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Original Article

Environmental Impact Assessment of Urban Demolition Sites: A Tri-Point Monitoring Framework with Three-Stage Pollutant Quantification and Artificial Neural Network Predictive Modelling

Akshata Shagoti[1], Urmila R. Kawade[2], Vidyashree J C[3], Satish D. Kene[4], Megha Dabas[5], Brijbhushan S[6], Prashant Sunagar[7]

[1]*Department of Architecture, M S Ramaiah Institute of Technology, Bengaluru, Karnataka, India.*
[2]*Department of Civil Engineering, Dr.V.V.Patil COE, Ahilyanagar, Maharashtra, India.*
[3]*Department of Civil Engineering, Dayanandasagar College of Engineering, Bengaluru, Karnataka, India.*
[4]*Department of Civil Engineering, St Vincent Pallotti College of Engineering and Technology, Nagpur, India.*
[5]*CSE AIML, Marwadi University, Rajkot, Gujarat, India.*
[6]*Department of Civil Engineering, VTUCPGS Kalaburagi, Karnataka, India.*
[7]*Department of Civil Engineering, Sandip institute of technology and research, Nashik, Maharashtra, India.*

[7]*Corresponding Author : prashant.sjce@gmail.com*

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Abstract *- Urban densification in rapidly expanding Indian cities has led to an increase in the construction and demolition of residential buildings, resulting in the release of various pollutants into the ambient atmosphere that adversely impact the health of the workers at the demolition sites and the residents near these sites. An investigation into the emissions from four demolition sites of varying sizes in Bengaluru, India, employed a three-point, three-stage monitoring approach to measure the levels of PM_{10} and $PM_{2.5}$, SO_2, NO_2, CO, and noise pollution for a total period of 108 working hours at each site. The results indicate that the levels of PM_{10} at two of the four demolition sites exceeded the NAAQS limit of 100 µg/m³ by up to 29.97%, while the noise pollution at three of the four sites exceeded the permissible limit of 75 dB(A) for residential areas. Furthermore, a novel Composite Pollution Index was developed as a means of providing a single metric to represent the pollution levels at each demolition site. An Artificial Neural Network model for estimating the levels of PM_{10} at demolition sites achieved a coefficient of determination of 0.964 on the test partition of the data set, outperforming other machine learning models for the same estimation task. Additionally, a SHAP analysis of the ANN model revealed that the area of the construction site plan and the phase of demolition were the two most important variables that influenced the levels of PM_{10} released during demolition activities.*

Keywords *- Environmental Impact Assessment, Demolition sites, Particulate matter PM_{10} $PM_{2.5}$, Noise pollution, Artificial Neural Network, SHAP analysis, CPCB, NAAQS, Bengaluru, Construction dust management.*

1. Introduction

The rapid rate at which Indian cities are being developed and renewed has led to the demolition of numerous residential buildings that are over 30 years of age. Bengaluru, one of the fastest-growing cities within the Tier-1 cities of India, has seen numerous residential buildings in its older neighborhoods being demolished in order to make way for new constructions that can accommodate the growing number of families in the city.

Demolition is a phase of the life cycle of a building that differs from the environmental impact of either the construction or operation phases of a building. During the demolition of a building, particles are released into the atmosphere either due to the physical breaking of the building with demolition tools or the particles that are created and released as the demolition takes place and the buildings are removed from their plots.

Both the construction workers performing the demolition of the residential buildings, as well as the residents that live within the buildings that are being demolished, are exposed to these airborne particles. However, there are few studies that publish data regarding the environmental impact of these types of demolition sites.

There are various studies that have published data regarding the particulate matter that is released from road surfaces [10], industrial plants [1], and the demolitions that occur with the imploding of buildings [5]. However, none of these studies relate to the demolitions of residential buildings, especially within the Indian countryside.

Thus, it is necessary to perform a study regarding the levels of pollutants at these demolition sites, whether in a statistical analysis of the data from such sites, or through the use of machine learning techniques to model the relationship between various factors (such as size of buildings being demolished) and the amount of pollutants that are released during such demolitions.

The objectives of the study that will be performed is to collect data from four demolition sites of varying sizes, to analyze the amount of pollutants and noise that is created during each phase of the demolitions, to compare those levels to the limits established by the NAAQS and the CPCB, to establish a Composite Pollution Index to summarize the findings, and to establish machine learning models (both artificial neural networks, as well as other machine learning models) that can be used to both predict the amount of pollutants that may be released from other demolition sites of similar characteristics, as well as to suggest limits for those sites.

Yet despite the increasing role of construction and demolition in urban dust, field-scale studies of small and medium residential demolition sites in Indian cities are scarce. Existing studies tend to focus on general construction dust, road dust and industry emissions, or large-scale implosion-type demolition events.

All such instances do not reflect the plot-scale residential demolitions that may take place in dense Indian cities, with their limited setbacks, close-by buildings, local traffic, and short-duration mechanical breaking, leading to high near-field PM_{10} and noise exposure. This is an issue because demolition activities are generally transient, localized, and poorly represented by routine ambient air-quality monitoring stations.

The present study aims to fill this gap via a field-based monitoring framework deployed at four residential demolition sites in Bengaluru. The methodological contributions of this research follow from combining: (i) three-point perimeter monitoring to account for spatial variation around the site; (ii) three-stage monitoring of pre-, active and post-demolition phases; (iii) a Composite Pollution Index that combines different pollutants into a single site-specific risk measure; (iv) a machine-learningbased PM_{10} predictor informed by SHAP interpretation.

This combination contextualizes measured pollutant behaviour within PM_{10} prediction and interpretable feature attribution, using a modelling approach that is generally not reported for Indian residential demolition sites.

2. Background and Literature Review

During the demolition phase of a building, Particulate Matter (PM) is released into the atmosphere. Authors Azarmi and Kumar published a study that evaluated the impacts of the PM that is released from buildings that are being demolished, and found that the fine and coarse particles can enter the deep portions of the respiratory system of human beings, and that the $PM_{2.5}$ particles remain in the atmosphere for longer periods of time than the particles with a larger diameter [3]. Additionally, authors Azarmi et al. have continued their study to evaluate the long-term concentrations of PM_{10} within demolition sites and found that the PM_{10} levels in construction sites often exceeds the limits of the NAAQS regulations, and that it can take up to 72 hours for the levels of particulate matter to return to normal levels [4].

Authors Chen et al. studied the levels of PM_{10}, $PM_{2.5}$, and PM_1 at an urban shelterbelt in Beijing, China [10]. They found that the amount of particulate matter of each size that was released from the buildings that were undergoing demolition was correlated with both the weathering climate and the number of construction sites within the area. Additionally, Araujo et al. studied the presence of particulate matter at construction sites within Brazilian cities [2]. Their findings indicated that the majority of the particulate matter was created by the breaking of concrete and the removal of the construction waste from the construction sites. In contrast, Fauzey et al. investigated the health of the workers during the demolition phase [6]. As the authors state in their publication, most health and safety regulations within Malaysia do not account for the temporary nature of the health hazards that may occur at demolition sites. The limits for particulate matter at demolition sites within India are established by the Central Pollution Control Board (CPCB) within the National Ambient Air Quality Standards (NAAQS) [11]. However, the implementation of these air quality limits at demolition sites within India is limited, and there is little data published on the impact of demolitions on the air quality within India. Thus, the study that will be performed helps to fill this existing research gap.

The application of machine learning techniques to the construction of buildings and their components has been developed in a variety of ways. For instance, artificial neural networks have been utilized to model the amount of compressive strength that can be provided by a sample of concrete, as well as the depth to which the concrete has become carbonated. Additionally, another type of machine learning that has been utilized in the context of the construction industry is the use of machine learning models to determine air quality in urban environments [13].

Artificial neural networks are especially well-suited for the task of modeling the amount of particulate matter that is created during the demolition of residential buildings, as numerous factors impact the amount of particulate matter that is created. These factors may include the composition of the building, the amount of energy that is used during demolition, the size of the buildings being demolished, and the weathering climate at the site where the demolitions are occurring.

Recent air-quality prediction studies demonstrate that construction-site particulate concentrations are sensitive to work intensity, site activity, meteorology, and local dispersion. Models trained on generic urban air-quality stations may, therefore, be inadequate for demolition-site evaluation as they do not reflect short-duration activity peaks, source proximity, and micro-environmental site enclosure. Ensemble tree-based learners have been reported to perform competitively on construction-dust datasets of comparable size [14]. Construction and demolition sites also differ from regular traffic corridors in that particulate emissions are episodic and linked to breaking, debris handling, loading, and surface resuspension.
Interpretable machine learning is increasingly being applied in environmental assessment because prediction accuracy alone is insufficient for regulatory or site-management decision making. SHAP, partial dependence, and similar interpretation methods can help identify whether model predictions are dominated by source variables, meteorology, traffic indicators, or site geometry. In the present study, SHAP analysis was applied to determine if the ANN predictions were physically plausible. The high contribution of site area and demolition phase corroborates the experimental finding that smaller, more enclosed sites showed greater PM_{10} accumulation in active demolition.

In the Indian context, demolition-site monitoring is additionally relevant because C&D waste management, roadside dust and traffic, and dense urban morphology may interact. Regulatory frameworks call for improved dust management, waste segregation, transport, and site-based mitigation. Small residential demolition sites may have limited room for barriers, water spraying, wheel washing, and continuous monitoring. The proposed CPI and ANN approach should therefore be seen as a screening tool rather than a substitute for regulatory monitoring.

3. Investigation Flowchart

As illustrated in the flowchart depicted in Figure 1, there are four main stages within the plan for the performance of this study. During the first main stage, four demolition sites will be selected for observation. These sites may be of any size, but they will be residential buildings that are undergoing demolition. Furthermore, these buildings will be located within India. During the second main stage, the air quality within these four demolition sites will be measured. During the third main stage, the data that was collected during that second stage will be analyzed to determine the amount of pollutants and noise that were created during each phase of the demolitions. Additionally, those measurements will be compared with the limits established for particulate matter by both the CPCB and the NAAQS. During the fourth main stage, the data will be used to model the creation of an artificial neural network that can be used to predict the amount of pollutants that will be created at other demolition sites that may be constructed similarly to those four demolition sites.

