

Eleven winters, ten Diwalis: separating weather, farm fires and fireworks in India's PM_{2.5}, 2016–2026

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ABSTRACT

Delhi's winter air is usually blamed on three things that arrive together: stagnant weather, smoke from paddy-residue fires in Punjab and Haryana, and Diwali fireworks. We separate them in an exploratory analysis of hourly data from 105 monitoring sites in 39 Indian cities (2016–2026), NASA VIIRS fire detections and ERA5 weather. Gradient-boosted models remove the effect of weather and, for Delhi, of farm-fire smoke carried by the wind; what remains on Diwali night is the festival's own contribution. Diwali's lunar date moved between 19 October and 14 November over the decade, and Delhi's firecracker rules changed four times, which lets us compare like with like. Three findings stand out. First, the reference monitor at the US Embassy stops reporting during the worst hours of Diwali night: 52% of late-night Diwali hours are missing, against 4% on ordinary autumn nights, so averages built on it understate the festival. Second, using the less-censored CPCB network median, Diwali night adds 127–392 $\mu\text{g}/\text{m}^3$ above the weather-and-fire baseline in every year observed, 6 of 7 nights beyond the 99th percentile of ordinary nights, and years with a full ban were not lower than years with green crackers. Third, VIIRS detections in Punjab and Haryana fell 94% between 2021 and 2025, but the share caught by the 1:30 am pass rose from 0.2% to 4.7%, and in 2025 each detected fire went with a roughly tenfold larger rise in Delhi's weather-adjusted PM_{2.5}, though with wide uncertainty. Both are consistent with burning that has moved out of the satellite's daytime view. We publish a locked, checksummed forecast for Diwali 2026 and release all code, derived data and an interactive companion site.

Introduction

Every October and November, PM_{2.5} in Delhi climbs to many times the Indian 24-hour standard of 60 $\mu\text{g}/\text{m}^3$. Three explanations dominate public debate. The first is meteorology: as the monsoon withdraws, the boundary layer becomes shallow, winds slacken and pollution builds up. The second is the burning of paddy residue in Punjab and Haryana, whose smoke north-westerly winds carry towards Delhi. The third is Diwali, which in most years falls inside the same weeks and brings a night of fireworks.

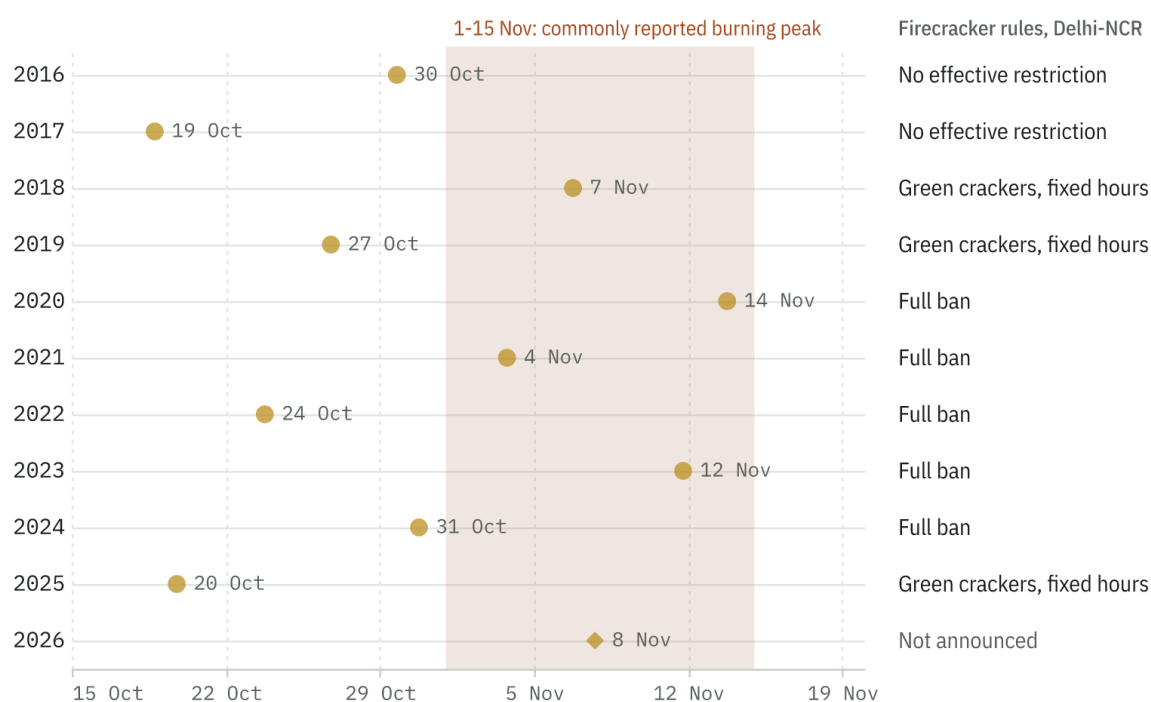
Because the three arrive together, a high reading in early November cannot be pinned on any one of them by looking at it. Earlier work has addressed parts of the problem. Weather-normalisation with machine learning (Grange et al. 2018) has been applied to Delhi (Verma et al. 2025) and to India's National Clean Air Programme cities (Health Effects Institute 2025). The best-known causal estimate of the Diwali effect used an event-study design for 2013–2017 but did not separate firecracker smoke from crop smoke (Ghei and Sane 2018). On the farm-fire side, recent studies report that burning in Punjab now happens later in the afternoon, after the polar-

