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Rainfall Intensity-Controlled Wet Scavenging of PM10 under Monsoon and Non-Monsoon Meteorological Regimes in Northern India

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Abstract - *In Agra, India, this study examines precipitation-driven wet scavenging of particulate matter (PM10) throughout the monsoon and non-monsoon seasons in 2021–2022. To test the effectiveness of rainfall-induced clearance, real-time PM10 concentrations were recorded prior to (BR), during (DR), and following (AR) rain events. Because of increased precipitation scavenging, the mean PM10 concentration was much lower during the monsoon season (48.86 µg m^{-3}) than it was during the non-monsoon season (196.41 µg m^{-3}). The Marshall–Palmer raindrop size distribution was used to determine the size-dependent scavenging coefficient (Λ, s^{-1}), which was then numerically integrated in Python. Rainfall intensity and scavenging rate showed strong positive associations ($R^2 > 0.99$), although wind speed had the greatest climatic influence ($R^2 = 0.93$). The findings show that hygroscopic development, wind-driven turbulence, and rainfall intensity all work together to control aerosol removal efficiency. The results offer region-specific parameterisation that is helpful for managing urban air quality and atmospheric modelling.*

Key Words**: Wet scavenging, PM10 concentration, Rain Intensity, Scavenging coefficient, Urban air pollution, Monsoon dynamics.**

1.INTRODUCTION

It is indisputable that pollution dispersing close to emission sources is influenced by climate conditions. The volume and variability of pollution are likely to be significantly influenced by meteorological conditions, which can affect both the concentration and dilution of pollutants [Seinfeld and Pandis 1998, van der Wal JT 2000]. One of the main processes influencing the volume reduction of solid particles is the deposition of solid particles.

When atmospheric aerosol particles impact and mix with raindrops, they are scavenged by both in-cloud and below-cloud processes [Connan O, Maro D, and Santachiara G, 2013]. In order to transmit pollutants from the air to the ground, scavenging is an essential action [Goncalves FF 2000]. It is consequently one of the most important processes to maintain a balance between the origins and outflow of aerosol particles [Chate DM et al 2003]. The term "wet below-cloud scavenging" describes any situation in which various forms of precipitation, such as rain, snow, fog, and ice, remove airborne particles. Because particles of different sizes and shapes are deposited and moved to the ground-level zone during this process, below-cloud scavenging seems to be more important from the standpoint of human health and the quality of the atmosphere (Bae SY et al. 2006). This claim is supported by the fact that below-cloud scavenging—where the main process is the collision of solid particles with raindrops—usually releases the PMs that pose an immediate risk to human health [Kim J-E, et al 2012].

The complicated process of wet aerosol scavenging is affected by a number of outside variables, including rainfall intensity, droplet size, particle size distribution, and the chemical makeup of the water. temperature of the surrounding environment, as well as the chemical and physical characteristics of aerosol and droplets, as well as the region where aerosol and droplets collide [Zhao H, et al. 2006]. The understanding of wet particle matter scavenging is currently at a stage where more insight is gradually being gained. When modelling long-distance air pollution transmission and chemical substance transfer, wet deposition approaches are essential. Below-cloud scavenging of aerosol particles is frequently described by the idea of collisions between raindrops and particulate matter [Chate DM et al 2003]. Higher rainfall intensities frequently improve PM_4^1 removal because more and larger raindrops provide more surface area for particle capture. According to research, scavenging ratios increase significantly with rainfall rate and PM_2^1 concentrations decrease rapidly during periods of heavy rainfall. However, moderate rainfall may not have much of an impact on PM_4^1 levels because of smaller droplet sizes and inadequate kinetic energy to efficiently scavenge coarse particles. The widely used Marshall–Palmer raindrop size distribution provides a theoretical basis for measuring the relationship between rainfall rate and drop concentration and diameter, allowing researchers to compute scavenging coefficients more precisely [Marshall, J. S., & Palmer, W. McK. 1948]. The current work offers season-specific parameterisation of PM_4^1 scavenging under differing monsoon and non-monsoon regimes in Northern India, supported by high-correlation statistical validation, in contrast to other studies that mainly concentrated on generalised wet deposition processes.