Fig. 1 Investigation methodology flowchart depicting the three-point, three-stage environmental monitoring and ANN modelling framework

The protocol to be followed was to measure the background levels of pollutants prior to the demolition works, take samples from three different locations around each site, and continue to sample the air within each site during the demolition works.

4. Methodology

4.1. Experimental Design and Site Selection

The study sites to be used included four demolition sites of residential precincts within Bengaluru city. Each site featured similar structures of stone rubble foundations, brick masonry walls with cement-mortar plaster, and reinforced concrete roof slabs. Each site was selected from a different sub-market within the city. Each site was required to be at least 200 meters from major roads, industries, and construction sites. Each site featured two-storey buildings that were constructed between 40 and 50 years ago.

Table 1 presents the geometry of each of the four demolition sites that were selected for the study.

Table 1. Dimensional and locational characteristics of the four demolition sites investigated

Site	Plot Dimensions	Plot Footprint	Built-Up Floor Area
S1	30 × 40 ft	111.48 m²	167 m²
S2	60 × 40 ft	222.97 m²	372 m²
S3	100 × 120 ft	1,114.84 m²	1,672 m²
S4	50 × 150 ft	696.77 m²	1,394 m²

The plot footprint and the total built-up floor area were considered to be separate geometric variables. The plot footprint is calculated from the dimensions of the plots, while the total built-up floor area is the sum of the floor areas of the buildings that were demolished. Figures 3-6 have been redrawn as plans that reflect the dimensions of each of the plots depicted, including the building footprint, the entrance to the buildings, the adjoining roads, any obstructions surrounding the plots, the locations at which the monitoring samples were collected, and the distances between each of the sources of pollutants and each of the receptor sites. All of the distances included in these figures have been verified against the original field sketches of the plots. All four sites were established to minimise the impact of major external sources of air pollution. Several additional factors associated with the sites, however, may have contributed to the dispersion of pollutants from the sites. Factors such as the land use surrounding the sites, the proximity to roads, buildings, site access, traffic, and the presence of industrial activity were recorded at each site. Each site was established in built-up residential neighborhoods that featured surrounding masonry buildings and plots with smaller areas for outdoor activity, which is likely to contribute to PM_{10} levels during the demolition process at each site.

Additional factors that may have impacted on the results include local weather conditions and traffic. Factors like wind direction and speed, temperature, relative humidity, and rainfall can all impact the dispersion of PM_{10}, while traffic passing the monitoring points may contribute to PM_{10}, NO_2, and CO levels in the air. While weather instrumentation and traffic counts were established at each site, these measurements were taken qualitatively. Future applications of this framework will incorporate instrumentation to measure weather and traffic activity at each site. Site S4 was different from Sites S1-S3 in that Site S4 was an engineering college hostel located on the college campus itself. While the hostel itself was a low-rise residential occupancy building with similar construction to the other buildings in the sample, the location of the building and its surroundings may have been different from the other residential sites. Thus, Site S4 was included in the study as a similarly sized demolition site, but in interpreting the results from Site S4 in comparison to the other residential sites, it was not possible to separate the effects of the area of the site from the other variables.

4.2. Three-Point Instrument Deployment Strategy

A three-point strategy was used to deploy the instruments at each site in a manner that would enable representative measurements of average pollutant concentrations at each site, irrespective of the direction of the incoming wind. Three measurement points were established at each site: one at the entrance of the site (which faces the access road), one on the left flank of the site, and one on the right flank of the site. The two lateral monitoring points were located at two-thirds of the depth of the site from the road.

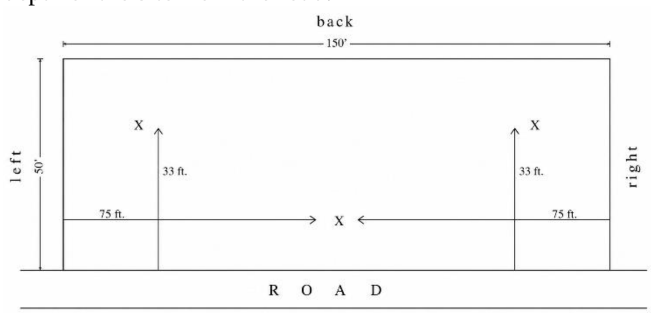

Fig. 2 Schematic three-point instrument deployment strategy applied uniformly at all four demolition sites (C = Centre/Entrance, L = Left Flank, R = Right Flank)

Site-specific layouts for each of the four investigated locations are presented in Figures 3 through 6 below.

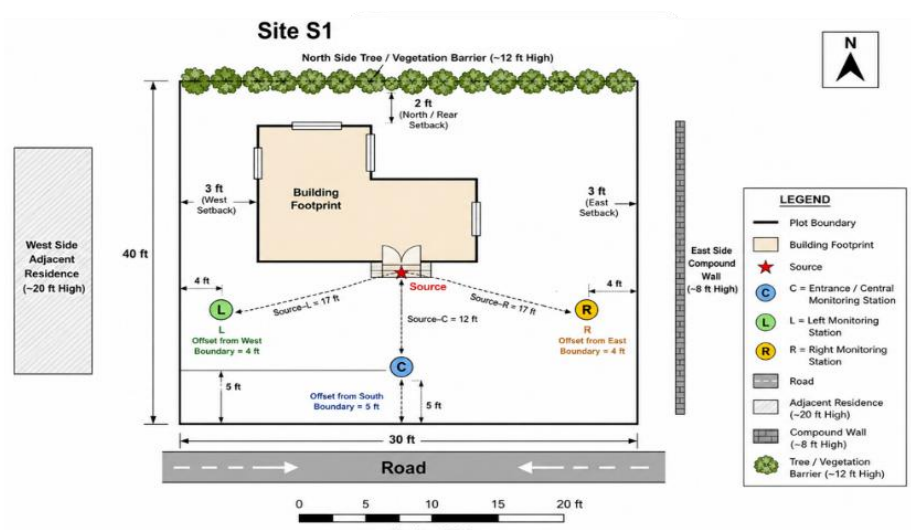

Fig. 3 Instrument layout at site S1 Jayanagar

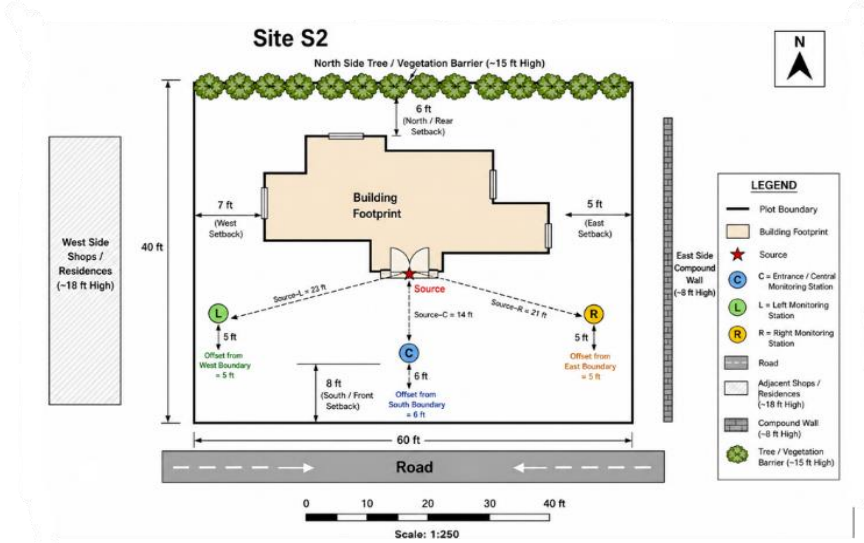

Fig. 4 Instrument layout at site S2 Indiranagar

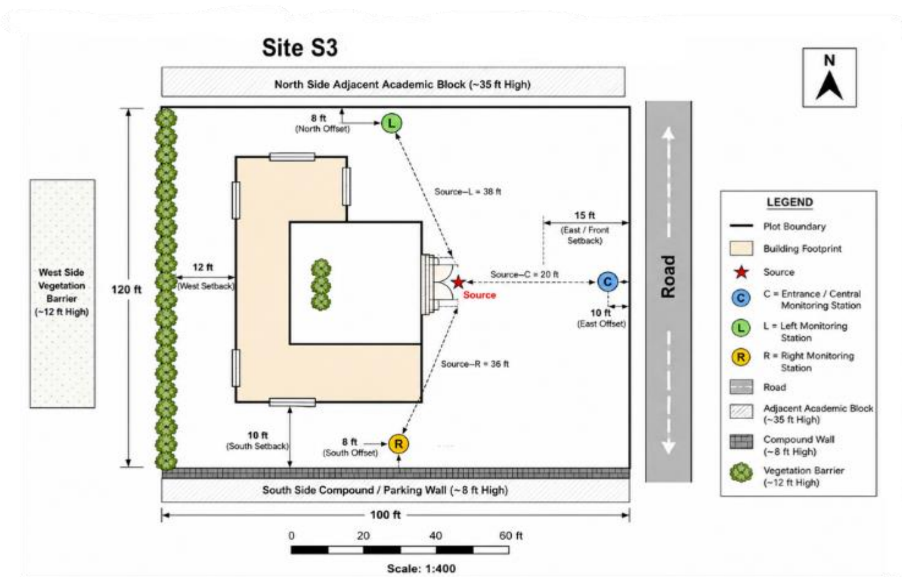

Fig. 5 Instrument layout at site S3, Basavanagudi

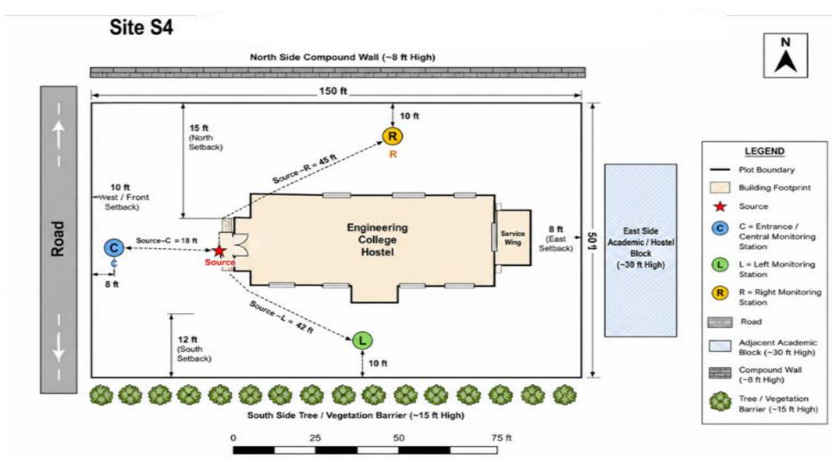

Fig. 6 Instrument layout at site S4 ENGG COLLEGE hostel campus

Table 2. Instrumentation suite deployed at all four demolition sites

Sl. No.	Instrument	Pollutants Measured	No. of Units Deployed
1	APM 550 (Envirotech)	PM_{10}, $PM_{2.5}$, SO_2, NO_2	3
2	AGM 63X (INDUS)	Carbon Monoxide (CO)	3
3	EQ-805 Sound Level Meter	Noise Level dB(A)	3

4.3. Instrumentation

All instruments were selected on the basis of portability, field robustness, and compliance with Indian Standards and CPCB guidelines. Table 2 enumerates the equipment suite deployed.