orbiting satellites have passed (NASA Earth Observatory 2025; iFOREST 2025; Biswal et al. 2025), and that Delhi's PM_{2.5} has become only weakly coupled to official fire counts (Mangaraj et al. 2025).

This study uses three things that change from year to year to pull the causes apart (Fig. 1). Diwali follows the lunar calendar, so its date moves across the burning season: in some years it comes before the main burning, in others in the middle of it. Delhi's firecracker rules changed from no effective restriction (2016–2017) to green crackers in fixed hours (2018–2019), a full ban (2020–2024) and back to green crackers in 2025 (Deccan Herald 2025). And the timing of crop burning itself appears to have shifted.

Our contributions are:

1. A weather-and-fire baseline for Delhi's hourly PM_{2.5}, against which each Diwali night is compared with 211 ordinary autumn nights scored the same way.
2. Evidence that the reference monitor most often used for Delhi goes dark at the peak of Diwali night, and a censoring-aware way to measure the festival.
3. A satellite-internal signature of the shift in burning time: a rise in the share of fires caught by VIIRS's night pass, which needs no other satellite.
4. A season-by-season estimate of how strongly Delhi's PM_{2.5} tracks upwind fire detections.
5. A pre-registered forecast for Diwali 2026, and an open, one-command pipeline that rebuilds every number, figure and the companion website.



Diwali (Lakshmi Puja) dates, 2016–2026, and the firecracker rules in force in Delhi-NCR. The shaded band marks 1–15 November, commonly reported as the peak of paddy-residue burning.