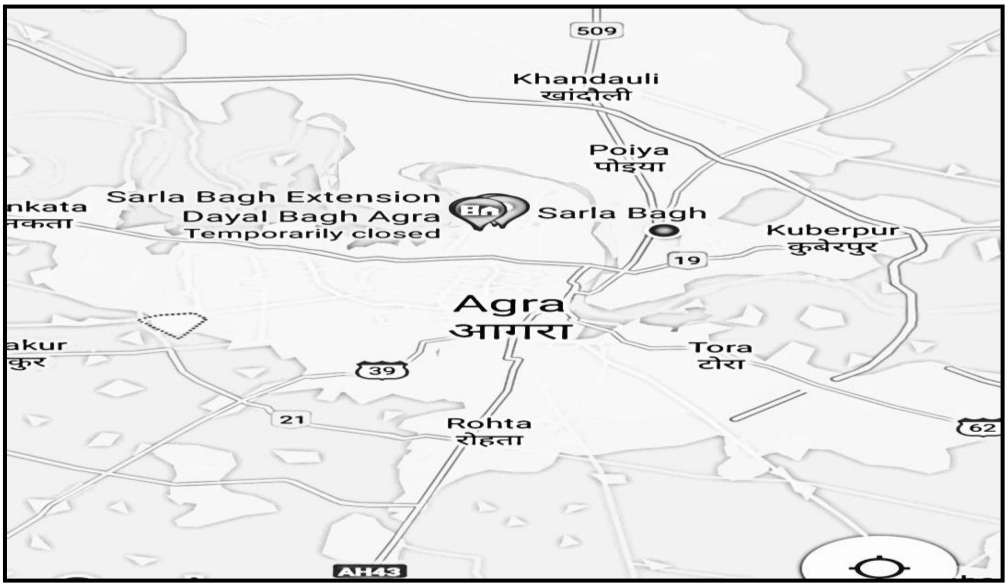
The objectives of this study are to: (1) quantify PM10 variation during BR–DR–AR phases; (2) estimate precipitation scavenging coefficients using the Marshall–Palmer distribution; (3) evaluate meteorological controls; and (4) compare monsoon and non-monsoon regimes.

2. Study area and method

One of India's major cities is Agra. It is located in north central India (27.18°N 78.02°E), with the Thar Desert of Rajasthan encircling two-thirds of its periphery (SE, W, and NW). Agra has 1.6 million people, according to the 2011 Census. Agra's climate is hot and dry in the summer, with daily averages between 21.9°C and 48°C, and between 4.2°C and 31.7°C in the winter. Agra's climate may be broadly classified into four seasons: winter (December to February), summer (March to June), monsoon (July to September), and post-monsoon (October to November). The annual rainfall in Agra is about are 736.6mm and the wind usually come from west and north-west direction.

3. Description of sampling site

From October 2021 to September 2022, the study was carried out in the Sarla Bagh Extension Dayal Bagh location in Agra city. Figure 1 shows a map of the sample site and its environs. The chosen location was within the city of Agra. Traffic emissions, industrial emissions, nearby economic activity, etc. were the main causes of air pollution. Depending on the seasonal variations in wind and direction, these sources have a significant impact on the site. The hourly PM10 concentration was monitored and compared during periods of rainfall and no precipitation in order to ascertain the purification impact of precipitation.



4. Sample collection

PM_4^1 samples were taken at the site 25 feet above the ground using a portable equipment. Three sets of samples were gathered in total: Before Rain (BR), During Rain (DR), and After Rain (AR) events. Rain intensity was calculated by measuring the amount of rain and collecting rainwater samples using the bottle and funnel method. Although showers in this area are often somewhat brief, they can occasionally be extremely intense. For a better understanding of PM10 aerosol washout, the meteorological data (temperature, relative humidity, wind direction, and speed) is shown in Table 1.

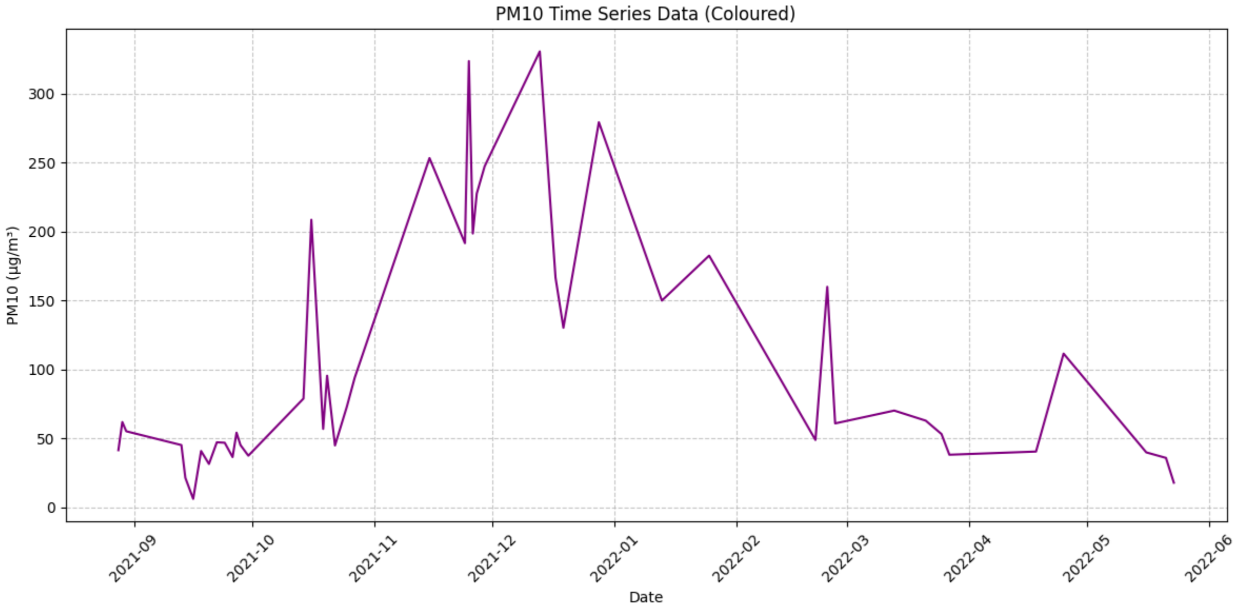


Fig.2 Time Series of PM10 Levels Highlighting Winter Peaks in Agra

The PM10 time series graph shows variations in particulate matter concentrations between September 2021 and June 2022, with notable peaks in December 2021 and January 2022. Seasonal impacts and potential connections to climatic or human variables are indicated by these increased numbers. All things considered, the graphic highlights the unpredictability of air quality and the significance of ongoing observation to spot pollution episodes and evaluate mitigation initiatives.

