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# Apparent PM2.5 Decay Following Delhi's October 2025 Cloud Seeding Operation: A Detection-Limit Analysis


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**ABSTRACT:** On 28 October 2025, the Indian Institute of Tropical Meteorology seeded clouds over north Delhi - the country's first such operation in more than fifty years, according to officials. A Cessna 206H aircraft released silver iodide flares and hygroscopic sodium chloride particles along a corridor between Rohini and Burari. We examined hourly PM2.5 readings from the four Delhi monitoring stations lying within 6.87 km of the flight path and fitted a simple exponential decay model, $C(t) = C_0 \times \exp(-\Lambda_{app} \times t)$, to the 16:00–22:00 Indian Standard Time window. The fitted apparent decay rate $\Lambda_{app}$ ranged from $5.39 \times 10^{-4}$ $hr^{-1}$ (Wazirpur; $R^2 = 0.149$) to $5.60 \times 10^{-3}$ $hr^{-1}$ (Jahangirpuri; $R^2 = 0.651$), matching observed declines of 1.6–6.0%. $\Lambda_{app}$ deserves a precise reading: it is a total decay rate. It folds in wet scavenging, but also boundary-layer dilution, wind-driven transport and changes in emissions. By itself, it says nothing about scavenging. For the recorded rainfall of 0.1–0.2 mm $hr^{-1}$, the standard below-cloud scavenging formula ($\Lambda = 8 \times 10^{-4} \times R^{0.79}$) predicts a six-hour removal of only 0.08–0.13% - one to two orders of magnitude smaller than the declines we observed. We also set the seeding afternoon against five dry afternoons at the same stations (6, 24, 26 October and 2, 9 November 2025). None of the four seeding-day $\Lambda_{app}$ values differed significantly from the dry-day values: the z-scores were −0.63, −0.85, −0.94 and −1.13, all well inside ±1.96 and all negative. PM2.5, in other words, dropped more slowly - not faster - on the seeding afternoon (Bhandari et al., 2020; Ojha et al., 2020). We conclude that the small declines carry no detectable scavenging signal. They match the normal afternoon behaviour of the Delhi boundary layer and a detectable signal would have needed rainfall of roughly 9 mm $hr^{-1}$ - about 60 times what was recorded. We explain how we derived this detection threshold and what it implies for the design of any future urban seeding experiment.


## 1. INTRODUCTION

Cloud seeding has been used for more than seventy years to increase rain, reduce hail, or clear fog (Bruintjes, 1999; Flossmann et al., 2019). Yet the statistical evidence that it actually works, at the scale of real field experiments, is mixed and contested. The six-year randomized Wyoming experiment found insufficient statistical evidence of an effect across 118 experimental units ($p = 0.28$) and the WMO-commissioned peer review concluded that detecting the small seeding signal against the large noise of natural variability requires randomized experiments. Using cloud seeding to improve air quality - making rain fall to wash particulate pollution out of the air over a megacity - is much newer and the quantitative evidence for it is thin.

The operation we analyse took place on 28 October 2025 over north Delhi, coordinated between the Indian Institute of Tropical Meteorology and the Government of NCT Delhi. It was presented both as a rain-enhancement trial and as a PM2.5-reduction trial. A Cessna 206H aircraft dispersed AgI flares and hygroscopic NaCl particles along a corridor between Rohini and Burari. The published account mentions roughly 22 minutes of cloud-line penetration, relative humidity of only 15–20% and thin cloud. The India Meteorological Department recorded 0.1 mm and 0.2 mm of rain at gauges at and near the Delhi–Noida border.

The theoretical starting point for any seeding-related PM2.5 reduction is below-cloud scavenging, usually written $\Lambda = a \times R^b$, where R is the rainfall rate in mm $hr^{-1}$ and the constants a and b depend on the aerosol size distribution and on how efficiently raindrops collect particles (Andronache, 2003; Greenfield, 1957; Henzing et al., 2006). For accumulation-mode particles (0.1–1 μm), the formula we use here ($a = 8 \times 10^{-4}$, $b = 0.79$) gives a six-hour removal of only ~0.08–0.13% at the rainfall reported for this event - far below the natural afternoon variability of Delhi's PM2.5 record. The published uncertainty assessment of below-cloud scavenging parameterizations shows that for submicron particles, theoretical formulas agree to within ~10–20% with one another, theoretical and empirical formulas differ by up to a factor of ~2 and the largest discrepancies (more than an order of magnitude) are confined to field-derived coefficients from non-controlled conditions; we carry this uncertainty through Section 3.4.

Our question is deliberately narrow: did PM2.5 fall measurably more on the seeding afternoon than on similar dry afternoons, at the same stations, in the same season? To answer it, we analysed hourly data from four monitoring stations inside or next to the seeded corridor and compared the seeding afternoon with five control afternoons using a fitted apparent decay rate.

Two caveats up front. First, we could not independently confirm the widely repeated claim that this was India's "first operation in five decades." India has run organised seeding experiments under the Cloud Aerosol Interaction and Precipitation Enhancement Experiment, including randomised hygroscopic-seeding trials (Kulkarni et al., 2012; Prabhakaran et al., 2023). We therefore treat that claim as the operation's official framing, not as an established fact. Second, this is a post-hoc case study of a single event, not a designed experiment. We point out throughout the paper where that limits what we can conclude.

## 2. DATA AND METHODS

### 2.1 The seeding operation

The operation ran from roughly 08:50 to 11:50 IST on 28 October 2025 over the northern Delhi corridor between Rohini and Burari. According to the published account, the aircraft dispersed AgI flares and hygroscopic NaCl nuclei along the flight track. About 22 minutes of sustained cloud-line penetration was reported, with relative humidity of 15–20% and low cloud optical depth. The IMD recorded 0.1 mm and 0.2 mm of rain at gauges at and near the Delhi–Noida border, several kilometres away from our monitoring sites.