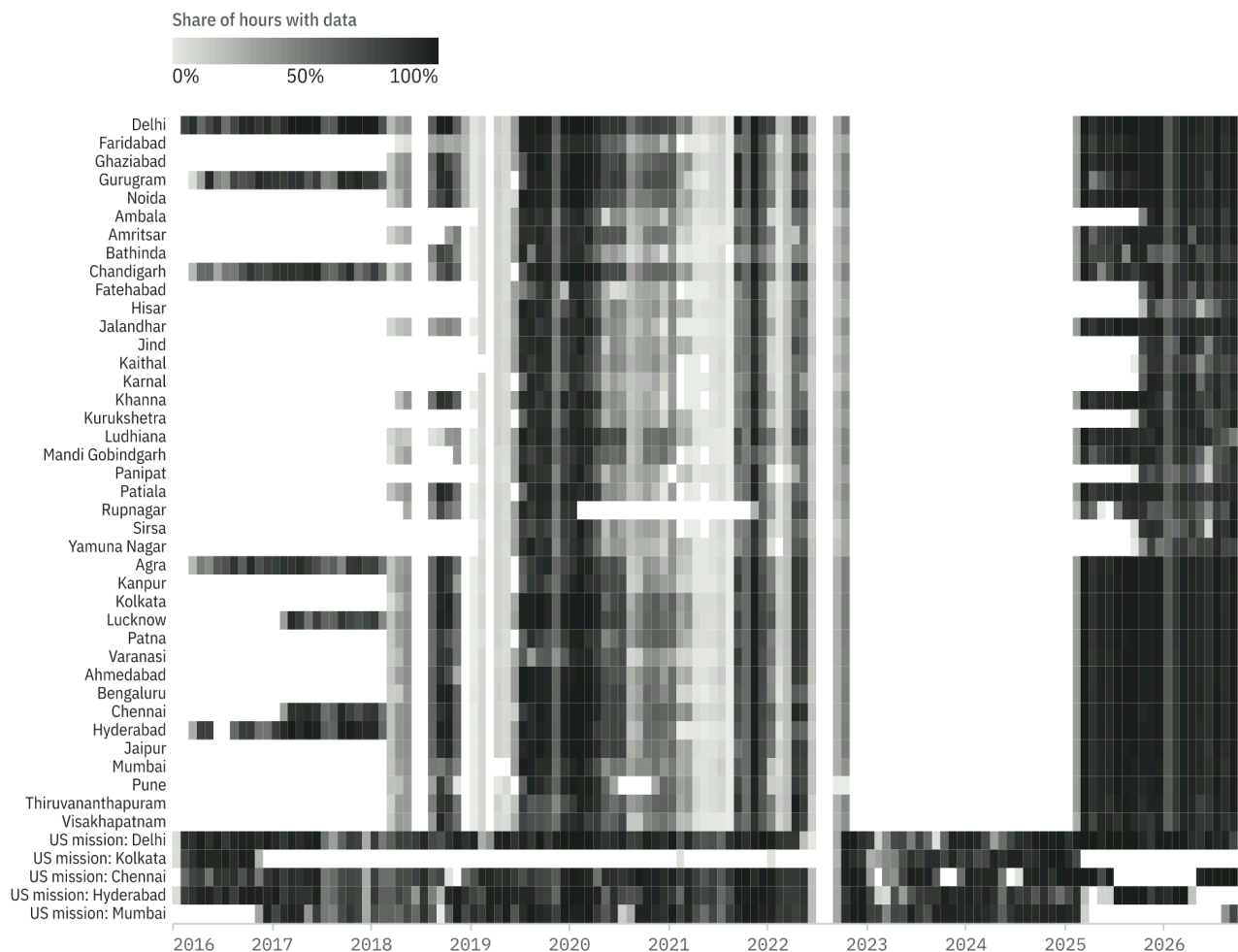
Data

Air-quality monitors

Hourly concentrations of PM_{2.5}, PM₁₀, NO₂, SO₂ and CO come from the public OpenAQ archive (OpenAQ 2026), which republishes the Central Pollution Control Board (CPCB) continuous monitoring network and the US Department of State's embassy and consulate monitors. We matched monitors to 39 study cities by distance and kept the longest-running sites in each, giving 100 CPCB-network sites and 5 US-mission sites (132 archive locations, since the same physical monitor often appears under two identifiers after a change of data feed). The archive timestamps mark the end of each averaging period; we label each hour by its start.

The archive has a gap that matters for this study: CPCB-network data are absent from late 2022 to early 2025 (Fig. 2). The US-mission monitors, which use reference beta-attenuation instruments, run almost without interruption, so the US Embassy in New Delhi provides the only continuous decade-long record for Delhi.

Quality control removed 4.6% of 2,841,635 site-hours of PM_{2.5}: values at or below zero or at the instrument ceiling, runs of six or more identical readings, single-hour spikes far above both neighbours, PM_{2.5} above PM₁₀, and a pattern we call a stall, in which a high reading is repeated for one or two hours just before the record goes blank. Multi-hour events such as Diwali nights are deliberately not removed.



