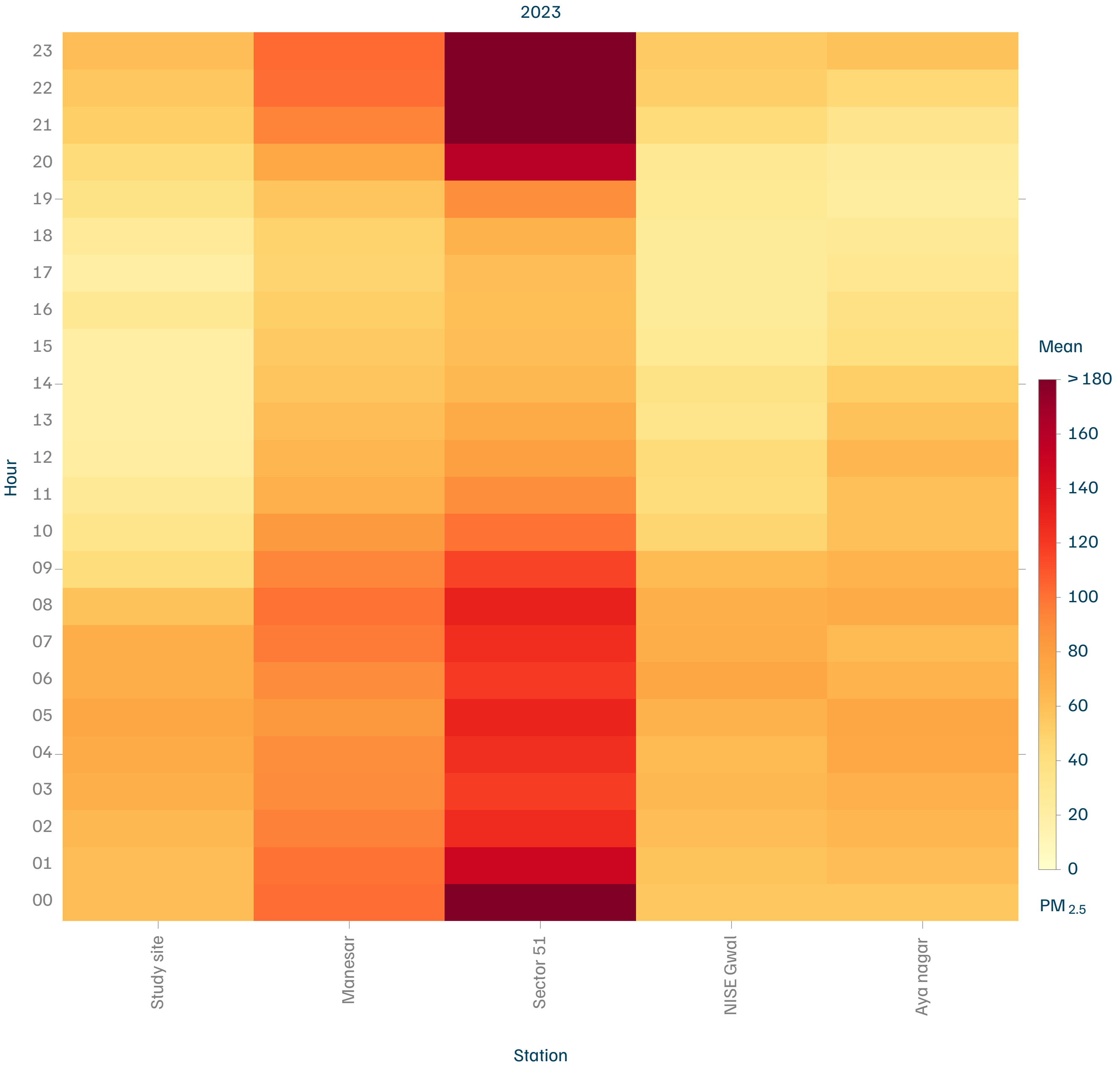


Source: Authors' analysis

Annexure IV

The figure compares hourly $PM_{2.5}$ levels from an LCS deployed at the study site with four nearby CAAQMS stations over a month. The nearest CAAQMS is in Manesar, which is about 9.5 km away from the study site. Differences in land use, land cover, and occasional data gaps led to variations in average concentrations, making exact matches difficult. However, it was observed that the diurnal trend follows a similar pattern, with lower $PM_{2.5}$ levels typically observed during working hours (7 a.m.–7 p.m.).