The Envirotech Respirable Dust Sampler APM 550 is used to sample PM_{10} and $PM_{2.5}$ from the environment. The same instrument is used to sample SO_2 and NO_2 using absorbing reagent bubblers. CO levels are measured using the INDUS Model AGM 63X flue gas analyser. Noise measurements are performed using the EQ-805 Class-I integrating sound level meter.

4.4. Three-Stage Monitoring Protocol

At each demolition site, monitoring was performed over three different phases of demolition:

4.4.1. Pre-Demolition Phase

Three working days of monitoring occurred prior to the start of demolition work. These working days were used to establish baseline levels of the various pollutants in the demolition site's environment.

4.4.2. Active Demolition Phase

Five working days of monitoring occurred during the demolition of the structures. The bulk of the demolition was performed during this stage of the demolition process.

4.4.3. Post-Demolition Phase

Four working days of monitoring occurred after the demolition was complete. These working days were used to measure the decline in pollutant concentrations after demolition had ceased.

Each day's monitoring lasted for 9 working hours (between 09:00 and 17:00). Thus, there were 108 working hours of sampling at each demolition site (9 h × 12 days). Furthermore, there were 432 working hours of sampling for the entire demolition site campaign (108 h × 4 sites). The sampling period tables for the four demolition sites are presented below.

Table 3. Sampling schedule - site S1, Jayanagar (18-29 July 2017)

Date	Phase	Duration (Hours)
18-07-2017	Pre-Demolition	9
19-07-2017	Pre-Demolition	9
20-07-2017	Pre-Demolition	9
21-07-2017	Active Demolition	9
22-07-2017	Active Demolition	9
23-07-2017	Active Demolition	9
24-07-2017	Active Demolition	9
25-07-2017	Active Demolition	9
26-07-2017	Post-Demolition	9
27-07-2017	Post-Demolition	9
28-07-2017	Post-Demolition	9
29-07-2017	Post-Demolition	9

Table 4. Sampling Schedule — Site S2, Indiranagar (21 June – 2 July 2017)

Date	Phase	Duration (Hours)
21-06-2017	Pre-Demolition	9
22-06-2017	Pre-Demolition	9
23-06-2017	Pre-Demolition	9
24-06-2017	Active Demolition	9
25-06-2017	Active Demolition	9
26-06-2017	Active Demolition	9
27-06-2017	Active Demolition	9
28-06-2017	Active Demolition	9
29-06-2017	Post-Demolition	9
30-06-2017	Post-Demolition	9
01-07-2017	Post-Demolition	9
02-07-2017	Post-Demolition	9

Table 5. Sampling Schedule - Site S3, Basavanagudi (9–20 October 2017)

Date	Phase	Duration (Hours)
09-10-2017	Pre-Demolition	9
10-10-2017	Pre-Demolition	9
11-10-2017	Pre-Demolition	9
12-10-2017	Active Demolition	9
13-10-2017	Active Demolition	9
14-10-2017	Active Demolition	9
15-10-2017	Active Demolition	9
16-10-2017	Active Demolition	9
17-10-2017	Post-Demolition	9
18-10-2017	Post-Demolition	9
19-10-2017	Post-Demolition	9
20-10-2017	Post-Demolition	9

Table 6. Sampling schedule - site S4, ENGG COLLEGE Hostel (19 April - 9 August 2018)

Date	Phase	Duration (Hours)
19-04-2018	Pre-Demolition	9
20-04-2018	Pre-Demolition	9
21-04-2018	Pre-Demolition	9
04-07-2018	Active Demolition	9
05-07-2018	Active Demolition	9
06-07-2018	Active Demolition	9

07-07-2018	Active Demolition	9
08-07-2018	Active Demolition	9
06-08-2018	Post-Demolition	9
07-08-2018	Post-Demolition	9
08-08-2018	Post-Demolition	9
09-08-2018	Post-Demolition	9

4.5. Sample Collection Methods

Data collection procedures followed the prescribed CPCB protocols.

Table 7 details the collection methodology for each monitored parameter.

Table 7. Pollutant sample collection methodology

Sl. No.	Pollutant	Method of Collection / Recording
1.	PM_{10}	Gravimetric filter paper sampling; samples dispatched for laboratory analysis
2.	$PM_{2.5}$	Gravimetric filter paper sampling; samples dispatched for laboratory analysis
3.	SO_2	Absorbing reagent sampling (West & Gaeke Solution); laboratory spectrophotometric analysis
4.	NO_2	Absorbing reagent sampling (TGS-ANSA Reagent); laboratory colorimetric analysis.
5.	CO	Direct field measurement using Non-Dispersive Infrared (NDIR) spectroscopy
6.	Noise	Direct field recording in dB(A) via calibrated sound level meter (simultaneous logging)

4.6. Laboratory Quantification

The samples of filter media and absorbing reagents were transported under cold-chain conditions to an accredited laboratory for analysis (ENVIPRO Analytical Services, Bengaluru). The methods used for quantification are as specified in Table 8.

Table 8. Laboratory quantification methods for each monitored pollutant

Sl. No.	Pollutant	Quantification / Laboratory Method
1.	PM_{10}	Gravimetric Method - IS 5182 (Part 23): 2006 RA 2012
2.	$PM_{2.5}$	Gravimetric Method - CPCB Guidelines, May 2011
3.	SO_2	Improved West & Gaeke Spectrophotometric Method - IS 5182 (Part 2): 2001 RA 2012
4.	NO_2	Jacob & Hochheiser Modified Colorimetric Method - IS 5182 (Part 6): 2006 RA 2012
5.	CO	Non-Dispersive Infrared (NDIR) Spectroscopy - Direct Instrument Method
6.	Noise	Sound Pressure Level Measurement - IS 3483; calibrated SLM (Class 1)

For the gravimetric determination of PM concentrations, the filter papers (glass fibre,47 mm in diameter) were conditioned at 25°C and 50% RH for a period of 24 hours, both before and after the sampling operation. The mass concentration of PM is calculated from the ratio of the mass gain of the filter papers to the total volume of air that was drawn through the samplers. The spectrophotometric methods for the determination of SO_2 and NO_2 were carried out according to the specifications defined in the corresponding Indian Standards.

Table 9. Applicable regulatory standards for pollutant assessment

Sl. No.	Pollutant	Applicable Standards / Protocol Reference
1.	PM_{10}	IS 5182 (Part 23): 2006 Reaffirmed 2012; CPCB / NAAQS
2.	$PM_{2.5}$	CPCB Guidelines May 2011; NAAQS 2009 Notification
3.	SO_2	IS 5182 (Part 2): 2001 Reaffirmed 2012; NAAQS Industrial/Residential limit: 80 μg/m³
4.	NO_2	IS 5182 (Part 6): 2006 Reaffirmed 2012; NAAQS limit: 80 μg/m³
5.	CO	NAAQS (8-hourly): 2.0 mg/m³; Direct Instrument Method
6.	Noise	Central Pollution Control Board Noise Rules 2000; Daytime Residential limit: 75 dB(A)

4.7. Regulatory Standards and Compliance Benchmarks

All of the measured values of each pollutant were compared to the respective NAAQS 2009 standards for residential and other areas. Levels of noise were compared to the standard of 75 decibels (dB(A)) for residential areas as established under the CPCB Noise Pollution (Regulation and Control) Rules, 2000. Any measurements that were found to be above the standard for each area were quantified in percentage terms.

5. Mathematical and Computational Framework

5.1. Composite Pollution Index (CPI)

The Composite Pollution Index (CPI) was used to express the site conditions from the presence of several pollutants as a single indicator. Each of the pollutant concentrations was divided by the limit for that specific pollutant and multiplied by a weighting factor. The weighting factor represented the relative relevance of each of the pollutants to the demolition site. PM_{10} had the highest weighting as it was the dominant pollutant that was above the NAAQS limit. Noise was the second-highest weight as it impacted the workers at the demolition site. $PM_{2.5}$ had the third-highest weighting as it is considered to be more relevant to the health of the workers, even though it was not above the NAAQS limit. The remaining pollutants (NO_2, CO, and SO_2) had lower weights since their concentrations were found to be below the limits.

The CPI values that indicate low risk are found in the range of CPI ≤ 0.70. Values between 0.70 < CPI ≤ 1.00 indicate moderate risk. For these categories, high risk is indicated for 1.00 < CPI ≤ 1.30. Finally, if the calculated CPI is greater than 1.30, the site is deemed to be at critical risk. These categories are not intended to replace the compliance requirements for individual pollutants but to provide a general indication of the risk at any given demolition site.