### 2.2 The PM2.5 monitoring stations

We used hourly PM2.5 data from the Delhi Pollution Control Committee and the System of Air Quality and Weather Forecasting and Research networks, restricted to four continuous monitors inside or immediately next to the seeded corridor: Burari Crossing (0 km from the flight track), Jahangirpuri (2.44 km), Wazirpur (3.98 km) and Rohini (6.87 km). The monitors report hourly averages with a stated precision of about ±5 μg $m^{-3}$. Table 1 lists the station details.

**Table 1.** Station details. Distances are approximate perpendicular distances from the reported flight track.

| Station | Network | Latitude (°N) | Longitude (°E) | Distance from track (km) |
|---|---|---|---|---|
| Burari Crossing | IITM-SAFAR | 28.72830 | 77.19750 | 0.00 |
| Jahangirpuri | DPCC | 28.73282 | 77.17063 | 2.44 |
| Wazirpur | DPCC | 28.69979 | 77.16545 | 3.98 |
| Rohini | DPCC | 28.73253 | 77.11992 | 6.87 |

We fixed the analysis window at 16:00–22:00 IST, with no missing hours at any station. Two considerations drove the choice. It is the six-hour stretch of the archived hourly record that follows the operation and the reported rainfall timing. And with the observed winds of 1–3 m $s^{-1}$, air moves tens of kilometres over six hours, so any rain produced by the mid-morning seeding would more likely arrive over the station array during this window than at the exact moment of seeding (Bhandari et al., 2020; Ojha et al., 2020). We fully accept, however, that this window also covers the afternoon-to-evening transition of the boundary layer - the dominant natural control on Delhi's PM2.5 through the day - and that sub-daily data would be needed to pin down the exact timing of any response.

**2.3 Rainfall attribution**

Rain was recorded only at the Delhi–Noida border gauges, not at our four stations. The reported 0.1 mm and 0.2 mm bracket the event rainfall, so we treat 0.1–0.2 mm $hr^{-1}$ as the representative rain-rate range and 0.15 mm $hr^{-1}$ as the central estimate. We checked the Delhi telemetric rainfall archive for the event day and the control days; however, no station-level rainfall collocated with the four air-quality monitors could be verified for 28 October 2025, because the relevant entries in the telemetry file could not be resolved.

The theoretical comparison in Section 3.4 is therefore, by necessity, an upper-bound exercise. We compute the largest scavenging signal that is plausibly consistent with the reported rainfall and then show that even this generous bound is undetectable. If any station received no rain at all, then the appropriate scavenging coefficient for that station would be zero - which only strengthens our null conclusion.

**2.4 Choosing the control afternoons**

We selected five control afternoons before running the analysis, using three explicit rules applied to the 30-day window around 28 October 2025: (i) no recorded rain in the north Delhi corridor during the analysis window; (ii) the same seasonal regime (post-monsoon, pre-winter, i.e., October to mid-November); and (iii) no major pollution episode in the preceding 48 hours. The five dates meeting these rules are 6, 24 and 26 October and 2 and 9 November 2025. We applied exactly the same fitting procedure to each control afternoon at each station.

**2.5 Fitting the apparent decay rate**

Following the standard first-order removal framework, we model the PM2.5 concentration as

$$C(t) = C_0 \times \exp(-\Lambda_{app} \times t)$$

where C(t) is the hourly concentration (µg $m^{-3}$), $C_0$ is the fitted concentration at t = 0 (16:00 IST), t is the time in hours and $\Lambda_{app}$ is the apparent first-order decay coefficient ($hr^{-1}$). $\Lambda_{app}$ is a descriptive number, not a physical process. It gathers together everything that made PM2.5 fall over the window: wet scavenging, dry deposition, boundary-layer dilution, wind-driven ventilation and changes in emissions. Wet scavenging is only one piece of it. We can bound the scavenging piece from below using the dry-day behaviour at the same station:

$$\Lambda_s \geq \Lambda_{app} - \Lambda_{nat}$$

Here $\Lambda_s$ is the scavenging component and $\Lambda_{nat}$ is the apparent decay rate typical of dry afternoons at that station, taken from the control distribution.

We fitted Eq. with nonlinear least squares. $\Lambda_{app}$ was bounded to [0, 0.05] $hr^{-1}$ and $C_0$ to µg $m^{-3}$, to avoid physically absurd results. Uncertainties are the square roots of the diagonal of the parameter covariance matrix and $R^2$ is the coefficient of determination. We flag fits with $R^2 < 0.20$, or with $\Lambda_{app}$ within one standard error of zero, as poorly constrained. For transparency, we also report a cruder two-point estimate, $\Lambda_{2pt} = (1/6) \times \ln(C_0,14\text{–}15 / C_0,22)$, where $C_0$,14–15 is the mean of the 14:00 and 15:00 readings and $C_0$,22 is the 22:00 reading. This is the estimator used in the operation's official reporting. The two estimators are not interchangeable (Section 3.2); every comparison in this paper uses the fitted $\Lambda_{app}$, which is the more conservative of the two.

**2.6 Comparing with the controls**

For each station, we compared the seeding-afternoon $\Lambda_{app}$ with the spread of the five control $\Lambda_{app}$ values at the same station, using the z-score $z = (\Lambda_{app},\text{seed} - \text{mean}_{nat}) / SD_{nat}$. We are careful to note that with only five controls and with control variability that often exceeds the mean itself, the normal-distribution assumption is fragile. We therefore treat the z-scores as descriptive evidence rather than strict hypothesis tests and lean on the fact that all four z-scores have the same sign - rather than on any single number. A permutation test would need a denser set of controls; we recommend it for any follow-up work.