Table 1: Meteorological parameters, rain intensity and PM_{10} sampling duration throughout each set of the measurements

Date of Rain events	PM_{10} sampling duration (min)	WS (km/h)	WD (degrees)	RH (%)	Rainfall Intensity (mm/h)	Air temperature ©
17-10-2021	BR DR AR 226 118 64	BR DR AR 9.4 4.3 4.1	BR DR AR 121 121 121	BR DR AR 71 93 96	44	28
05-01-2022	486 432 397	12.3 0.3 0.3	122 122 122	86 86 86	28	27
22-01-2022	429 508 310	0.4 0.7 0.2	122 121 68	81 96 99	1.74	18
09-02-2022	123 110 106	0.6 0.2 0.2	139 139 139	68 68 69	5.5	21
01-05-2022	36 31 17	0.0 0.0 0.0	122 122 122	17 19 20	o.75	30
24-05-2022	79 33 31	0.0 0.0 0.1	57 57 58	95 82 89	9.2	28
16-06-2022	49 46 39	0.1 1 2.2	359 356 352	49 50 53	5.3	34

12-07-2022	76 45 39	2.7 0. 0 0.0	89 82 97	102 92 72	7.4	35
17-07-2022	102 64 46	0.0 0.0 0.6	175 180 130	93 93 99	9	32
23-07-2022	30 24 11	6.2 4.2 5.5	140 132 142	99 99 114	20	29
07-08-2022	136 69 33	0.0 0.0 0.0	348 268 92	112 99 99	10	30
20-08-2022	21 13 7	0.8 0.0 0.0	102 95 95	89 97 96	8	28
15-09-2022	46 37 63	1.8 1.4 2.9	129 353 356	98 89 88	3.2	27
20-09-2022	51 91 36	1.6 0.6 2.6	140 352 352	97 100 91	14.3	30

BR Before Rain, DR During Rain, AR After Rain, PM10 Particulate Matter≤10 μm in diameter, WS: Wind Speed: WD: Wind Direction: RH: Relative Humidity

The duration of each sampling for each set of measures, BR, DR, and AR, as well as the sampling time for each of the three sets of samples given in the table, are determined by the single rain event. In the Agra region, rains are typically quite brief, although occasionally they can be extremely intense. Rainfall lasts for 15 to 30 minutes, with an intensity of 3.2 to 20 mm hr^{11} during monsoon seasons and 1.74 to 44 mm hr^{11} during non-monsoon seasons. The Dayalbagh Educational Institute provided the meteorological data.

5 Method: Scavenging Rate Estimation

The precipitation scavenging coefficient (λ) for aerosol particles was calculated using the Marshall–Palmer raindrop size distribution (Marshall and Palmer, 1948):

$$N(D) = N_0 \exp(-\Lambda D)$$

Where

- N(D) = number of raindrops per unit volume with diameter D,
- $N_0 = 8000 \text{ m}^{-3} \text{ mm}^{-1}$,
- $\Lambda = 4.1R^{-0.21}$

The general expression for the **size-dependent scavenging coefficient** Λ(dp) is:

$$\boxed{\Lambda(d_p) = \int_0^{\infty} (\frac{\pi D^2}{4}) V_t(D)\, E(d_p, D)\, N(D)\, dD}$$

Where:

Terms

- d_p = aerosol particle diameter
- D = raindrop diameter

- $V_t(D)$= terminal fall velocity of raindrop (Atlas et al., 1973)
- $E(d_p, D)$= collection efficiency (Slinn, 1984)
- $N(D)$= Marshall–Palmer raindrop size distribution
- Units of Λ(dp) = $\mathbf{s^{-1}}$

This equation tells us how fast particles of size d_p are removed from the atmosphere by raindrops following the MP drop size spectrum.

with v(D)=9.65-10.3exp⁡(-0.6D) as the terminal velocity parameter (Best, 1950). Diffusion, interception, and impaction effects were included in collection efficiency E(a,D) (Slinn, 1983). Simpson's rule was used for numerical integration, and the results are expressed in s 〖^(-1).〗 .

All model computations in this work were performed using the Python programming language (version 3.x) due to its open-source nature, transparency, and extensive use in atmospheric science. The Marshall–Palmer exponential drop size distribution was implemented as a user-defined function [Atlas, D., Srivastava, R. C., & Sekhon, R. S.1973] to allow dynamic evaluation for different rainfall rates. Raindrop terminal velocities were computed using the empirical formulation, and aerosol-drop collection efficiencies were determined using size-dependent relations [Slinn, W. G. N. (1984)]. The scavenging coefficient Ψ(dp) was obtained by numerically integrating the traditional scavenging equation using scipy.integrate.quad. All data arrays were maintained using NumPy, and parameter studies (such as altering particle size and rainfall rate) were automated using Python loops and vectorised operations. This computational framework not only provides a fully replicable scenario but also facilitates the extension or modification of scavenging parameterizations in future studies.