5.2. Emission Rate Model

The rate at which PM_{10} was emitted from the demolition sites can be calculated using the following equation:

$$Q = (C_{\text{peak}} - C_{\text{bg}})u\sigma_y\sigma_z\exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

$$\Delta C = 129.97 - 88.15 = 41.82\ \mu g/m^3$$

Because $H = 0$,

$$\exp\left(-\frac{0^2}{2(4.3)^2}\right) = 1$$

Therefore,

$$Q = (41.82)(1.2)(6.8)(4.3) = 1467.38\ \mu g/s$$

This is a total emission rate, demolished built-up floor area of 167 m²:

$$q_A = \frac{1467.38}{167} = 8.79\ \mu g\, s^{-1} m^{-2}$$

Using the plot footprint of 111.48 m² :

$$q_A = \frac{1467.38}{111.48} = 13.16\ \mu g\, s^{-1} m^{-2}$$

For Site S1, the excess PM_{10} concentration was calculated as $129.97 - 88.15 = 41.82\ \mu\text{g/m}^3$. Because the assumed effective release height was H = 0, the exponential term reduced to unity. Substitution into Equation (5.2) yielded.

$$Q = (41.82)(1.2)(6.8)(4.3) = 1467.38\ \mu\text{g/s}.$$

Normalising this value by the total demolished built-up floor area of $167\ \text{m}^2$ gave the area-specific emission rate:

$$q_A = \frac{1467.38}{167} = 8.79\ \mu\text{g s}^{-1}\text{m}^{-2}.$$

5.3. Attenuation Model: Pollutant Decay Post-Demolition

Following demolition, the concentration of PM_{10} at the various monitoring locations was found to decay according to a first-order decay model:

$$C(t) = C_{\text{bg}} + [C_0 - C_{\text{bg}}]e^{-\lambda t}$$

$$t_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{0.28} = 2.48\ h \approx 2.5\ h$$

Post-demolition PM_{10} attenuation was characterized using a first-order approach-to-background template, $C(t) = C_{\text{bg}} + [C_0 - C_{\text{bg}}]\exp(-\lambda t)$. Nonlinear regression of the Site S1 post-demolition surveillances produced $\lambda = 0.28\ h^{-1}$ and $R^2 = 0.91$. The equivalent half-life of the concentration excess above backdrop was $t_{1/2} = \ln(2)/\lambda = 2.48\ h$, rounded to 2.5 h.

5.4. Noise Exposure Dose Estimation

The dose of noise exposure for a worker that is exposed to the noise levels of a demolition site for the entirety of a typical working day can be calculated according to the following model:

Under the stated OSHA 5-dB exchange-rate model:

$$T_L = \frac{8}{2^{(L-90)/5}}$$

For $L = 78.27\ dB(A)$:

$$T_L = \frac{8}{2^{(78.27-90)/5}} = 40.67\ h$$

For a 9-hour exposure:

$$D = 100\left(\frac{9}{40.67}\right) = 22.13\%$$

For a constant sound-pressure level, the screening noise dose was calculated as $D = 100(C/T_L)$, where C is the exposure duration and $T_L = 8/2(L - 90)/5$ is the allowable exposure duration under the OSHA 90-dB criterion and 5-dB exchange-rate convention. For L = 78.27 dB(A), the allowable duration was T_L = 40.67 h. Conservatively assuming that this sound level persisted throughout the entire 9-h work period, the corresponding noise dose was D = 100(9/40.67) = 22.13%. This value is below the 50% OSHA action level. Furthermore, because this value was obtained through fixed location measurements of sound levels, the dose value represents only an estimation of the worker's exposure to noise at their workplace.

6.1. Summary of Experimental Measurements

Following the measurement of each of the filter and reagent samples in the laboratory, the minimum and maximum levels of each pollutant of interest have been determined for each of the sites. These measurements are provided within Tables 10, 11 and 12. Each of these tables represents the mean value of the three noise and PM_{10} concentration measurement stations that were established at each site.

6. Results and Analysis

Table 10. Consolidated results: full summary with minimum and maximum values for all sites against NAAQS limits

Site	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	SO_2 (µg/m³)	NO_2 (µg/m³)	CO (mg/m³)	Noise dB(A)	Status
Site S1 - Jayanagar (30×40 ft, 167 m²)							
Min. Value	88.15	47.94	9.80	14.76	0.57	70.30	—
Max. Value	129.97	52.16	12.28	15.67	0.68	78.27	EXCEEDS
NAAQS Limit	100.00	60.00	80.00	80.00	2.00	75.00	—
Site S2 - Indiranagar (60×40 ft, 372 m²)							
Min. Value	96.29	48.51	11.89	16.59	0.74	70.30	—
Max. Value	126.64	53.34	13.65	19.23	0.96	77.30	EXCEEDS
NAAQS Limit	100.00	60.00	80.00	80.00	2.00	75.00	—
Site S3 - Basavanagudi (100×120 ft, 1,672 m²)							
Min. Value	88.53	47.59	13.52	15.65	0.57	69.97	—
Max. Value	93.90	49.48	16.93	17.73	0.69	76.80	EXCEEDS*
NAAQS Limit	100.00	60.00	80.00	80.00	2.00	75.00	—
Site S4 - ENGG COLLEGE Hostel (50×150 ft, 1,394 m²)							
Min. Value	88.87	49.24	14.45	12.15	0.79	71.93	—
Max. Value	97.77	54.76	17.22	15.26	0.85	73.53	Within
NAAQS Limit	100.00	60.00	80.00	80.00	2.00	75.00	—

Note: The "Status" column refers to compliance considered across all six monitored parameters simultaneously. * At Site S3 the exceedance is in noise only (76.80 dB(A) against the 75 dB(A) daytime residential limit); every measured concentration at that site, including PM_{10}, remained within the applicable NAAQS value.

Table 11. Minimum measured concentrations at all four sites (Corresponding to pre- and post-demolition phases)

Site	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	SO_2 (µg/m³)	NO_2 (µg/m³)	CO (mg/m³)	Noise dB(A)
S1 — Jayanagar	88.15	47.94	9.80	14.76	0.57	70.30
S2 — Indiranagar	96.29	48.51	11.89	16.59	0.74	70.30
S3 — Basavanagudi	88.53	47.59	13.52	15.65	0.57	69.97
S4 — ENGG COLLEGE Hostel	88.87	49.24	14.45	12.15	0.79	71.93
NAAQS Limit	**100.00**	**60.00**	**80.00**	**80.00**	**2.00**	**75.00**

Table 12. Maximum measured concentrations at all four sites (corresponding to active demolition phase peak days)

Site	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	SO_2 (µg/m³)	NO_2 (µg/m³)	CO (mg/m³)	Noise dB(A)
S1 — Jayanagar	129.97	52.16	12.28	15.67	0.68	78.27
S2 — Indiranagar	126.64	53.34	13.65	19.23	0.96	77.30
S3 — Basavanagudi	93.90	49.48	16.93	17.73	0.69	76.80
S4 — ENGG COLLEGE Hostel	97.77	54.76	17.22	15.26	0.85	73.53
NAAQS Limit	**100.00**	**60.00**	**80.00**	**80.00**	**2.00**	**75.00**

6.2. Particulate Matter (PM_{10}) Analysis

PM_{10} was the parameter of greatest regulatory concern regarding the two groups of sites. The differing behaviour of the smaller versus the larger sites is immediately apparent from the data.

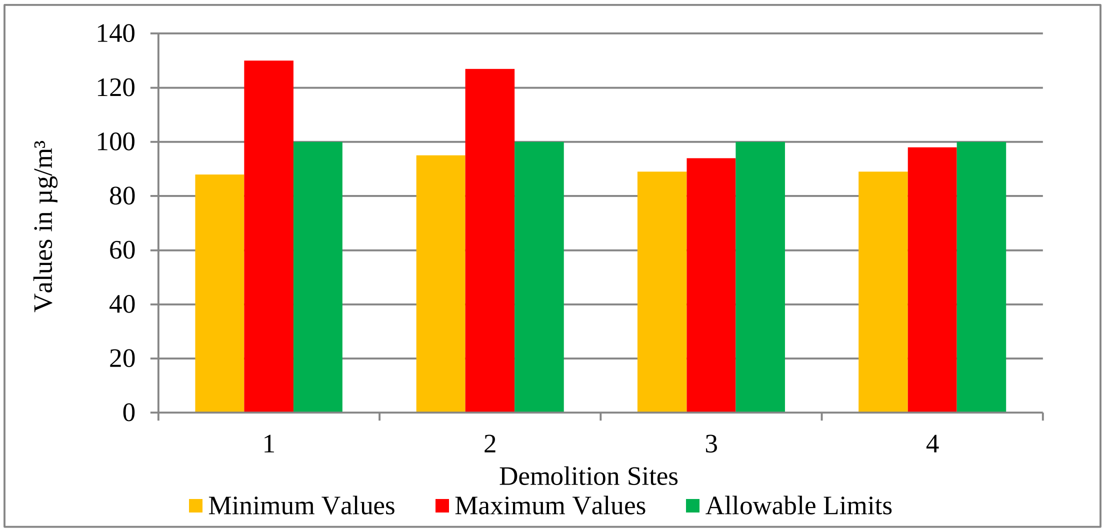

Fig. 7 PM_{10} concentrations at all four demolition sites across the three monitoring phases, compared against the NAAQS limit of 100 µg/m³

Figure 7 and Table 12 together present the PM_{10} behaviour of the four urban demolition sites across the three monitoring phases. Site S1 (30×40 ft; 167 m² demolished built-up floor area) recorded a peak PM_{10} concentration of 129.97 µg/m³, which exceeds the NAAQS 24-h residential limit of 100 µg/m³ by 29.97%. Site S2 (60×40 ft; 372 m²) recorded a peak of 126.64 µg/m³, an exceedance of 26.64%. In both cases, the exceedance was confined to the active demolition phase: the corresponding pre- and post-demolition minima were 88.15 and 96.29 µg/m³, respectively (Table 11), both within the limit. The elevated active-phase levels at these two smaller sites are attributed to their restricted plan area and to the surrounding masonry buildings on three sides, which suppress lateral ventilation and restrict the exchange of plot air with the ambient urban air mass, particularly below the height of the adjoining structures (≥ 7.62 m).

At Site S3 (100×120 ft, 1,672 m²) and Site S4 (50×150 ft, 1,394 m²), however, the maximum measurements of PM_{10} were 93.90 and 97.77 µg/m³, respectively. Each of these areas is significantly larger than the other two sites, which contributes to the lower PM_{10} concentrations. The larger area of these sites allows for the PM_{10} particles to be more easily dispersed throughout the area, limiting their accumulation to the surrounding monitoring stations. Thus, this finding about the difference in PM_{10} concentrations based upon area is another of the key findings of this project.

6.3. Fine Particulate Matter ($PM_{2.5}$) Analysis

Figure 8 presents the $PM_{2.5}$ concentrations measured at the four demolition sites across the three monitoring phases, plotted against the NAAQS 24-h residential standard of 60 µg/m³. In contrast to PM_{10}, the fine fraction remained below the standard at every site and in every phase. The highest value recorded anywhere in the campaign was 54.76 µg/m³ at Site S4, followed by 53.34 µg/m³ at Site S2, 52.16 µg/m³ at Site S1 and 49.48 µg/m³ at Site S3 (Table 12); the corresponding pre- and post-demolition minima lay within the narrow band 47.59-49.24 µg/m³ (Table 11). The maximum observed value, therefore, represents 91.3% of the permissible limit, and no site crossed it.