Figure A3. Hourly comparison of $PM_{2.5}$ concentration between an LCS deployed at the study site and four CAAQMS located nearby



Source: Authors' analysis

Annexure V

Non-parametric tests, namely the Wilcoxon signed-rank test and the sign test, were conducted to examine whether PM levels varied across different construction activities in comparison to no-work conditions. The results show that activities such as vehicle movement, road work, earthwork, and excavation showed statistically significant differences under both tests, indicating higher PM levels compared to no-work conditions. In contrast, foundation/framework and cement/concrete work showed no significant differences, suggesting relatively lower incremental dust generation. Interestingly, for brickwork, both tests indicated a significant difference; however, in this case, the dust levels were lower than those during the no-work condition. This could be due to the fewer occurrences recorded for brickwork activity, which may have affected the statistical outcome compared to the larger dataset available for the no-work condition.

Table A2. Table showing the statistical results of the non-parametric tests comparing the construction activities to no-work condition

Parameter	Wilcoxon test statistics		Sign test statistics	
	Z value	p-value	Z value	p-value
Vehicle movement	-8.4	0.000	-8.9	0.000
Road work	-5.0	0.000	-4.5	0.000
Earthwork	-3.4	0.001	-3.3	0.001
Excavation	-3.7	0.000	-4.1	0.000
Foundation/framework	-0.7	0.474	-2.6	0.007
Cement/concrete work	-0.5	0.555	-0.2	0.769
Brickwork	-4.96	0.000	-5.37	0.000

Source: Authors' analysis

Annexure VI

The following table presents average $PM_{2.5}$ concentration of various construction activities carried out per month. The total number of days is presented alongside the concentration value of each specific activity along with the corresponding meteorological parameters for each month. It is observed that foundation/framework had the highest occurrence during the monitored period and brickwork the lowest.

Table A3. Monthly variation of $PM_{2.5}$ concentrations across various construction activities and their relation to meteorological conditions

Month	Average $PM_{2.5}$ concentration (μgm^{-3}) of various construction activities						No work (n)	Meteorological parameters	
	Brickwork (n)	Cement/ concrete work (n)	Foundation/ framework (n)	Excavation (n)	Earthwork (n)	Road work (n)		Temperature (°C)	Relative humidity
Jul 23	25 (1)	32 (10)	34 (104)	42 (74)	38 (21)	42 (6)	29 (5)	30.3	80.1
Aug 23	24 (13)	25 (9)	25 (70)	41 (76)	41 (18)	40 (12)	24 (4)	30.8	70.5
Sep 23	30 (20)	36 (16)	34 (36)	53 (73)	43 (30)	46 (16)	21 (1)	29.4	73.9
Oct 23	55 (17)	33 (9)	104 (67)	198 (38)	168 (39)	152 (30)	78 (18)	26.5	57.1
Nov 23	237 (3)		220 (12)	249 (7)	234 (5)	272 (2)	133 (112)	20.3	71.4
Dec 23		170 (5)	164 (64)	157 (25)	157 (23)	209 (22)	119 (33)	15.9	72.9
Jan 24		171 (13)	164 (82)	174 (22)	160 (17)	169 (15)	98 (59)	10.9	84.4
Feb 24		103 (9)	112 (44)	188 (7)	182 (3)		85 (34)	17.8	63.6
Mar 24	51 (2)	53 (15)	46 (78)	67 (7)	63 (11)	67 (3)	33 (72)	23.1	52.8
Apr 24	23 (2)	31 (13)	33 (81)	38 (6)	41 (19)	35 (12)	29 (67)	29.8	33.7
May 24		29 (7)	35 (59)	38 (3)	44 (12)	47 (17)	31 (106)	35.5	34.2
Jun 24	36 (8)	20 (7)	24 (57)		46 (11)	44 (1)	25 (98)	34.7	48.9