6 Results and Discussion

6.1 PM10 level distribution

Figure 2 displayed the PM10 values for three sets of samples throughout the monsoon and non-monsoon seasons. The impact of particulate matter washout from the atmosphere is shown in Fig. 2. The mean PM10 in the DR sample was found to be considerably lower than the mean of the BR samples.

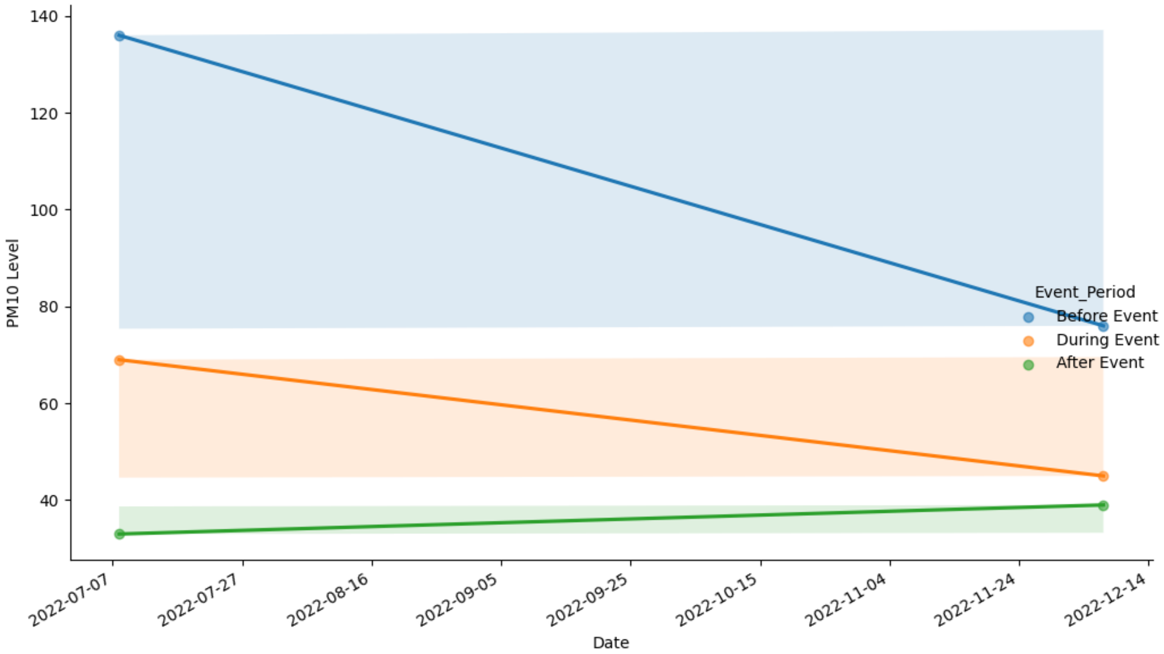


Fig.3 This graph shows three set of PM10 (Before, during and after) level in monsoon seasons.