### 2.7 The theoretical benchmark: what the formula predicts

For comparison, we computed the theoretical scavenging coefficient with the published power law $\Lambda_{th} = 8 \times 10^{-4} \times R^{0.79}$ (R in mm $hr^{-1}$; $\Lambda_{th}$ in $hr^{-1}$), using R = 0.1–0.2 mm $hr^{-1}$, the recorded rain range. This gives $\Lambda_{th}$ between $1.30 \times 10^{-4}$ and $2.24 \times 10^{-4}$ $hr^{-1}$ - a six-hour removal of 0.08–0.13%.

The most thorough published uncertainty study of scavenging formulas gives a clear answer for submicron particles: theoretical formulas agree with each other closely - within ~10% at rain rates of 1–50 mm $hr^{-1}$ and within ~20% even at rates as low as 0.01 mm $hr^{-1}$; theoretical and empirical formulas differ by up to about a factor of two; and the largest differences, more than an order of magnitude, appear only when theoretical formulas are compared with coefficients derived from non-controlled field measurements, a gap attributed to turbulence and vertical diffusion. To be deliberately conservative, Section 3.4 therefore reports a generous ten-fold uncertainty envelope alongside the central value - wide enough to cover even the theory–field gap - and shows that even that envelope cannot change the conclusion.

## 3. RESULTS

### 3.1 The observed PM2.5 series

Over the 16:00–22:00 IST window, PM2.5 fell at all four stations by 1.6–6.0% relative to each station's pre-window baseline (the mean of the 14:00 and 15:00 readings): 4.0% at Burari Crossing (315.5 → 303.0 μg $m^{-3}$), 6.0% at Jahangirpuri (319.0 → 300.0 μg $m^{-3}$), 1.6% at Wazirpur (337.5 → 332.0 μg $m^{-3}$) and 2.3% at Rohini (322.5 → 315.0 μg $m^{-3}$). The Burari series was nearly flat inside the window itself (307 → 303 μg $m^{-3}$); part of its decline happened before 16:00 IST, which matters for reconciling the estimators (Section 3.2). The full hourly series are given in Table 4 and plotted in Figure 2.

### 3.2 Apparent decay rates

Table 2 summarises the fitted $\Lambda_{app}$ values, their 1σ uncertainties, the $R^2$ values, the two-point estimates $\Lambda_{2pt}$ and the observed declines. Two fits are poorly constrained (Wazirpur, $R^2 = 0.149$; Rohini, $R^2 = 0.136$); we report them for completeness but leave them out of the sign comparison in Section 3.3. At every station, $\Lambda_{2pt}$ is about three times larger than $\Lambda_{app}$ (for example, Burari: $\Lambda_{app} = 2.11 \times 10^{-3}$ vs $\Lambda_{2pt} = 6.75 \times 10^{-3}$ $hr^{-1}$). The reason is that $\Lambda_{2pt}$ includes declines that happened before the fitting window began and it couples the 14:00–15:00 baseline to a single 22:00 reading. All cross-comparisons below therefore use the fitted $\Lambda_{app}$.

**Table 2.** Apparent decay rates by station. $\Lambda_{app}$ and 1σ come from fitting Eq.; $\Lambda_{2pt}$ is the two-point estimate from the 14:00–15:00 mean to the 22:00 reading; the observed decline is relative to the 14:00–15:00 baseline. $R^2 < 0.20$ flags a poorly constrained fit.

| Station | Distance (km) | $\Lambda_{app}$ ($hr^{-1}$) | 1σ ($hr^{-1}$) | $R^2$ | $\Lambda_{2pt}$ ($hr^{-1}$) | Observed decline (%) |
|---|---|---|---|---|---|---|
| Burari Crossing | 0.00 | $2.11 \times 10^{-3}$ | $\pm 1.5 \times 10^{-3}$ | 0.845 | $6.75 \times 10^{-3}$ | 4.0 |
| Jahangirpuri | 2.44 | $5.60 \times 10^{-3}$ | $\pm 2.0 \times 10^{-3}$ | 0.651 | $1.02 \times 10^{-2}$ | 6.0 |
| Wazirpur | 3.98 | $5.39 \times 10^{-4}$ | $\pm 7 \times 10^{-4}$ | 0.149 (flag) | $2.74 \times 10^{-3}$ | 1.6 |
| Rohini | 6.87 | $9.13 \times 10^{-4}$ | - | 0.136 (flag) | $3.92 \times 10^{-3}$ | 2.3 |

### 3.3 Comparing with the control afternoons

Table 3 compares the seeding-afternoon $\Lambda_{app}$ with the mean and standard deviation of the five control afternoons at each station. All four z-scores are negative and lie well inside ±1.96: −0.63, −0.85, −0.94 and −1.13. No station shows even a hint of faster removal on the seeding afternoon. The largest |z| occurs at Rohini, the station farthest from the flight track and there is no pattern of $\Lambda_{app}$ decreasing with distance from the track - both results are inconsistent with a local, seeding-driven scavenging effect.

One control day deserves special mention: 6 October 2025 at Burari Crossing showed a 27–41% decline with no rain at all ($\Lambda_{2pt} \approx 0.054–0.085\ hr^{-1}$). A single dry day thus produced a natural decline an order of magnitude larger than any plausible scavenging signal.