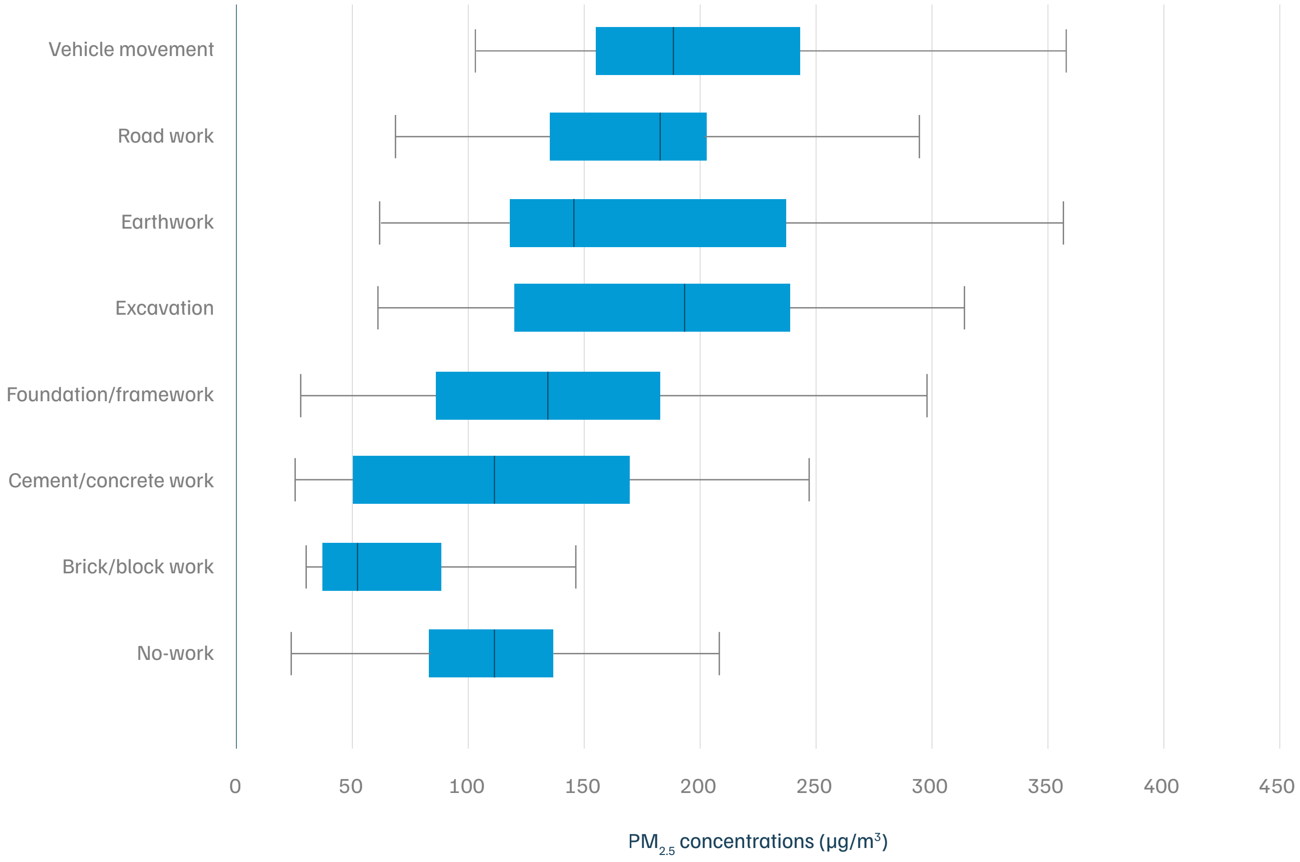
Source: Authors' analysis

Note: (n) denotes the number of days

Annexure VII

The following boxplot shows the distribution of $PM_{2.5}$ concentrations for different construction activities at the study site. Pollutant-intensive activities are associated with higher median $PM_{2.5}$ levels and wider ranges, indicating more variability in emissions. However, non-pollutant-intensive activities show much lower concentrations. The long whiskers in some activities indicate occasional extreme pollution events. The elevated ambient pollution levels in winter from other probable sources integrate with the activity-wise concentrations and make it difficult to detect significant differences during the season.

Figure A4. $PM_{2.5}$ concentration variation of different activities during post-monsoon and winter season (Oct 23–Feb 24)



Source: Authors' analysis

Annexure VIII

The table presents the reduction in $PM_{2.5}$ concentrations observed following the implementation of water sprinkling as a dust mitigation measure. The data represent working hours between 7 a.m. and 7 p.m., during which water sprinkling was carried out at different time intervals across multiple days. The corresponding meteorological parameters are also included to illustrate that the observed decrease in $PM_{2.5}$ levels primarily resulted from the mitigation measure itself, rather than variations in weather conditions.