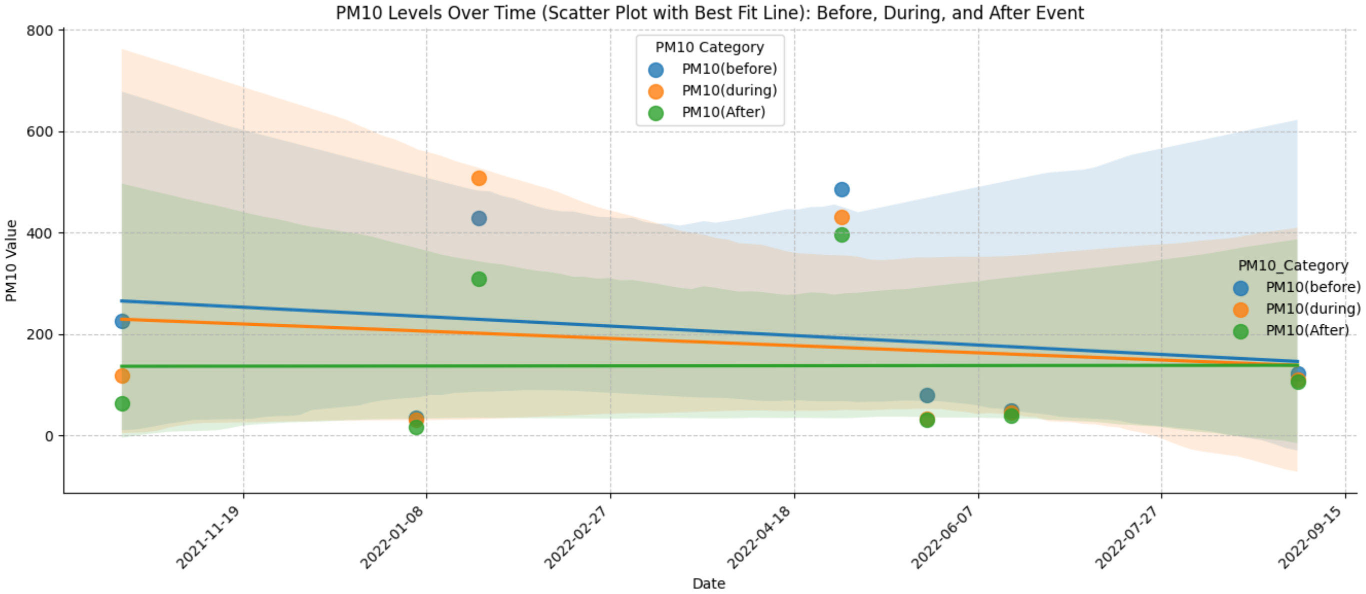


Fig.4 This graph shows three set of PM10 (Before, during and after) level in non-monsoon seasons.

The accumulation of particulate matter emitted from multiple sources may be the cause of the decrease in the mean PM level seen from DR to AR. Measuring aerosol concentrations prior to and following rain episodes can be helpful in controlling the factor generating aerosol loading in the atmosphere, according to Marshall, J. S., & Palmer, W. McK. (1948). According to a number of studies [Atlas, D., Srivastava, R. C., & Sekhon, R. S. (1973)], aerosol washout is also dependent on raindrop collecting efficiency, which is further dependent on raindrop size/area, aerosol diameter, and Brownian dispersion of aerosols in the atmosphere. Aerosols' hygroscopic properties also have a major impact on climate, atmospheric processes, and health problems (Slinn, W. G. N. 1984, Chate and Pranesha 2004, Chate and Kamre 1997, Tang 1996). Additionally, hygroscopicity is crucial for the creation of Cloud Condensation Nuclei (CCN), which alter the volumes and patterns of precipitation in a particular area [Hiller 1991]. Particle diameter and relative humidity have an impact on aerosol hygroscopic development [Gysesl et al. 2002, Ferron et al. 2005]. The washout of pollutants and aerosols in the atmosphere is therefore influenced by rain intensity, aerosol particle size, and hygroscopic growth [Reuter et al., 2009]. The purpose of collecting PM_{20} before, during, and after a rainstorm was to determine how the concentration of PM_{20} aerosols changed.