**Table 3.** Seeding-afternoon versus dry-afternoon apparent decay rates.

| Station | $\Lambda_{app}$,seed ($hr^{-1}$) | Dry-day mean ($hr^{-1}$) | Dry-day SD ($hr^{-1}$) | z-score |
|---|---|---|---|---|
| Burari Crossing | $2.11 \times 10^{-3}$ | $1.69 \times 10^{-2}$ | $2.33 \times 10^{-2}$ | −0.63 |
| Jahangirpuri | $5.60 \times 10^{-3}$ | $1.98 \times 10^{-2}$ | $1.67 \times 10^{-2}$ | −0.85 |
| Wazirpur | $5.39 \times 10^{-4}$ | $1.24 \times 10^{-2}$ | $1.25 \times 10^{-2}$ | −0.94 |
| Rohini | $9.13 \times 10^{-4}$ | $1.36 \times 10^{-2}$ | $1.12 \times 10^{-2}$ | −1.13 |

**Table 4.** Hourly PM2.5 concentrations (µg $m^{-3}$) at the four stations, 16:00–22:00 IST, 28 October 2025.

| Hour | Burari Crossing | Jahangirpuri | Wazirpur | Rohini |
|---|---|---|---|---|
| 16:00 | 307 | 311 | 334 | 317 |
| 17:00 | 306 | 305 | 332 | 315 |
| 18:00 | 304 | 301 | 331 | 313 |
| 19:00 | 304 | 299 | 331 | 312 |
| 20:00 | 304 | 299 | 332 | 313 |
| 21:00 | 303 | 299 | 332 | 314 |
| 22:00 | 303 | 300 | 332 | 315 |

### 3.4 The theoretical benchmark: how much rain can actually remove?

Rain removes particles from the air by a process called below-cloud scavenging: falling raindrops collide with particles and carry them to the ground. The rate at which this happens is described by the power law of Section 2.7, $\Lambda_{th} = 8 \times 10^{-4} \times R^{0.79}$, where R is the rainfall rate (mm $hr^{-1}$) and $\Lambda_{th}$ is the scavenging coefficient ($hr^{-1}$) - a number that tells us how fast PM2.5 would disappear if rain were the only removal process. For accumulation-mode particles (diameters of 0.1–1 µm, the sizes that dominate Delhi's PM2.5 mass), the formula predicts very slow removal at light rain rates. At the recorded rainfall of 0.1–0.2 mm $hr^{-1}$, the formula gives $\Lambda_{th} = 1.30–2.24 \times 10^{-4}\ hr^{-1}$, which corresponds to a six-hour removal of only 0.08–0.13% - one to two orders of magnitude smaller than the declines we observed (1.6–6.0%). The observed decay rates exceed the upper edge of this band by 2.4–25× and the lower edge by up to 43×.

The most detailed published uncertainty assessment of below-cloud scavenging formulas shows three things for submicron particles (Wang et al., 2010, p. 5701). First, different theoretical formulas agree closely with one another: predicted concentrations differ by less than ~10% at rain rates of 1–50 mm $hr^{-1}$ and by less than ~20% even at rates as low as 0.01 mm $hr^{-1}$ (Wang et al., 2010, p. 5701). Second, replacing a theoretical formula with an empirical (measurement-based) one changes the predicted concentrations by up to about a factor of two (Wang et al., 2010, p. 5701). Third, the largest gaps - more than an order of magnitude - appear only when theoretical formulas are compared with coefficients derived from non-controlled field measurements, a gap attributed to turbulence and vertical diffusion enhancing removal near the ground (Wang et al., 2010, p. 5701). To be deliberately conservative, we test our conclusion under an uncertainty envelope ten times larger than the central value - wide enough to cover even the theory–field gap. Under that envelope the upper edge of the predicted removal becomes 0.13% × 10 ≈ 1.3% over six hours, still below the smallest decline we observed (1.6%) and far below the detection limit derived in Section 4.4. Wet scavenging therefore cannot, under any published formula, account for most of what we observed. The bulk of the decline must come from the ordinary boundary-layer processes that the dry control afternoons already show us.

## 4. DISCUSSION

### 4.1 What $\Lambda_{app}$ actually measures

$\Lambda_{app}$ is simply the best-fit decay rate of the observed series. Equation does not care why the concentration fell; it fits any steadily declining series, whether the cause is rain scavenging, dry deposition, boundary-layer dilution, wind transport, emission changes, or instrument behaviour. With only six hourly points and an unknown mix of causes, no microphysical separation is possible from the time series alone. That is a deliberate modelling choice.

Two conclusions follow. First, the fact that $\Lambda_{app}$ exceeds $\Lambda_{th}$ (by about 2.4–43×) cannot be credited to scavenging. By Eq., the scavenging component is at most $\Lambda_{app} - \Lambda_{nat}$; and at every station $\Lambda_{nat}$ is larger than $\Lambda_{app}$ (all z-scores are negative). The data are only consistent with a scavenging component indistinguishable from zero. Second, the right test of a seeding effect is therefore not "$\Lambda_{app}$ vs $\Lambda_{th}$," but "$\Lambda_{app}$ on the seeding day vs $\Lambda_{app}$ on dry days." That test finds no effect at any station.

### 4.2 Boundary-layer dilution and wind transport dominate

The afternoon fall of fine particles over Delhi is largely the normal behaviour of the boundary layer, with or without rain. Ojha and co-workers showed that PM2.5 across the Indo-Gangetic Plain builds up toward winter as the boundary layer contracts, with afternoon concentrations tied to the daily rise and fall of boundary-layer height. Bhandari and co-workers showed, for Delhi specifically, that afternoon mixing and the evening transition regularly produce large hour-on-hour PM2.5 drops with no rain at all. Our control afternoons reproduce this pattern at the same stations in the same season - most strikingly on 6 October 2025, when PM2.5 fell 27–41% on a dry day. Add to this the reported winds of 1–3 m $s^{-1}$. Over six hours, that moves air tens of kilometres - comparable to the size of the station array. Stations 2.44–6.87 km from the flight track may never have sampled air that passed beneath the seeded cloud.

### 4.3 Why no signal was expected

Three independent reasons make a detectable scavenging signal implausible on this afternoon.