Share of hours with a valid PM_{2.5} reading, by city and month. CPCB-network data are missing from the OpenAQ archive from late 2022 to early 2025; the US mission monitors run almost without a break.

Fire detections

Active-fire detections come from NASA FIRMS (NASA LANCE FIRMS 2026): VIIRS on Suomi-NPP at 375 m (Schroeder et al. 2014), which crosses India at about 1:30 pm and 1:30 am local time, and MODIS (Giglio et al. 2016). We keep detections classified as presumed vegetation fires, assign them to Punjab or Haryana with state boundaries from geoBoundaries (Runfola et al. 2020), and, as a robustness check, drop 0.02° grid cells that light up in four or more months outside the two crop-burning seasons (likely kilns, flares and other fixed heat sources). VIIRS detections in Punjab and Haryana in October–November track the official Punjab season counts closely in the three years for which we have both.

Weather

Hourly temperature, humidity, precipitation, surface pressure, 10 m wind, cloud cover, solar radiation and boundary-layer height for each city come from the ERA5 reanalysis (Hersbach et al. 2020) through the Open-Meteo archive API (Zippenfenig 2023).

Methods

Weather normalisation

For each site with at least 500 valid days we fit a LightGBM model (Ke et al. 2017) of daily log PM_{2.5} on daily weather summaries and calendar terms (a linear time trend, day of year and day of week). Following Grange et al. (2018), the weather-normalised value for each day is the average of 200 predictions in which the weather columns are replaced by draws from the site's whole record while the calendar terms are kept. Predictions are back-transformed with Duan's smearing factor (Duan 1983). Model skill comes from five-fold cross-validation in which whole calendar years are held out together. To compare winter with the monsoon, we compute the winter (November–January) minus monsoon (July–September) gap in the observed and the normalised series; the share of the observed gap that disappears after normalisation is the share attributable to weather. For Delhi we test for trend in the deseasonalised normalised monthly series with the Theil–Sen estimator (Sen 1968) and Kendall's test, and search for change points with PELT (Killick et al. 2012).

The Diwali baseline

For Delhi and four other cities we fit an hourly business-as-usual (BAU) model of log PM_{2.5} on weather, rolling 6- and 24-hour summaries of wind, boundary-layer height and rain, calendar terms and, for northern cities, a wind-aware fire index (below) with lags of 0–3 days. Diwali windows (three days either side) are never used for training, and every hour is predicted out of fold, with whole ISO weeks held out together, so that Diwali nights and ordinary nights are judged by the same standard. The out-of-fold R^2 on log PM_{2.5} for ordinary hours is 0.75 for the US Embassy and 0.78 for the CPCB network median.

The Diwali-night excess is the mean of observed minus BAU from 6 pm on Diwali to 3 am the next morning. Because monitors often go missing during the worst hours (Section 4.1), we fill missing hours inside the window with the last valid reading. This is a rough lower bound, since the monitors fail while concentrations are rising. Our main receptor is the median across CPCB Delhi sites in hours with at least three reporting, which is far less affected by single-monitor failures; the US Embassy series is used as a cross-check. As a reference distribution we apply the same calculation to every ordinary night between 1 October and 15 December, excluding the days around Dussehra, Chhath and Gurpurab.

For the fingerprint we compare 6 pm to midnight on Diwali with the same hours on the five nights a week earlier at each CPCB Delhi site, for the PM_{2.5}/PM₁₀ ratio, SO₂, CO and NO₂, using Wilcoxon signed-rank tests.