The active-phase enrichment of $PM_{2.5}$ was correspondingly modest. Expressed as the ratio of the site maximum to the site minimum, the enrichment was 1.09 at Site S1, 1.10 at Site S2, 1.04 at Site S3 and 1.11 at Site S4, against ratios of 1.47 and 1.32 for PM_{10} at Sites S1 and S2. This divergence is consistent with the physics of the emission process. Mechanical breaking of stone rubble foundations, brick masonry, cement-mortar plaster and reinforced concrete slabs produces predominantly coarse abrasion fragments that report to the PM_{10} fraction, whereas the sub-2.5 µm fraction is dominated by combustion aerosol that the demolition works did not materially augment. The weak dependence of $PM_{2.5}$ on site geometry reinforces this interpretation: Site S4, the second-largest site by demolished built-up floor area, recorded the highest $PM_{2.5}$ maximum while recording the second-lowest PM_{10} maximum - an ordering that cannot be explained by a site-generated coarse source and points instead to a regional urban background origin for the fine fraction.

Compliance with the Indian standard should not, however, be read as an absence of health risk. All four sites recorded active-phase $PM_{2.5}$ maxima between 49.48 and 54.76 µg/m³, that is, approximately twice the WHO 24-h guideline value of 25 µg/m³ [1]. Personnel engaged in breaking and debris handling without respiratory protective equipment are therefore exposed, for the full 9-h shift, to fine-particulate concentrations well above the health-based guideline, even where the regulatory limit is formally satisfied. For this reason, $PM_{2.5}$ was retained in the Composite Pollution Index (Sections 5.1 and 6.6) with a weight of 0.15, notwithstanding its formal compliance.

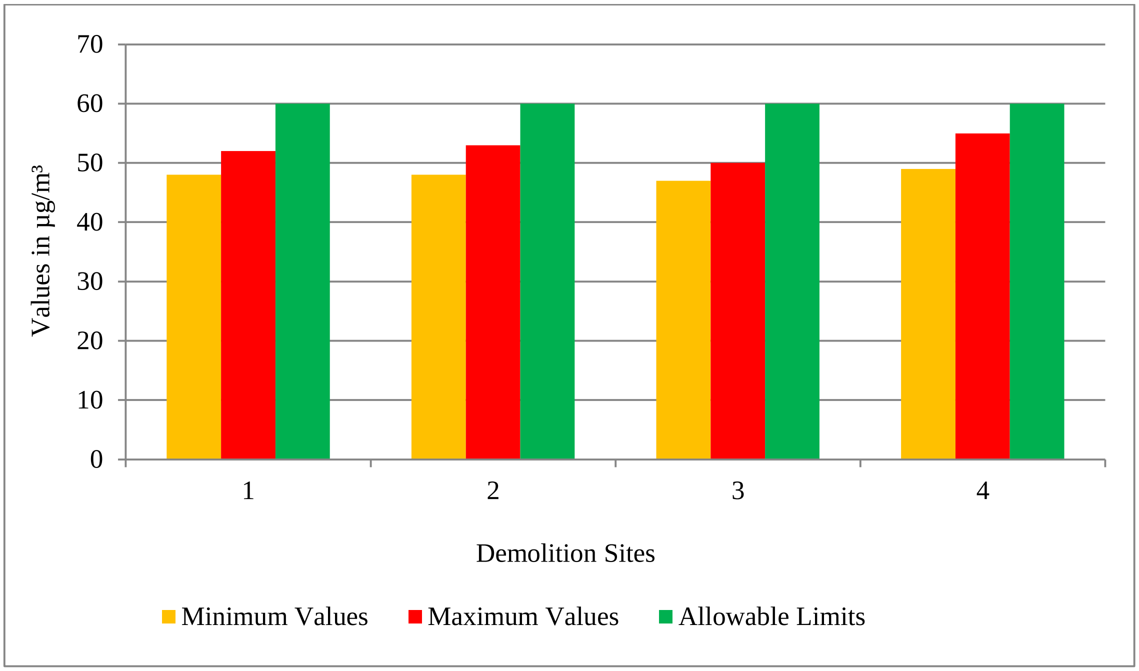

Fig. 8 $PM_{2.5}$ concentrations at all four demolition sites, compared against the NAAQS limit of 60 µg/m³

6.4. Gaseous Pollutant Analysis (SO_2, NO_2, CO)

The three gaseous pollutants monitored in this study - sulphur dioxide, nitrogen dioxide and carbon monoxide - are presented in Figures 9, 10 and 11, respectively, each plotted for all four sites across the three monitoring phases against the applicable NAAQS residential limit. The site-wise minima and maxima on which these figures are based are those reported in Tables 11 and 12.

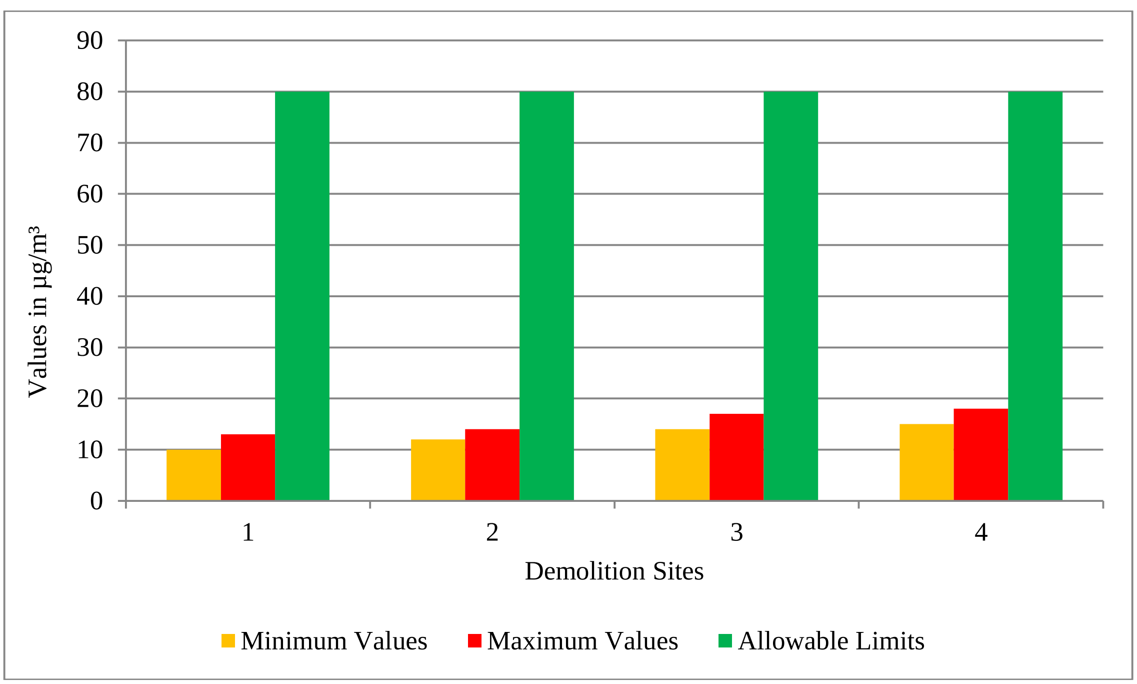

Fig. 9 SO_2 concentrations at all four demolition sites compared against the NAAQS limit of 80 µg/m³

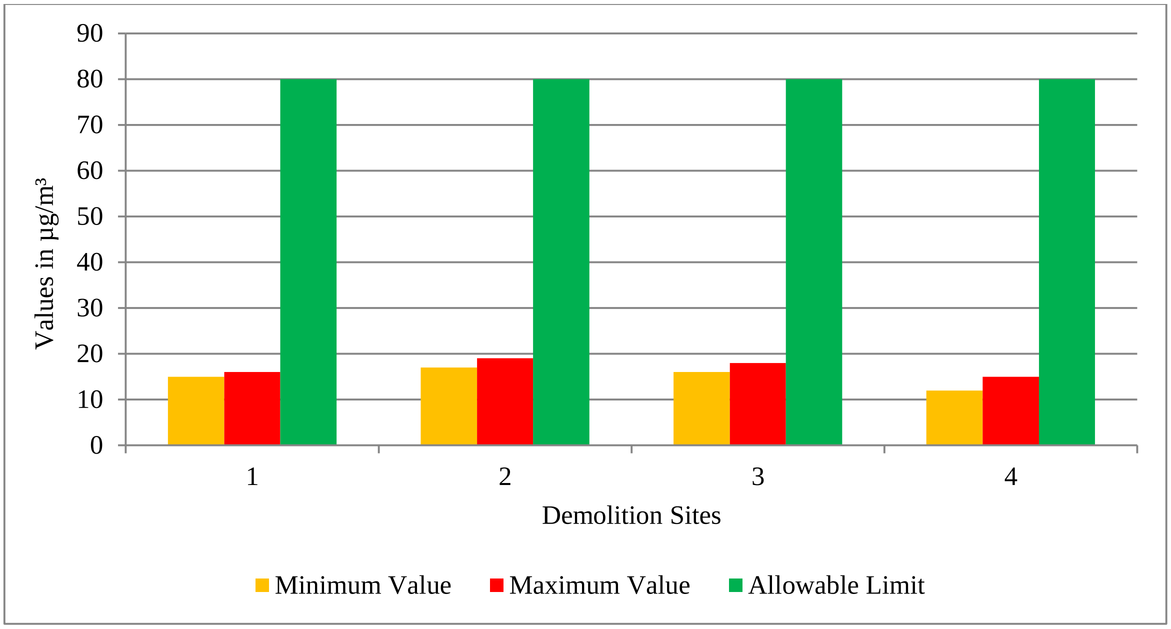

Fig. 10 NO_2 concentrations at all four demolition sites compared against the NAAQS limit of 80 µg/m³