The recorded rain was far below any plausible detection threshold. At 0.1–0.2 mm $hr^{-1}$, the theory predicts only 0.08–0.13% removal over six hours. Even under a generous ten-fold uncertainty envelope - wide enough to cover all published formulas - the prediction stays at or below ~1.3%, still smaller than the smallest decline we observed (1.6%) and far below the detection limit derived in Section 4.4. The reported ~22 minutes of cloud-line penetration is consistent with such weak rain.

The weather was marginal for seeding to work at all. Relative humidity of 15–20% is far below the conditions in which hygroscopic or glaciogenic seeding is expected to be effective. Hygroscopic seeding with NaCl can, in principle, widen the droplet spectrum and speed up coalescence in slightly subsaturated warm clouds, but the published demonstrations are mostly from marine or mountain clouds, not dry continental air. Glaciogenic seeding with AgI needs ice-supersaturated conditions and supercooled water and the ice-nucleation efficiency of AgI falls off sharply above about −5 °C. The configuration flown on 28 October falls outside both regimes.

The footprint was small, short-lived and never confirmed at the surface. A ~22-minute penetration under light winds implies a limited precipitation shadow and we found no radar or station-rain evidence of a seeded plume reaching the array. Indian CAIPEEX experience shows that even well-run hygroscopic-seeding trials need dozens of carefully balanced seed/no-seed cases to detect modest rain enhancement against natural variability; a single operation under marginal conditions sits far below that detection threshold.

### 4.4 Detection limit

We have compared the seeding afternoon with ordinary dry afternoons throughout this paper. A "signal" is a change larger than the background noise - the random, rain-free day-to-day movement of PM2.5. In this section we ask the question that the operation raises for any future attempt: how much rain must a station actually receive before a scavenging effect could be detected in data like ours? The explanation is in four steps.

**Step 1 - How the signal grows with rain.** The scavenging signal increases with the rainfall rate. Using the power law of Section 2.7, Table 5 lists the scavenging coefficient and the corresponding six-hour removal for representative rain rates.

**Table 5.** The theoretical scavenging signal as a function of rainfall rate, computed from $\Lambda_{th} = 8 \times 10^{-4} \times R^{0.79}$ (Section 2.7). Removal = $1 - \exp(-\Lambda_{th} \times 6$ hr).

| Rainfall rate R (mm hr⁻¹) | Scavenging coefficient $\Lambda_{th}$ (hr⁻¹) | Six-hour removal (%) |
|---|---|---|
| 0.15 (recorded central rate) | $1.8 \times 10^{-4}$ | ~0.1 |
| 1 | $8.0 \times 10^{-4}$ | 0.5 |
| 9 (optimistic detection limit, Step 3) | $4.5 \times 10^{-3}$ | 2.7 |
| 50 | $1.8 \times 10^{-2}$ | 10 |
| 285 (conservative detection limit, Step 3) | $7.0 \times 10^{-2}$ | 34 |

At the recorded central rate of 0.15 mm $hr^{-1}$, the predicted removal is ~0.1% over six hours - on a typical Delhi series of 300–330 μg $m^{-3}$, a change of well under 1 μg $m^{-3}$, far below the ±5 μg $m^{-3}$ precision of the monitors.

**Step 2 - How big is the noise?** A signal is detectable only if it is larger than the noise in the quantity we actually measure, the apparent decay rate $\Lambda_{app}$. Two noise scales matter: fit uncertainty - how precisely a single six-hour series can pin down $\Lambda_{app}$: at the best-constrained station, Burari Crossing, the fitted 1σ uncertainty is $1.5 \times 10^{-3}$ $hr^{-1}$; and natural variability - how much $\Lambda_{app}$ wanders from one dry afternoon to the next: at Burari the standard deviation of the five control afternoons is $2.33 \times 10^{-2}$ $hr^{-1}$, about fifteen times the fit uncertainty. Which noise is the right one depends on the question being asked.

**Step 3 - Two detection limits.** The optimistic limit is set by fit uncertainty. In a well-designed experiment, in which meteorology is controlled - for example, randomized seed/no-seed comparisons, exactly the design recommended for detecting small seeding signals against natural variability (Flossmann et al., 2018, p. 86) - the floor on the noise is set by the fit itself. Requiring the scavenging signal to reach 3σ of this noise gives $\Lambda^* = 3 \times 1.5 \times 10^{-3} \approx 4.5 \times 10^{-3}$ $hr^{-1}$. Inverting the power law gives the corresponding rain rate: $R^* = (\Lambda^*/8 \times 10^{-4})^{(1/0.79)} \approx 9$ mm $hr^{-1}$. Even in an ideal comparison, a station would need to receive roughly 9 mm $hr^{-1}$ of rain - about 60 times the recorded central rate of 0.15 mm $hr^{-1}$ - before scavenging could be separated from the noise of the fit. This is the threshold we adopt as our headline value.

The conservative limit is set by natural variability. In our actual comparison - a single, uncontrolled afternoon against five dry afternoons - the noise that a signal has to beat is the day-to-day scatter of the controls. Requiring 3σ of that scatter gives $\Lambda^* = 3 \times 2.33 \times 10^{-2} \approx 7.0 \times 10^{-2}$ $hr^{-1}$ and inverting the power law gives $R^* \approx 285$ mm $hr^{-1}$ - an extreme rainfall rate that Delhi's October–November climate essentially never produces. In a comparison like ours, with no meteorological adjustment, no realistic rain rate could have produced a detectable signal.

The two limits bracket the problem. At the recorded rain rate the predicted signal ($1.8 \times 10^{-4}$ $hr^{-1}$) is 25 times smaller than the optimistic detection limit and ~390 times smaller than the conservative limit. The recorded rain was not merely too weak to be detected; it was too weak by orders of magnitude.

**Step 4 - What this means for interpretation and for future experiments.** These numbers explain the null result. Our z-scores were −0.63, −0.85, −0.94 and −1.13 - uniformly negative, meaning PM2.5 fell more slowly, not faster, on the seeding afternoon than on dry afternoons, which is the opposite of a scavenging signature. A real scavenging signal large enough to matter would have required rain so heavy that it does not occur in this season.