7 Statistical evaluations of atmospheric scavenging processes under Meteorological Variability.

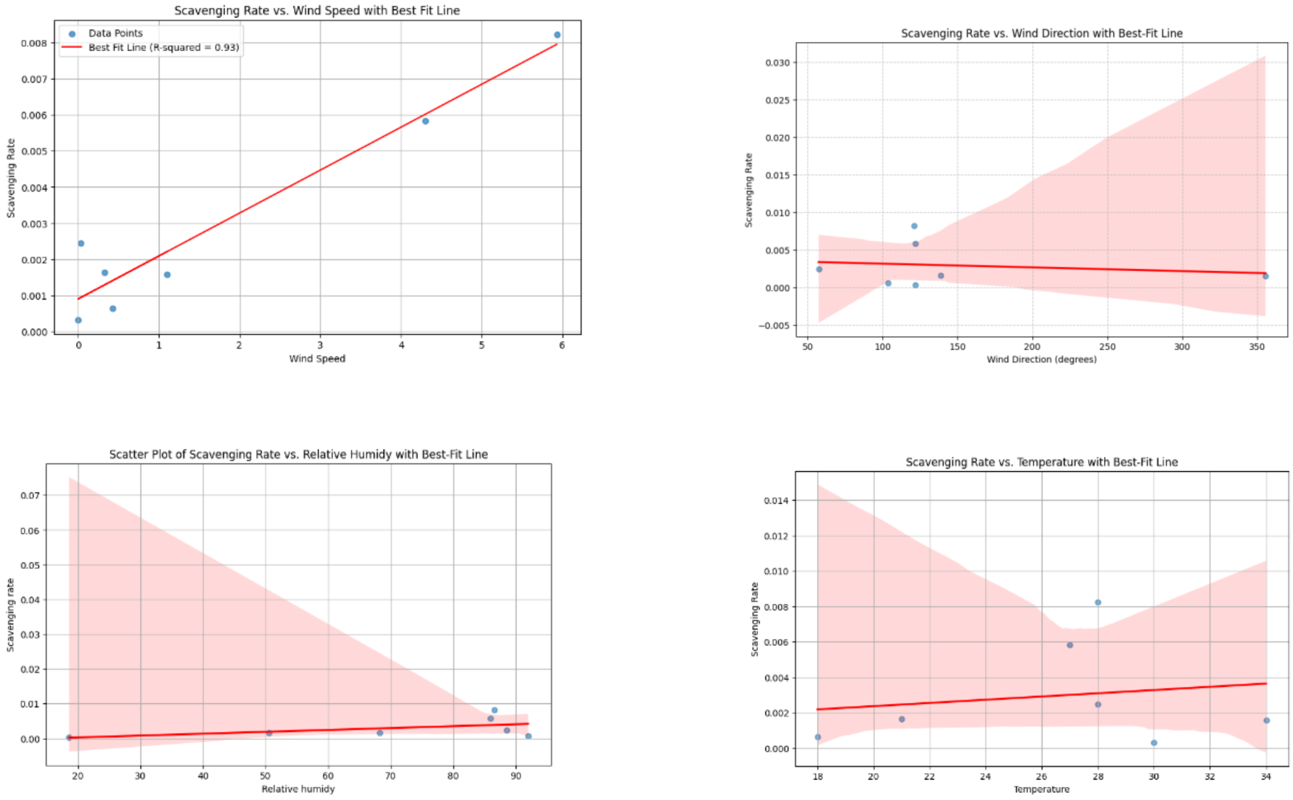


Figure 5 illustrates the relationship between scavenging rate and meteorological parameters (wind speed, wind direction, temperature, and relative humidity) during the non-monsoon season.

The scatter plot analysis show clear correlations between important climatic parameters and scavenging rate. An R2 value of 0.93 indicates a strong positive correlation between wind speed and scavenging rate, indicating that higher wind velocity improves particle removal through turbulent mixing and collision mechanisms. The plot of wind direction vs scavenging rate, on the other hand, reveals a weak and ambiguous trend with a large confidence interval surrounding the regression line, suggesting that complicated source-receptor dynamics may make directional flow alone an unreliable predictor of scavenging effectiveness. Relative humidity alone may not have a significant impact on the scavenging process in this dataset, as evidenced by the modest positive correlation between relative humidity and scavenging rate, the large confidence interval, and the notable data spread. Finally, there is a slight positive correlation between temperature and scavenging rate, which may be due to improved droplet production and condensation processes in colder climates. These results highlight the multifaceted nature of atmospheric scavenging, where the effectiveness of removing particles from the atmosphere is influenced by a combination of heat conditions, moisture availability, and wind-driven motion.

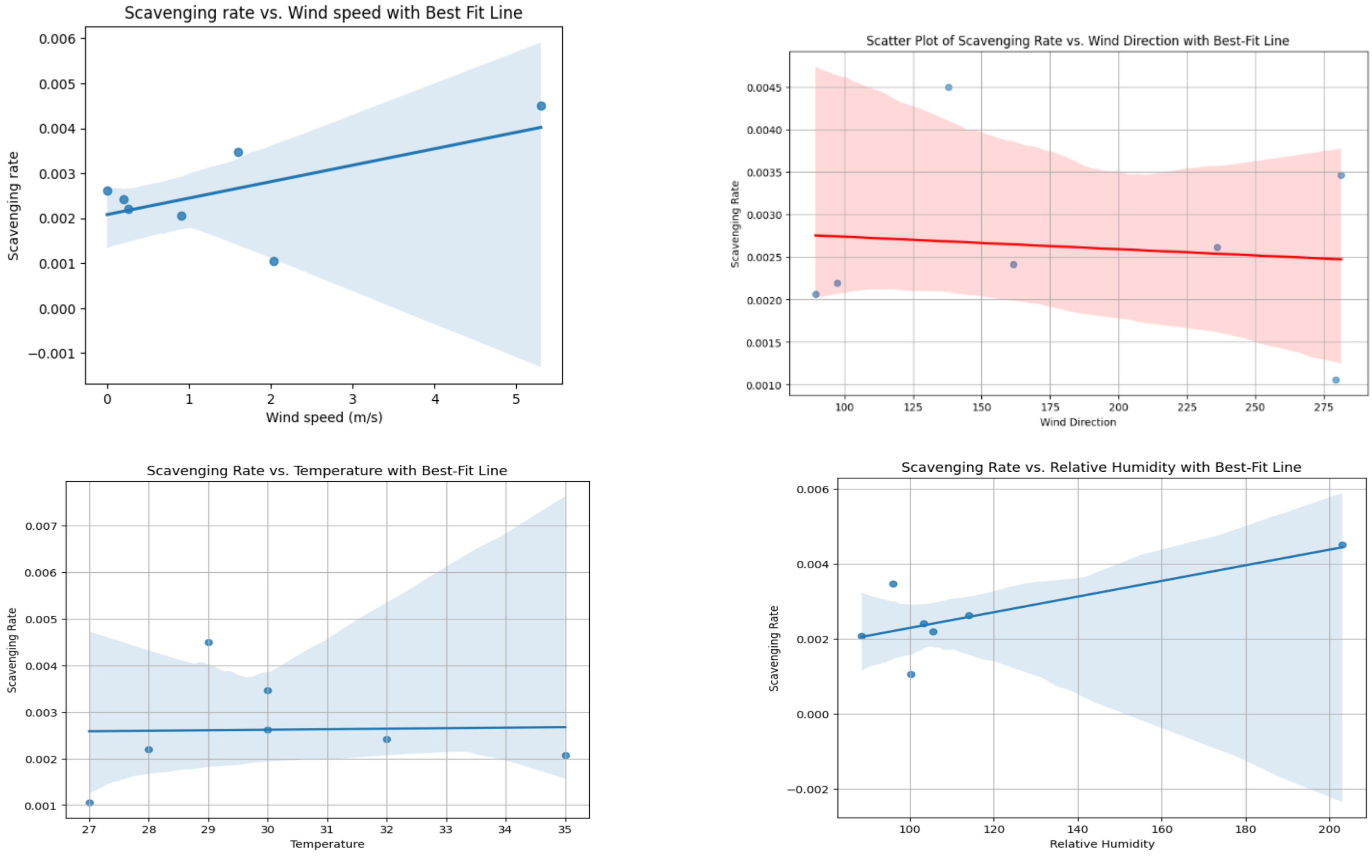


Figure 6 presents the relationship between scavenging rate and meteorological parameters during the monsoon season.