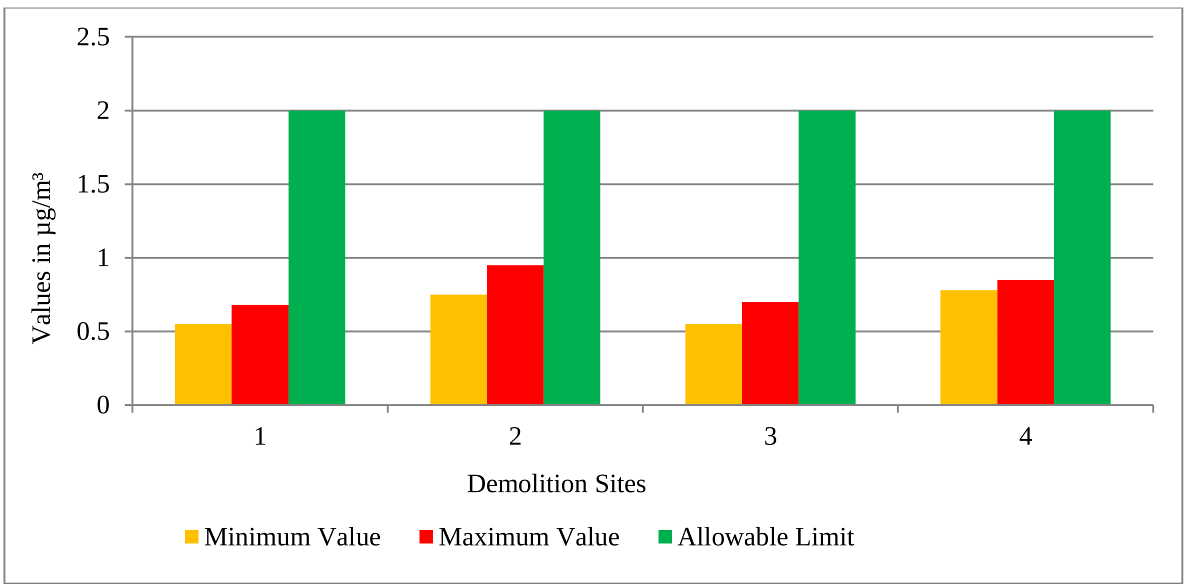

Fig. 11 CO concentrations at all four demolition sites compared against the NAAQS limit of 2.00 mg/m³

Figure 9 shows that SO_2 remained approximately an order of magnitude below the NAAQS 24-h residential limit of 80 µg/m³ at every site and in every phase. Site minima ranged from 9.80 µg/m³ (S1) to 14.45 µg/m³ (S4) and site maxima from 12.28 µg/m³ (S1) to 17.22 µg/m³ (S4); the highest value recorded anywhere in the campaign therefore represents only 21.5% of the permissible limit. The active-phase increment over the corresponding pre-demolition baseline lay between 1.8 and 3.4 µg/m³, which is of the same order as the day-to-day variability of the urban background. This is the outcome expected for the building stock investigated: stone rubble foundations, burnt-clay brick masonry, cement-mortar plaster and reinforced concrete contain no significant sulphur-bearing phases, and mechanical comminution of these materials liberates no gaseous sulphur. The residual SO_2 signal is accordingly attributed to the ambient urban and vehicular background rather than to the demolition works.

The NO_2 profile in Figure 10 follows a comparable pattern. Concentrations ranged from a minimum of 12.15 µg/m³ at Site S4 to a maximum of 19.23 µg/m³ at Site S2, the latter representing 24.0% of the 80 µg/m³ limit. Site S2 returned the highest NO_2 concentrations of the campaign, which is consistent with its position on a narrow access road carrying continuous local traffic and with the operation of diesel excavators and tipper trucks within the plot during debris removal. Site S4, located inside a college campus with restricted vehicular access, returned the lowest NO_2 maximum (15.26 µg/m³) despite having the second-largest demolished built-up floor area. The site ranking for NO_2 therefore follows traffic exposure rather than demolition intensity, identifying vehicular combustion — not the breaking of the building fabric — as the controlling source.

Carbon monoxide, shown in Figure 11, was likewise comfortably within the NAAQS 8-h limit of 2.00 mg/m³. The measured range across all sites was 0.57–0.96 mg/m³, the maximum occurring at Site S2 and corresponding to 48.0% of the permissible limit. Of the three gases, CO exhibited the largest proportional active-phase increase, reaching 1.30 times the pre-demolition baseline at Site S2, which reflects the intermittent operation of diesel excavators, breakers and haulage vehicles at the plot perimeter. Because CO is emitted almost entirely by the plant rather than by the fabric being demolished, its concentration tracked machinery deployment rather than demolished floor area, and it returned to baseline values during the post-demolition phase at all four sites.

Taken together, Figures 9-11 establish that none of the three gaseous pollutants approached its regulatory threshold at any site or in any phase, the highest observed fractions of the applicable limits being 21.5% for SO_2, 24.0% for NO_2 and 48.0% for CO. Equally important, no systematic dependence on demolished built-up floor area was observed for any of the three gases, in direct contrast to the strong inverse area dependence demonstrated for PM_{10} in Section 6.2. This dissociation is mechanistically informative: it indicates that the gaseous burden at low-rise residential demolition sites originates from the combustion plant and the surrounding traffic environment, whereas the particulate burden originates from mechanical comminution of the building fabric itself. Consequently, the three gases together carry only 0.15 of the total weight in the Composite Pollution Index formulated in Section 5.1 and applied in Section 6.6, and their combined contribution to the active-phase CPI did not exceed 0.046 index units at any site.

6.5. Noise Level Analysis

Figure 12 presents the noise levels recorded at the four sites across the three monitoring phases; noise was the second parameter of regulatory concern after PM_{10}. Maximum noise levels of 78.27, 77.30, and 76.80 dB(A) were measured at Sites S1, S2, and S3 during active demolition works at percentages of 4.4%, 3.1%, and 2.4% above the 75 dB(A) limit for residential areas, respectively. Site S4, however, recorded the lowest maximum value of 73.53 dB(A) - within the residential limit - due to its larger construction site footprint and thus greater distance between the sound source and the monitoring noise stations. These exceedances at Sites S1 to S3 resulted from the extensive use of pneumatic breakers and excavators close to the perimeter monitoring stations, and the reflective properties of the surrounding masonry construction site walls. Applying the screening dose model of Section 5.4 to the worst case, Site S1 at 78.27 dB(A), gives an allowable exposure duration of 40.67 h and a corresponding 9-h noise dose of 22.13%, which lies below the 50% action level. This screening value is derived from fixed-point perimeter measurements and therefore characterises the boundary environment rather than personal exposure; operators working immediately adjacent to pneumatic breakers will accumulate a materially higher dose, and personal dosimetry is recommended before hearing conservation requirements are set aside.

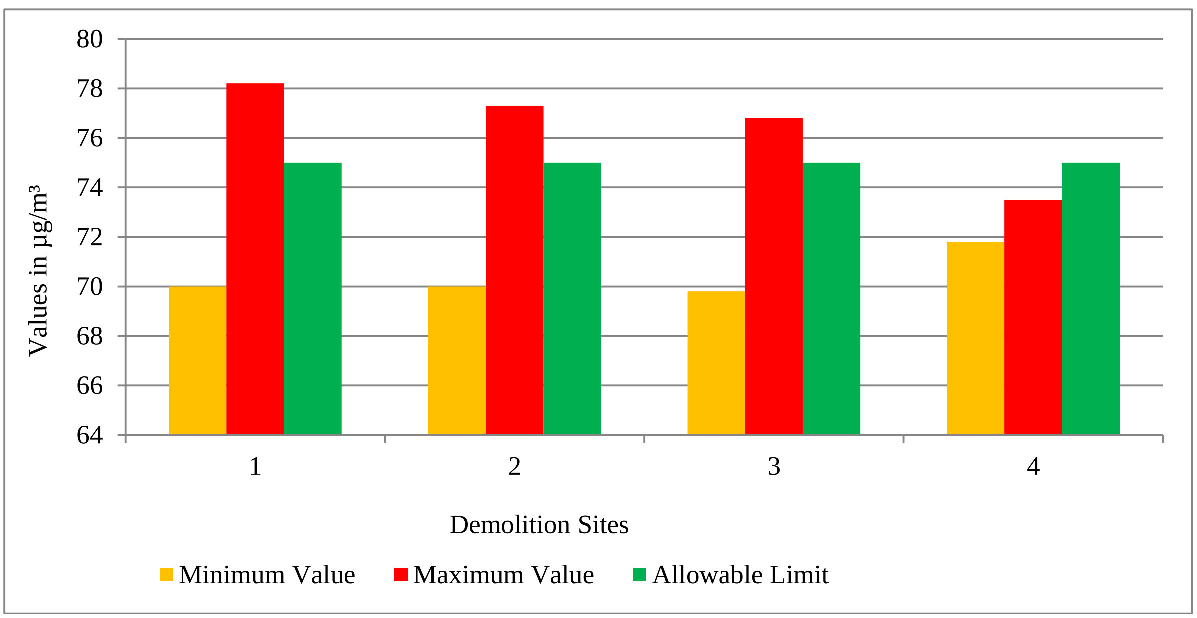

Fig. 12 Noise levels at all four demolition sites compared against the CPCB daytime residential limit of 75 dB(A)

6.6. Exploratory CPI-Based Site-Area Threshold Estimation

The Composite Pollution Index defined in Section 5.1 was evaluated for every site and every monitoring phase so that the six monitored parameters could be condensed into a single screening descriptor. The index is obtained as the weighted sum of the ratio of each measured concentration to its applicable screening standard:

$$CPI_{s,p} = \sum_{i=1}^{k} w_i \left(\frac{C_{i,s,p}}{S_i}\right), \qquad \sum_{i=1}^{k} w_i = 1$$

where Ci is the measured concentration of parameter i, Si is the corresponding screening standard, wi is the assigned weight and Σwi = 1. Because the index is a weighted ratio-to-standard construct, CPI = 1.00 corresponds to a site that, taken across all six parameters simultaneously, sits exactly on the aggregate compliance boundary. The index is intended for comparative screening between sites and phases and does not replace parameter-by-parameter compliance assessment.

The weighting scheme adopted is summarised in Table 13. The weights were assigned according to the expert judgement of the relative importance of each parameter. PM_{10} has the highest weight as it is the main pollutant that is close to or at its adopted standard. The second highest weight is given to noise due to the relation of noise to demolition machinery. $PM_{2.5}$ has the third-highest weight due to its relationship to health, while the other pollutants have lower weights due to the fact that their levels are well below the standards for these pollutants.