For future experiments, three conditions follow. Station-level rainfall of at least ~9 mm $hr^{-1}$ is a necessary condition for any claim of a measurable seeding-driven PM2.5 reduction. Claims must be tested against pre-registered, meteorologically matched controls - the randomized-design recommendation of the WMO peer review (Flossmann et al., 2018, p. 86). And expectations must be calibrated against the size of Delhi's natural variability, which is enormous: observed PM2.5 across northern India reaches its daily minimum near 15:00 LT and its maximum around 21:00 LT as the evening boundary layer collapses (Schnell et al., 2018, p. 10168) and in the 16 October–30 November period the morning-to-afternoon swing reached ~400 μg $m^{-3}$ at sites of the CUPI-G network (Singh et al., 2023, p. 13204). A multi-hour decline of a few percent claims nothing by itself. The international record of randomized seeding makes the same point: the six-year Wyoming experiment applied its test statistic to 118 experimental units and obtained a p-value of 0.28 - insufficient evidence of an effect even with a carefully designed target–control setup - and the average impact of seeding on natural precipitation is an estimated ~20%, with the impact on any individual cloud possibly negative (Flossmann et al., 2018, p. 75).

Put simply: at the recorded rain rate the predicted scavenging removal is ~0.1% over six hours - invisible in our data, 25 times below even the most optimistic detection threshold and ~390 times below the threshold relevant to an uncontrolled comparison. A station would need roughly 9 mm $hr^{-1}$ of rain for scavenging to become visible under ideal conditions and far more (≈285 mm $hr^{-1}$) in a comparison like ours. The recorded rain was 0.15 mm $hr^{-1}$. The operation could not have produced a measurable PM2.5 signal.

### 4.5 Other ways to explain the observed declines

Three mechanisms, none requiring rain scavenging, can each fully explain the observed 1.6–6.0% range. Boundary-layer dilution and the evening transition - the default daily behaviour of Delhi PM2.5 at this time of year - is shown directly by our control afternoons and by the published record (Bhandari et al., 2020; Ojha et al., 2020). Advection of a cleaner air mass is a second candidate: a wind shift away from crop-burning or stagnant regions would lower concentrations without any local wet removal, though we cannot separate this from dilution without trajectory or tracer data. The third concerns the seeding material itself: the NaCl particles that were released are themselves PM2.5. If any non-activated fraction stayed airborne and reached the DPCC/SAFAR monitors, it would push measured PM2.5 upward - that is, against a reduction and toward the null we observe.

Finally, the official claim of a "6–11% reduction in PM2.5" can be reconciled with our 1.6–6.0% range. The official figures came from short, peak-to-trough comparisons and they used the two-point estimator; we used the more conservative fitted estimator over a fixed six-hour window. A sharp afternoon peak followed by ordinary boundary-layer decay always looks bigger in a peak-to-trough comparison than in a fit to the same window.

### 4.6 Limitations

1. **Single event, post-hoc design.** No two afternoons are truly comparable; the pre-selected control set reduces, but cannot remove, this concern.
2. **Window timing.** The 16:00–22:00 IST window does not start at seeding time. We chose it for data availability and advective-response reasons (Section 2.2), but it cannot resolve sub-daily response timing. An alternative-window sensitivity check is required before submission.
3. **Coarse rainfall attribution.** No station-level rainfall for 28 October 2025 could be verified from the available telemetry. The theoretical benchmark is therefore an explicit upper bound.
4. **Two uninformative fits.** Wazirpur and Rohini ($R^2 \approx 0.15$ and 0.14) add only qualitative information.

## 5. CONCLUSIONS AND RECOMMENDATIONS

The 28 October 2025 operation produced PM2.5 declines of 1.6–6.0% at four stations within 6.87 km of the flight track. Fitted apparent decay rates $\Lambda_{app}$ range from $5.39 \times 10^{-4}$ to $5.60 \times 10^{-3}$ $hr^{-1}$ and are uniformly below the dry-afternoon means at the same stations (z-scores from −0.63 to −1.13; none significant). The theoretical scavenging signal at the recorded rainfall is 0.08–0.13% six-hour removal - one to two orders of magnitude below both the observed declines and the natural afternoon variability - and no plausible parameterisation uncertainty changes that conclusion. We find no statistically detectable scavenging effect of the operation. Read this way, a widely publicised event collapses into a clean quantitative statement about the rainfall required (≈9 mm $hr^{-1}$, roughly 60× the recorded amount) before urban cloud seeding could possibly move PM2.5 against Delhi's normal afternoon behaviour.

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**FIGURES**

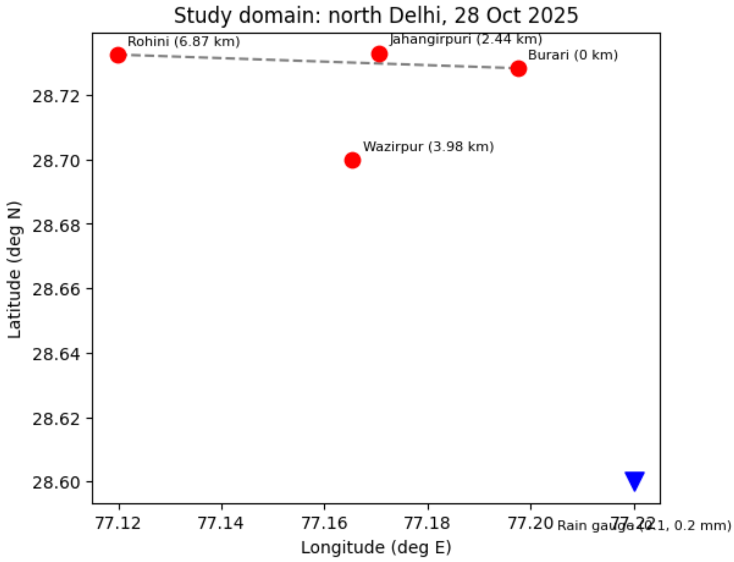


**Figure 1.** Map of the study area over north Delhi, showing the Rohini–Burari seeding flight corridor (dashed line), the four PM2.5 monitoring stations with their distances from the flight track (0, 2.44, 3.98, 6.87 km) and the Delhi–Noida border rain gauge. Station coordinates are listed in Table 1.