Stronger winds improve particle removal, as the analysis demonstrates that the scavenging rate rises with wind speed. Certain wind patterns may lower scavenging effectiveness, as indicated by a modest negative trend with wind direction. Additionally, there is a positive association between temperature and scavenging rates, suggesting that warmer settings may encourage higher rates. The scavenging rate tends to rise along with relative humidity. These correlations demonstrate how climatic variables affect atmospheric purification processes.

Summary statistics data are presented in Table. 2 including data regarding the selected air pollutant (PM_{10}), meteorological parameters, and the precipitation analyses during 2021-2022year experiment. The analyses of these parameters found that the

Table. 2: PM_{10} and meteorological parameters characterization

	PM_{10} (μg m^{-3})	**T (°C)**	**WS (ms^{-1})**	**Wd (degrees)**	**RH (%)**
Count	8.000000	8.000000	8.000000	8.000000	42.000000
mean	121.346250	28.237500	1.952500	148.087500	82.452381
std	140.478325	4.167883	2.347222	90.314442	22.650260
min	13.600000	21.000000	0.000000	57.300000	17.000000
25%	43.645000	26.575000	0.225000	105.425000	74.250000
50%	66.300000	28.500000	1.155000	130.500000	91.500000
75%	133.852500	30.150000	2.682500	152.225000	97.750000
max	438.300000	35.000000	5.900000	355.600000	100.000000

Note: T – temperature, RH – relative humidity, WS – wind speed, WD – wind direction, Avg. – average, Med. – median, Min. – minimum, Max – maximum.

The descriptive data show that PM_2^1 concentrations and related meteorological parameters varied significantly over the course of the investigation. With a mean value of 121.35 μg m^{-3} and a high standard deviation (140.48), PM_1^1 levels ranged from 13.60 to 438.30 μg m^{-3}, indicating significant temporal oscillations probably caused by seasonal climatic circumstances, especially during monsoon and non-monsoon seasons. With an average of 28.24 °C and a moderate standard deviation of 4.17, the air temperature ranged from 21.0 to 35.0 °C, indicating comparatively stable thermal conditions. With a mean of 1.95 ms^{-1}, the wind speed ranged from calm circumstances (0.00 ms^{-1}) to 5.90 ms^{-1}; the observed variability (standard deviation = 2.35) and lower quartile values suggest frequent low-wind conditions that may promote pollutant accumulation. With a mean of 148.09° and a significant standard deviation (90.31), wind direction showed a broad dispersion from 57.30° to 355.60°, suggesting varying airflow regimes and several possible source influences.

With a mean of 82.45% and a standard deviation of 22.65%, relative humidity ranged from 17% to 100%, indicating generally moist air conditions during rainfall episodes. In order to preserve physical consistency, values that exceeded 100% during periods of heavy precipitation were capped at 100% during data preprocessing and were ascribed to sensor-related supersaturation artefacts. Overall, the strong seasonal and atmospheric restrictions guiding PM_2^1 concentration dynamics and wet scavenging efficiency are highlighted by the significant diversity across meteorological parameters.

8 Variations of scavenging rate with rain intensity

Two important mechanisms that account for the moist scavenging of aerosols from the atmosphere are rainout and washout. The washout of different atmospheric species is best explained by the quantity or intensity of rainfall [20]. Figure 4

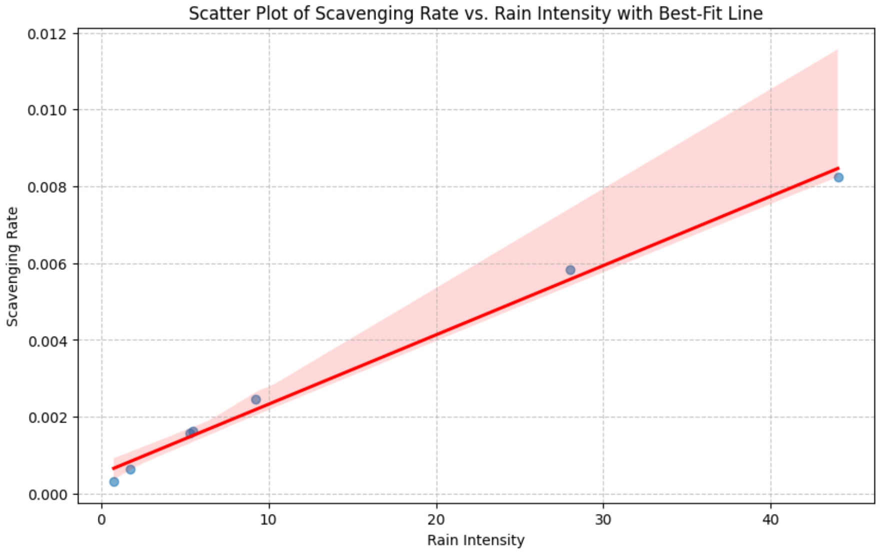


Figure 7 shows the correlation between rainfall intensity and the calculated scavenging rate during the monsoon season.