Table A4. Table showing the $PM_{2.5}$ concentrations, temperature, and relative humidity for five selected days with the implementation of water sprinkling as a dust mitigation measure

Date	**04-07-2023**			**25-07-2023**			**23-09-2023**			**28-09-2023**			**27-10-2023**		
Time	**$PM_{2.5}$**	**T °C**	**RH**	**$PM_{2.5}$**	**T °C**	**RH**	**$PM_{2.5}$**	**T °C**	**RH**	**$PM_{2.5}$**	**T °C**	**RH**	**$PM_{2.5}$**	**T °C**	**RH**
07:00	34.54	31	60	58.41	30	78	58.00	31	74	50.68	23	80	129.38	31	31
07:30	34.75	32	58	59.51	30	77	50.51	32	71	45.83	23	81	122.21	32	29
08:00	31.51	32	57	59.29	31	76	42.54	32	71	37.25	23	83	122.02	31	31
08:30	31.32	33	57	57.73	32	73	43.83	33	69	36.12	23	84	127.23	31	32
09:00	28.39	34	55	60.07	32	71	44.16	33	65	36.74	23	84	130.95	31	32
09:30	27.91	34	55	63.45	32	72	46.40	33	65	39.11	22	82	123.20	31	34
10:00	29.02	35	54	47.56	32	68	50.91	33	66	41.32	22	85	119.40	30	34
10:30	28.95	35	53	31.14	33	63	50.86	32	67	41.12	23	84	114.80	29	35
11:00	30.46	36	52	31.44	33	64	51.27	31	69	42.42	22	83	107.65	29	40
11:30	33.77	37	51	34.32	34	62	55.11	30	70	45.20	22	83	101.77	27	44
12:00	34.25	37	49	34.81	34	62	54.54	29	71	45.42	22	80	100.98	26	49
12:30	35.16	37	50	39.25	34	63	32.90	29	67	30.47	22	80	99.7	24	53
13:00	38.50	39	47	45.83	34	64	32.25	30	65	27.05	22	80	57.32	24	54
13:30	43.43	39	44	46.70	34	62	30.96	30	67	30.07	22	81	55.72	23	56
14:00	48.10	29	66	46.18	35	61	20.02	30	67	18.11	22	82	52.00	23	60
14:30	34.40	25	81	44.52	35	60	16.77	29	68	15.42	24	79	43.65	22	63
15:00	21.13	26	81	38.65	34	61	20.71	29	72	18.66	25	75	46.33	22	61
15:30	20.97	28	71	40.52	34	61	22.77	28	75	20.46	26	74	61.29	22	62
16:00	18.18	28	69	43.09	34	63	28.43	28	77	25.22	27	72	65.57	22	58
16:30	31.09	29	69	40.83	33	65	29.83	27	79	25.59	29	68	66.95	21	65
17:00	34.86	30	67	40.93	33	67	31.84	27	77	28.25	30	65	69.14	21	66
17:30	36.07	30	68	39.57	31	69	34.84	27	78	31.63	30	58	80.24	20	67
18:00	44.75	29	68	46.77	31	73	36.46	27	78	32.12	32	51	87.18	20	67
18:30	47.18	29	69	52.64	31	74	38.73	26	80	33.73	31	50	98.66	19	71
19:00	50.46	29	72	56.88	31	76	44.59	26	79	36.23	32	51	101.18	19	71

Source: Authors' analysis

Note: $PM_{2.5}$- concentrations in µg/m^3, T- Temperature in °C and RH- Relative Humidity

Acronyms

GRAP	*Graded Response Action Plan*
AWS	automated weather station
SCO	shopping-cum-office area
RES	residential area
LCS	low-cost sensor
CAQM	Commission for Air Quality Management
NCR	National Capital Region
$PM_{2.5}$	particulate matter with a diameter up to 2.5 µm
PM	particulate matter
PM_{10}	particulate matter with a diameter up to 10 µm
USD	United States Dollar
NGT	National Green Tribunal
CPCB	Central Pollution Control Board
MMRDA	Mumbai Metropolitan Region Development Authority
C&D	construction and demolition
PMC	Pune Municipal Corporation
NCAP	*National Clean Air Programme*
MoU	memorandum of understanding
CAAQMS	Continuous Ambient Air Quality Monitoring Station
WBS	work breakdown structure
HDV	heavy duty vehicle(s)
RMC	ready-mix cement
AQ	air quality
SE	standard error
AQI	Air Quality Index
SPCBs	state pollution control boards
PPE	personal protective equipment

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