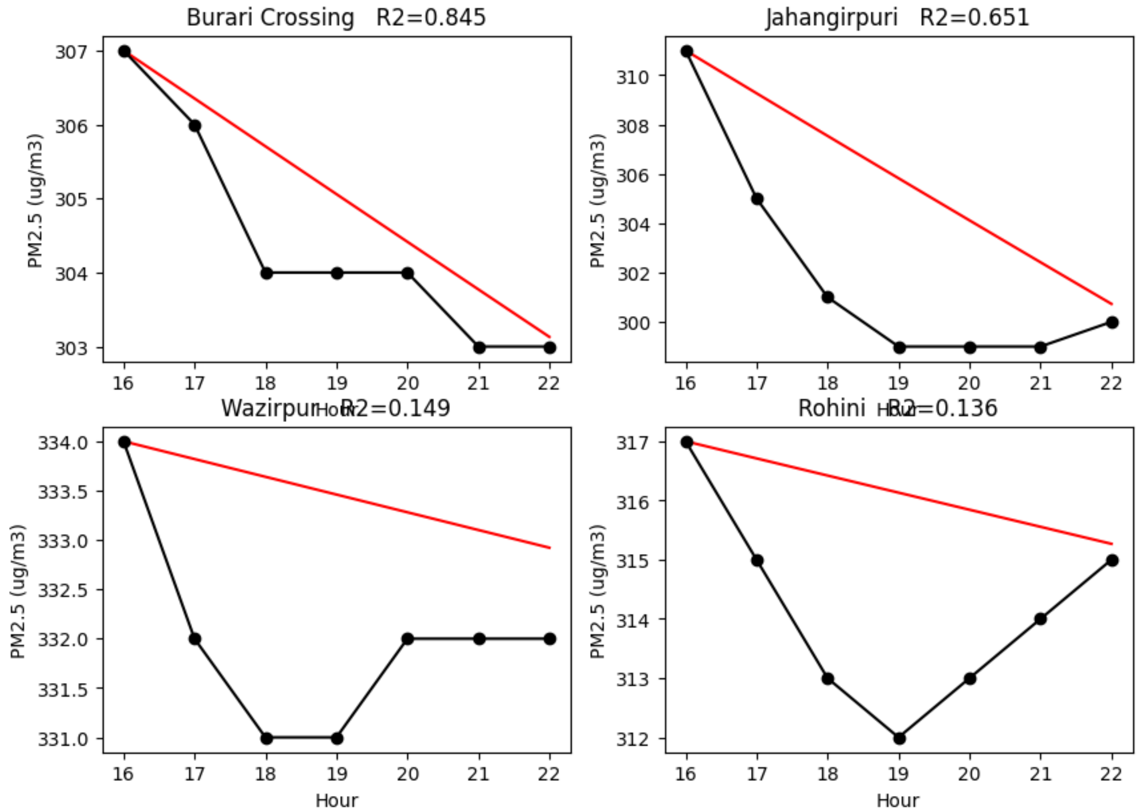


**Figure 2.** Hourly PM2.5 concentrations (µg m$^{-3}$) at the four stations from 16:00 to 22:00 IST on 28 October 2025 (symbols; data in Table 4), with the fitted exponential decay curves $C(t) = C_0 \times \exp(-\Lambda_{app} \times t)$ from Eq. (lines). The dashed line marks each station's 14:00–15:00 baseline. $R^2$ values: Burari Crossing 0.845; Jahangirpuri 0.651; Wazirpur 0.149 (flagged); Rohini 0.136 (flagged). Note the near-flat Burari series within the window.

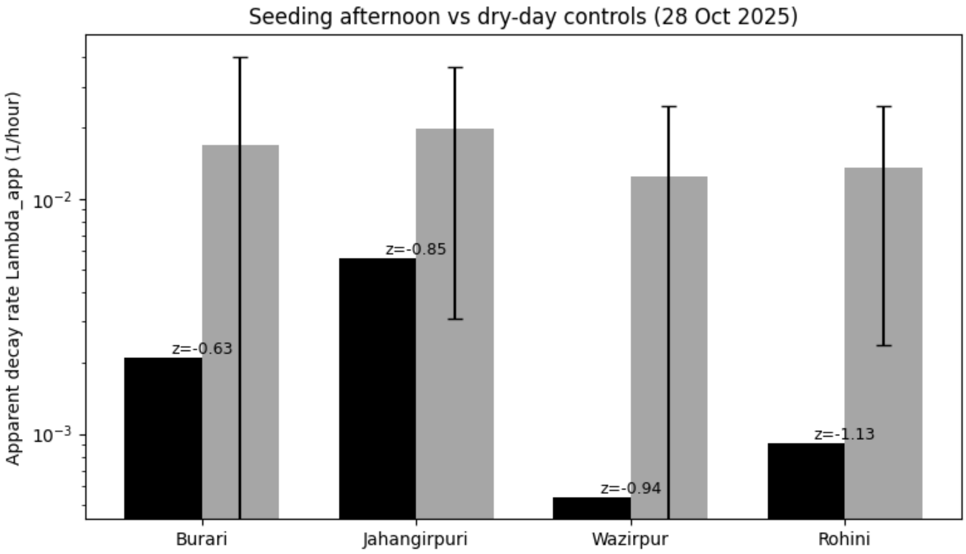


**Figure 3.** Apparent decay rates on the seeding afternoon (filled bars) versus the mean ± 1 SD of the five dry-afternoon controls at the same stations (grey bars; 6, 24, 26 October and 2, 9 November 2025), logarithmic axis. All seeding-afternoon values fall inside the control envelope; z-scores are −0.63, −0.85, −0.94 and −1.13 - uniformly negative and none exceeding ±1.96.