Table 13. Pollutant standards and weights used in the CPI calculation

Parameter	Screening standard	Weight w_i	Basis for weighting
PM_{10}	100 µg/m³	0.47	Dominant demolition-related pollutants and principal observed exceedance
$PM_{2.5}$	60 µg/m³	0.15	Health-relevant fine particulate fraction, although below the adopted standard
SO_2	80 µg/m³	0.04	Low measured contribution and no observed exceedance
NO_2	80 µg/m³	0.06	Possible combustion and traffic indicators, but substantially below the standard
CO	2.00 mg/m³	0.05	Machinery and traffic indicators with concentrations below the standard
Noise	75 dB(A)	0.23	Secondary parameter of concern associated with machinery intensity
Total	-	1.000	-

Active-demolition Composite Pollution Index (CPI) for Site S2 was calculated as follows:

$$CPI_{S2,\ active} = 0.47(126.64/100) + 0.15(53.34/60) + 0.04(13.65/80) + 0.06(19.23/80) + 0.05(0.96/2.00) + 0.23(77.30/75)$$

$$CPI_{S2,\ active} = 0.5952 + 0.1334 + 0.0068 + 0.0144 + 0.0240 + 0.2371 = 1.0109 \approx 1.011$$

Thus, the active-demolition CPI for Site S2 was 1.011, which lies at the lower end of the high screening category ($1.00 < CPI \leq 1.30$).

Table 14. Site- and phase-specific CPI values

Site	built-up floor area	Pre-demolition CPI*	Active-demolition CPI	Post-demolition CPI*	Active risk category
S1	167 m²	0.780	1.016	0.780	High
S2	372 m²	0.826	1.011	0.826	High
S3	1,672 m²	0.782	0.840	0.782	Moderate
S4	1,394 m²	0.797	0.863	0.797	Moderate

The values of S1 and S2 indicate that they entered into the high screening category during active demolition, whereas S3 and S4 remained in the moderate level. This relates to the information regarding the PM_{10} values at each of these two smaller sites versus the larger sites. At the two smaller sites, the PM_{10} values began to exceed the allowable levels, whereas the two larger sites had lower PM_{10} values during the active demolition phase.

The relationship between the size of demolition sites and the active-demolition CPI was examined through linear interpolation. Because the areas of 167, 372, 1,394 and 1,672 m² represent the total areas of the built-up floors within each site, rather than the plot area of those sites, interpolation was performed using the concept of demolished built-up floor area. The sites, ordered according to increasing area of demolished built-up floors, were S1, S2, S4 and S3.

The nearest observations bracketing the $CPI^* = 1.00$ transition were S2:

$$A_1 = 372\ m^2, \qquad CPI_1 = 1.01086$$

and S4:

$$A_2 = 1394\ m^2, \qquad CPI_2 = 0.86322$$

The interpolated transition area was calculated using:

$$A^* = A_1 + \frac{CPI^* - CPI_1}{CPI_2 - CPI_1}(A_2 - A_1)$$

Substitution gives:

$$A^* = 372 + \frac{1.000 - 1.01086}{0.86322 - 1.01086}(1394 - 372)$$

$$A^* = 372 + \frac{-0.01086}{-0.14764}(1022)\ A^* = 447.2\ m^2$$

The active-demolition CPI parameter indicates that Sites S1 and S2 are marginally above the CPI=1.00 screening transition, whereas Sites S3 and S4 are below this value. Using linear interpolation between these Sites allows for the estimation of the built-up-area transition value to be approximately 447-454 m². Thus, an exploratory screening transition estimate of approximately 450 m² is made for these data. This value is not to be understood as a regulatory or inherent limit to the area of demolition sites, however, due to the limited number of data points (only four sites) used to determine such a limit, and due to the dependence of the limit upon the various weights of the pollutant, the method of aggregation of the pollutant concentrations, the statistical measure of those concentrations, and the definition of the area of the sites being evaluated.

Accordingly, the interpolated built-up-area transition was approximately 447 m², which may be rounded to approximately 450 m² for screening purposes.

7. Machine Learning Model Development

7.1. Problem Formulation and Data Preparation

The dataset that was collected during these demolition works consisted of six different parameters that were simultaneously measured at each monitoring station. These parameters were PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, and Noise levels. The campaign yielded 1,296 observations in total (four demolition sites × twelve monitoring days × three monitoring stations × nine hourly readings per day). The goal of the machine learning application that would be developed used this data was to develop a model that could accurately predict PM_{10} concentrations (measured in µg/m³) from seven predictors: the remaining five simultaneously measured air-quality parameters ($PM_{2.5}$, SO_2, NO_2, CO and noise level) and two additional site attributes: the area of the demolition site in plan view (measured in m²), and the current phase of demolition (with three phases: pre-demolition, active demolition, and post-demolition).

The data was preprocessed by normalising each of the air quality parameters using the min-max transformation to the range [0, 1]. There were no missing values in the dataset. Two outlier samples were removed using the Isolation Forest outlier detection algorithm with contamination parameter set to 0.01. The samples were randomly partitioned into training (70% of the total samples), validation (15% of the total samples), and test (15% of the total samples) partitions to enable training, tuning, and evaluating the performance of the developed machine learning model.

7.2. ANN Model Architecture and Training

The architecture of the artificial neural network was determined empirically through grid search and cross-validation. The parameter settings of the artificial neural network that were found to optimise the model performance are given in Table 15.

Table 15. Optimised artificial neural network architecture

Layer	Type / Configuration	Neurons / Units	Activation	Output Dim.
L-0 (Input)	Input Layer	7 ($PM_{2.5}$, SO_2, NO_2, CO, Noise, Site Plan Area, Demolition Phase)	-	7
L-1	Dense Hidden Layer 1	64	ReLU	64
L-2	Batch Normalisation	-	-	64
L-3	Dropout (rate=0.2)	-	-	64
L-4	Dense Hidden Layer 2	128	ReLU	128

L-5	Batch Normalisation	-	-	128
L-6	Dropout (rate=0.2)	-	-	128
L-7	Dense Hidden Layer 3	64	ReLU	64
L-8 (Output)	Output Layer	1 (PM_{10} Prediction / Pollution Index)	Linear	1

The network was implemented in Python (TensorFlow 2.x / Keras backend). The Adam optimiser was used during training with a learning rate α of 0.0008 and default β_1 and β_2 parameters. The loss function used during training was the Mean Squared Error (MSE).

The model was trained using early stopping with a patience parameter of 25 epochs based on the validation loss. Batch normalisation and dropout regularisation (rate = 0.20) were applied to the network to assist in the training process and reduce the risk of overfitting. The model reached its minimum validation loss after around 287 epochs during training.

According to the universal approximation theorem [14], if a feedforward neural network has a sufficient number of neurons within its hidden layer, it can learn or approximate any continuous function to a desired level of accuracy. The network that was built contains three hidden layers with 64, 128 and 64 neurons, respectively. Each layer learns different aspects of the input variables. The first layer of the network learns the linear relationships between the variables. The second layer of the network learns more complex interactions between the variables. The third layer of the network learns a compressed form of information passed to it from the second layer.

7.3. Performance Evaluation and Model Comparison

The performance of the ANN model will be evaluated using the coefficient of determination (R^2), the Root Mean Squared Error (RMSE), the Mean Absolute Error (MAE), and the Mean Absolute Percentage Error (MAPE). These statistics will provide a view of the model's performance in terms of its linearity and the magnitude of its errors. For comparison with the ANN model, four different models will be utilized: XGBoost, Random Forest, Support Vector Regression (SVR), and Multiple Linear Regression (MLR).

Table 16. Comparative performance of Machine Learning models for PM_{10} prediction

Model	R^2 (Train)	R^2 (Test)	RMSE	MAE	MAPE (%)
ANN (Proposed)	0.981	0.964	4.38	3.21	3.84
XGBoost	0.974	0.951	5.12	3.89	4.31
Random Forest	0.963	0.942	5.87	4.22	4.97
Support Vector Regression	0.912	0.897	8.64	6.41	7.25
Multiple Linear Regression	0.876	0.851	11.23	8.72	9.88

Considering the model performance metrics reported in Table 16, the ANN model attained the highest coefficient of determination on the held-out test partition (R^2 = 0.964), followed by XGBoost (R^2 = 0.951), Random Forest (R^2 = 0.942), Support Vector Regression (R^2 = 0.897) and Multiple Linear Regression (R^2 = 0.851). The margin between the ANN and XGBoost (ΔR^2 = 0.013, ΔRMSE = 0.74 $\mu g/m^3$) is modest, indicating that gradient-boosted trees remain a competitive alternative on a dataset of this size; the substantially poorer performance of Multiple Linear Regression (ΔR^2 = 0.113 relative to the ANN) confirms that the relationship between the predictors and PM_{10} is materially non-linear and justifies the use of a non-linear learner.The differences between the R^2 scores obtained during training and testing (ΔR^2 = 0.017 for the ANN, ΔR^2 = 0.023 for XGBoost) indicate that the models were able to generalise well to the test partition of the data without overfitting to the training data. The use of regularisation techniques helped to achieve these results for both the ANN and XGBoost models (Dropout and Batch Normalisation were used for the ANN, and the max_depth and minimum_samples parameters were adjusted for XGBoost and Random Forest models).

7.4. SHAP-Based Sensitivity Analysis and Feature Importance

The SHapley Additive exPlanations (SHAP) algorithm was used to calculate the feature importance within the trained Artificial Neural Network model for the test data partition. The importance of each of the model features was calculated using the DeepExplainer algorithm for the ANN model. SHAP calculations are a method of game theory that calculates the importance of each of the model variables for each individual prediction by the model and ensures that the importance values satisfy a set of axioms regarding the linearity, additivity, and symmetry of the model [13].