The BR aerosol concentration levels were already very low because of previous rain, which washed the aerosols away, which explains the poor removal shown in Figure 3. It should be mentioned that aerosol concentrations before rain, as well as the length and intensity of the rain, all affect the removal of contaminants. The rain intensity plays an important role in scavenging of PM_{10} concentration. This correlation study explains the relationship between PM_{20} scavenging rate and rain intensity.

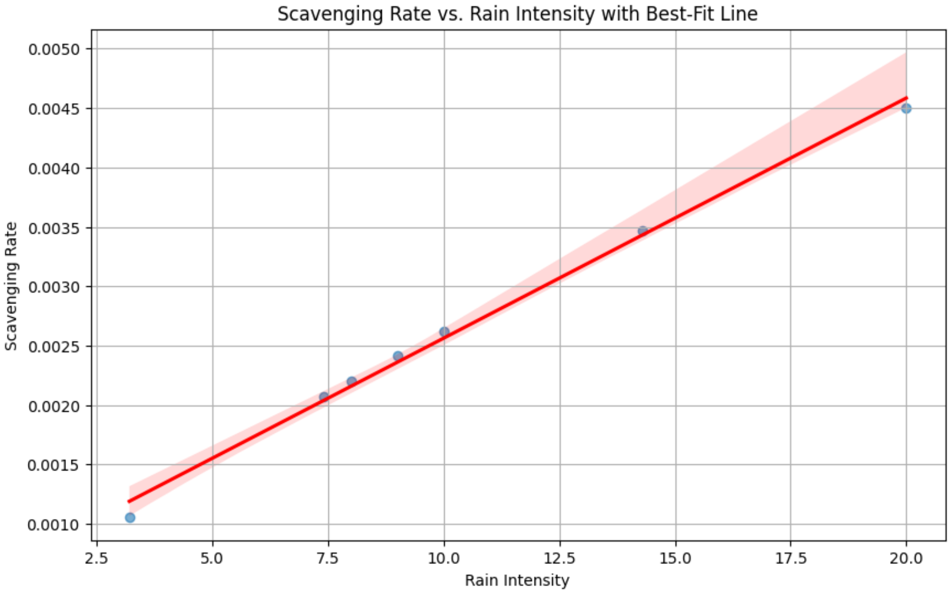


Figure 8 represents the relationship between rainfall intensity and scavenging rate during the non-monsoon season.

The SR of PM10 concentration in the rainwater was higher during the non-monsoon season than it was during the monsoon season. These particles can be easily removed from the atmosphere because of their larger size and increased hygroscopicity. The buildup of the aerosol contents was observed in addition to removal. During the study period, PM10 bound SR(M) showed a positive correlation (R^2=0.9965) with rain intensities, while SR(NM) showed a high positive correlation (R^2=0.9977). Correlation studies revealed this relationship between the rate of PM10 scavenging and the intensity of the rain. SR was significantly impacted by rainfall intensity (R). Overall, higher atmospheric scavenging of the PM10 concentration was shown by the percentage decline from BR to DR and from DR to AR.

Conclusion

The current study shows how rainfall intensity significantly affects PM_4^1 elimination through wet scavenging in Northern India under monsoon and non-monsoon meteorological regimes. It is evident from a systematic comparison of PM_2^1 concentrations during the Before Rain (BR), During Rain (DR), and After Rain (AR) phases that there is a significant decrease in particulate matter levels due to precipitation. Enhanced scavenging effectiveness under sustained monsoonal rainfall circumstances is confirmed by the much lower average PM_4^1 concentration during the monsoon season (48.86 $\mu g\ m^{-3}$) compared to the non-monsoon period (196.41 $\mu g\ m^{-3}$).

Scavenging rate and important climatic parameters were shown to have strong statistical correlations. The most significant predictor (R2 = 0.93) was wind speed, highlighting the contribution of air turbulence on particle clearance. Temperature had a moderate but discernible impact, while relative humidity promoted improved deposition through hygroscopic development. Further evidence that longer and heavier rainfall episodes greatly increase PM_4^1 washout efficiency comes from a strong positive association between rainfall intensity and scavenging rate.

The slow re-accumulation of PM_2^1 after precipitation emphasises the transient character of rain-induced air cleansing, even when rainfall events substantially lowered particle concentrations. A repeatable and physically based methodology for predicting size-dependent scavenging coefficients is provided by applying the Marshall-Palmer raindrop size distribution in conjunction with numerical integration in Python.

Overall, this study offers region-specific insights into wet scavenging dynamics in a monsoon-dominated urban environment and contributes to improved atmospheric modeling, seasonal air quality forecasting, and evidence-based pollution mitigation strategies.

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