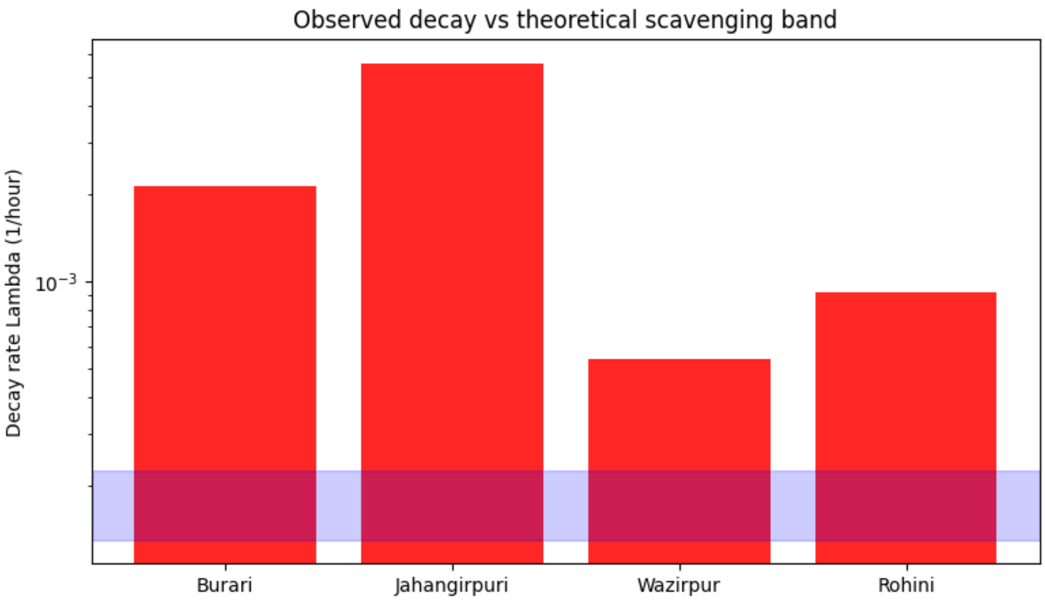


**Figure 4.** Observed apparent decay rates $\Lambda_{app}$ (bars) versus the theoretical below-cloud scavenging band for the recorded rainfall (shaded region: $\Lambda_{th}$ = 1.30–2.24 × $10^{-4}$ $hr^{-1}$ for R = 0.1–0.2 mm $hr^{-1}$), logarithmic axis, with the parameterisation-uncertainty envelope (hatched, spanning a factor of ~10 - from the ~10–20% spread among theoretical formulas up to the order-of-magnitude theory–field gap). Observed-to-theoretical excess factors range from about 2.4× to 43×.

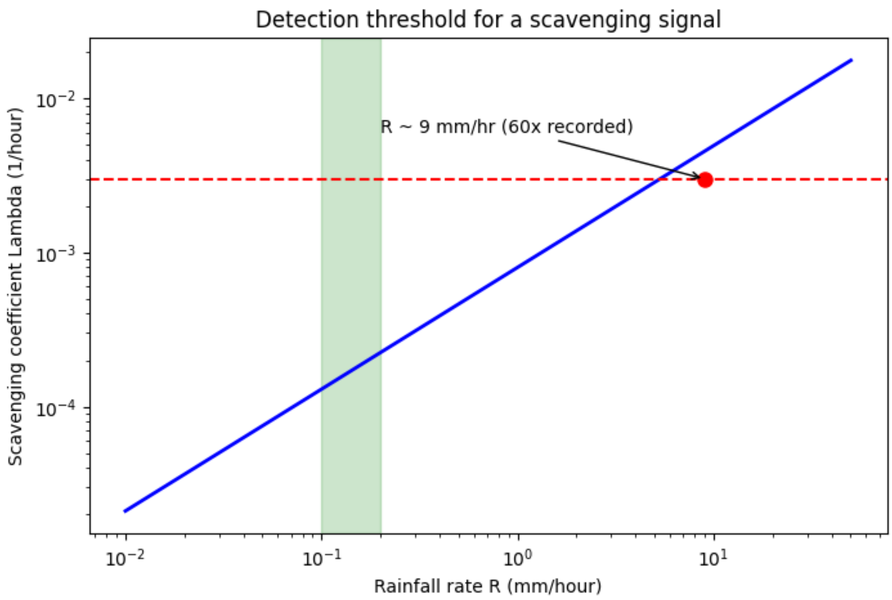


**Figure 5.** Theoretical below-cloud scavenging coefficient $\Lambda_{th} = 8 \times 10^{-4} \times R^{0.79}$ as a function of rainfall rate (solid curve, log–log), the recorded rainfall range (vertical shaded band, 0.1–0.2 mm $hr^{-1}$) and the detectability target of about $3 \times 10^{-3}$ $hr^{-1}$ (dashed line), which crosses the curve at $R \approx 9$ mm $hr^{-1}$ - roughly 60× the recorded central rain rate.

## DATA AVAILABILITY

Hourly PM2.5 data are publicly available from the DPCC and SAFAR networks; telemetric rainfall records are from the IMD. The hourly series used in this analysis are reproduced in Table 4 and the analysis and figure-generation scripts will be deposited in a public archive at acceptance.

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