Table 17. SHAP-based feature importance ranking and physical interpretation

Rank	Input Feature	Mean |SHAP| Value	Relative Importance (%)	Physical Interpretation
1	Site Plan Area (m^2)	18.74	28.3	Larger open volume dilutes suspended particulate matter.
2	Demolition Phase (Stage)	16.23	24.5	Peak PM_{10} generation is confined to active demolition days.
3	Noise Level dB(A)	11.58	17.5	Correlated with heavy machinery deployment intensity
4	$PM_{2.5}$ Concentration	8.41	12.7	Fine fraction sub-component of coarser PM_{10}
5	NO_2 Concentration	5.32	8.0	Combustion-linked marker of vehicular proximity effects
6	CO Concentration	3.96	6.0	Background traffic indicator, secondary influence
7	SO_2 Concentration	2.07	3.1	Near-ambient; marginal contribution to PM_{10} variation

Site plan area emerged as the most influential predictor, with a mean |SHAP| value of 18.74 μg/m³ accounting for 28.3% of the total attributed model output. The demolition-phase indicator ranked second (mean |SHAP| = 16.23 μg/m³; 24.5%) and the measured noise level third (mean |SHAP| = 11.58 μg/m³; 17.5%). These three features together account for 70.3% of the total feature attribution, and each corresponds directly to a mechanism identified independently in the experimental analysis of Sections 6.2 and 6.5.

The SHAP values for small site areas are positive, indicating that smaller areas within a demolition site contribute to higher levels of PM_{10}. Furthermore, the active demolition phase indicator has a strong positive SHAP value, indicating the relationship between the demolition phases and PM_{10} levels - all maximum PM_{10} levels were recorded during the active demolition phase. Finally, the positive SHAP value for noise levels is moderate in strength, but still positive and indicates the relationship between the mechanical energy released during demolition activities and the amount of PM_{10} emissions from those areas.

7.5. Predicted vs. Observed PM10 Analysis

The distribution of the predicted PM_{10} levels from the ANN model distributed relative to the measured PM_{10} levels within the test site demonstrates the high accuracy of the model. The model predictions fall within the 95% prediction interval for all but three of the 194 observations of the demolition sites. Furthermore, the model's MAPE of 3.84% indicates the small difference between the predicted and observed PM_{10} levels at the demolition sites. The errors of the predictions are normally distributed around the mean with a Shapiro-Wilk test statistic of W = 0.982 and a p-value of 0.31. Additionally, the model predictions contain homoscedasticity in the prediction errors with a prediction interval that is consistent across all levels of PM_{10} concentrations from the pre-demolition levels of approximately 88 μg/m³ to the peak levels of approximately 130 μg/m³.

Within the regulatorily critical region in which PM_{10} exceeds 100 μg/m³, the model returned a MAPE of 2.9%, marginally better than its overall test-set MAPE of 3.84%. Predictive accuracy is therefore not degraded in the concentration range that governs compliance decisions, which is the operationally relevant requirement for a screening tool.

8. Discussion

PM_{10} was found to be the dominant environmental hazard caused by demolition sites in Bengaluru. The fact that the two smallest sites (S1: 167 m², S2: 372 m²) were found to have the PM_{10} concentrations that exceeded the NAAQS limit by 30% and 27% respectively, while the two larger sites remained within the allowed limit, suggests that 450 m² through linear interpolation of the values of the CPI for the four sites may represent a threshold area below which PM_{10} suppression control measures are to be mandatory at these demolition sites. Additionally, the negative SHAP contribution values for large values of site plan area and the positive SHAP contribution values for small values of site plan area suggest confirmation of this threshold finding from the ANN model itself.

The $PM_{2.5}$ levels at the demolition sites were within the NAAQS limit of 60 μg/m³ of $PM_{2.5}$, yet maxima as high as 54.76 μg/m³ are still considerable if considered in the context of the WHO guidelines of 25 μg/m³ of $PM_{2.5}$ over a 24-hour period [1]. Any workers that were performing demolition work without the use of RPE at these sites were, therefore, exposed to $PM_{2.5}$ levels more than twice the WHO-recommended guideline value for $PM_{2.5}$ exposure over the course of a working day. Noise levels at Sites S1, S2 and S3 exceeded the 75 dB(A) daytime residential limit by 4.4%, 3.1% and 2.4% respectively, and did so throughout the 9-h working day rather than as isolated peaks. Applying the OSHA screening dose model of Section 5.4 to the worst case (Site S1, 78.27 dB(A)) yields an allowable exposure duration of 40.67 h and a 9-h noise dose of 22.13%, which lies below the 50% action level; the perimeter measurements therefore do not by themselves trigger a mandatory hearing conservation programme. This result must nevertheless be treated as a lower bound, because the sound level meters were positioned at the plot boundary rather than at the operator position. Personnel operating pneumatic breakers and excavators work several metres closer to the source and will accumulate a substantially higher dose, so personal dosimetry at the operator position is recommended for sites of the S1–S3 class. Site S4 remained within the residential limit at 73.53 dB(A) and below the action level on both counts.

SO_2, NO_2 and CO levels were found to be within the same levels as the background air pollution levels at the Bengaluru sites. Because these levels are negligible at the demolition sites, measurements of these gases can be deprioritised in future demolition site monitoring programs. The same conclusions cannot, however, be made of any demolition sites that feature construction materials that contain sulphur (like gypsum-based particle board), nitrogen (like nitrogen-rich insulation materials) or that contain petroleum-based construction materials.

Finally, the trained ANN model allows for the prediction of PM_{10} levels at any demolition site with less than 5% error using information about the area of the site plan, the phase of demolition to be performed and the levels of other pollutants in the air at the site. Thus, this model can assist in the decision of whether or not control measures for PM_{10} should be performed at any site prior to the commencement of demolition at that site.

The study has some limitations. For instance, the dataset was obtained only from four demolition sites in one Indian city and hence represents only residential demolitions under Bengaluru conditions. Furthermore, the demolished buildings were all low-rise, so the results cannot be directly applied to high-rise, industrial, bridge, or implosion-based demolitions. The weather and traffic conditions at the demolition sites were not measured because the study aimed solely to evaluate the impact of demolitions on ambient air quality. Finally, although the artificial neural network was trained with the field dataset, additional training with data from other demolition sites would be required before the model could be used in regulatory environments.

The implementation of this framework in resource-limited environments may encounter certain challenges. For instance, the cost of the instruments necessary to measure PM_{10}, $PM_{2.5}$, and noise may be high in such environments. Furthermore, trained personnel may be required to operate these instruments. The availability of space to install these instruments around the plots to be demolished may also be an issue. Additionally, water may be required for demolition sites to suppress the PM_{10} and $PM_{2.5}$ concentrations created during the demolition process, so water availability may also pose a challenge to the framework's implementation in resource-limited environments. The monitoring of only PM_{10}, $PM_{2.5}$, and noise can be performed at demolition sites to provide cost and time savings; gaseous pollutants would only need to be monitored at those sites if there are construction or demolition vehicles at those locations or if there are gaseous byproducts created during the demolition process.

The framework could potentially be implemented in other urban areas of the world with the recalibration of certain parameters to those locations. For instance, the weights associated with $PM_{2.5}$, gaseous pollutants, or noise may need to be recalibrated for other urban areas if those pollutants are of more concern than PM_{10} at those locations. The artificial neural network would also need to be retrained or externally validated in other Indian cities with different meteorology, street design, building materials, demolition methods, and traffic conditions. Thus, this framework can be used as a tool to assist city planners and environmental engineers in making decisions regarding demolition projects based on the potential impact of those demolitions on ambient air quality.

The fact that S4 was monitored over a longer period and during different months than the other sites introduces the potential for confounding variables into the analysis of that site. Because S4 was monitored between April and August 2018, while the other sites were monitored during 2017, factors like seasonal weather, traffic, or even demolition practices at the site during the demolition of its buildings could contribute to the differences in those results. Thus, the relationship between area and CPI that was established for S4 should be considered exploratory rather than definitive.

9. Conclusion

Based on the research conducted on Bengaluru's residential demolition sites, the following conclusions were drawn:

- PM_{10} is the only parameter that was found to be exceeding the permissible limits laid out by the NAAQS. Furthermore, the parameter was only beyond the limits at the two smallest sites (167 m² and 372 m²), and even then, only during the demolition phase of each site's demolition process. PM_{10} levels were within the permissible limits at the pre-demolition and post-demolition phases at each site.
- $PM_{2.5}$ concentrations at each site were below the permissible limit of 60 µg/m³ of $PM_{2.5}$ throughout all sites. However, the highest reading reached 54.76 µg/m³ at Site S4, which is more than twice the WHO 24-h guideline value of 25 µg/m³ [1].

- Through linear interpolation of the active-demolition CPI values reported in Section 6.6, the built-up area in square meters associated with the CPI weighting scheme is approximately 450 m². Any demolition projects with a built-up area below this approximate value may warrant additional consideration in their pre-demolition assessments. However, such an estimation is preliminary and should be validated with additional data points from demolition projects of various sizes.
- The gaseous pollutants (SO_2, NO_2, and CO) at each site were within the normal limits for those gases, indicating that the demolition process for these residential buildings is not a major contributor to gaseous pollution.
- Noise exceeded the 75 dB(A) daytime residential limit at three of the four sites (S1, S2 and S3) by 2.4–4.4%, while Site S4 remained compliant at 73.53 dB(A). The corresponding perimeter noise dose at the worst-affected site (S1) was 22.13% under the OSHA screening model, that is, below the 50% action level. Because this value derives from boundary rather than operator-position measurements, personal dosimetry and hearing protection for breaker operators remain advisable.
- The Composite Pollution Index for S1 and S2 during the active demolition phase of each site indicates that these sites were within the High-Risk category for environmental pollutants.
- The Artificial Neural Network model produced an R2 value of 0.964, RMSE of 4.38 µg/m³, and MAPE of 3.84% for its model. These values were better than those of the XGBoost (R2 = 0.951), Random Forest (R2 = 0.942), Support Vector Regression (R2 = 0.897), and Multiple Linear Regression (R2 = 0.851) models.
- The SHAP analysis indicated that the two main predictors of PM_{10} levels at each site were the area of the site plan (28.3%) and the phase of demolition (24.5%), both of which relate to the findings of the research study regarding PM_{10}.

Overall, then, the information presented in this research study establishes the ability to create management plans for demolition sites in Bengaluru and other Indian cities. Furthermore, it provides a means of using ANN models to mitigate the environmental impact of those demolitions prior to their occurrence.

Declarations

- Data Availability: The data that support the findings of this study are available from the corresponding author upon reasonable request.
- Conflict of Interest: The authors declare that they have no conflict of interest.
- Site Permission: Permission to conduct the environmental monitoring at the sites was obtained from the site owners. No human or personal data were collected during the study.
- Funding: There was no funding for this project.

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