Wind-aware fire index and coupling

For each day the fire index adds up VIIRS detections in Punjab and Haryana, each weighted by $\max(0, \cos \theta)$, where θ is the angle between the bearing from Delhi to the fire and the direction the wind is blowing from, and by $\exp(-d/300 \text{ km})$, where d is the distance to Delhi. The transport wind is the daily vector-mean 10 m wind at Delhi, Panipat, Patiala and Ludhiana, along the Punjab–Delhi corridor. To find how long smoke takes to arrive, we correlate the index at lags of 0–5 days with the daily log-residual of a weather-only model of Delhi's PM_{2.5} (US Embassy), after

removing each season's mean. For coupling, we regress the same residual on the index averaged over the strongest lags, separately for each season (10 October–30 November, Diwali excluded), with Newey–West standard errors (Newey and West 1987).

Ground test of a shift in burning time

If burning has moved into the evening, the evening share of PM_{2.5} at monitors inside Punjab and Haryana should rise during the harvest. For each site and season we compute the ratio of mean PM_{2.5} at 6 pm–midnight to that at 10 am–4 pm, during 15 October–30 November and during 5–31 December of the same year, and compare the ratio of the two between seasons.

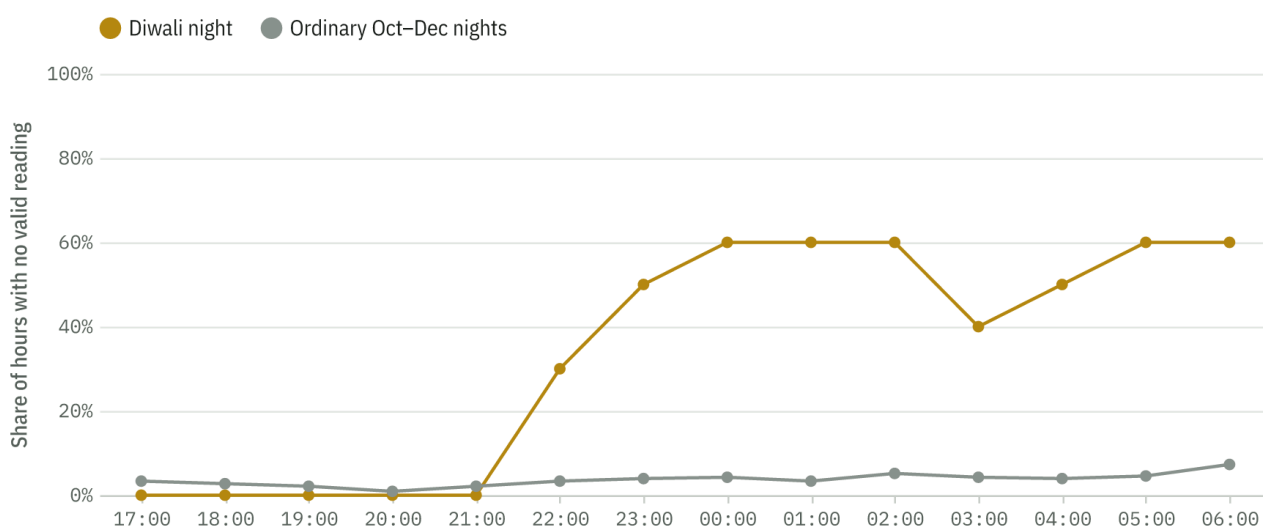
Pre-registered forecast

Before Diwali 2026 (8 November) we lock a forecast of the CPCB-network Diwali-night excess for each possible firecracker regime: the mean of past Diwalis under the same rules, with an 80% prediction interval from the variance pooled across regimes. The record is committed to the public repository with its SHA-256 checksum.

Results

The monitor that goes dark

At the US Embassy, 52% of the hours between 10 pm and 3 am on Diwali nights have no valid reading, against 4% on ordinary autumn nights when the monitor was running, about 13 times as often (Fig. 8). Gaps occurred on 7 of 10 Diwali nights. They begin at 10 pm, one to three hours into the evening rise, and often follow an hour or two in which the instrument repeats its last reading. The CPCB network median, which combines many monitors, lost 14% of the same hours in the 7 Diwalis it covers. The two records also disagree from year to year: their Diwali-night excesses are uncorrelated (Pearson $r = -0.11$, 7 years). Any Diwali estimate built from the Embassy record alone leaves out the peak.

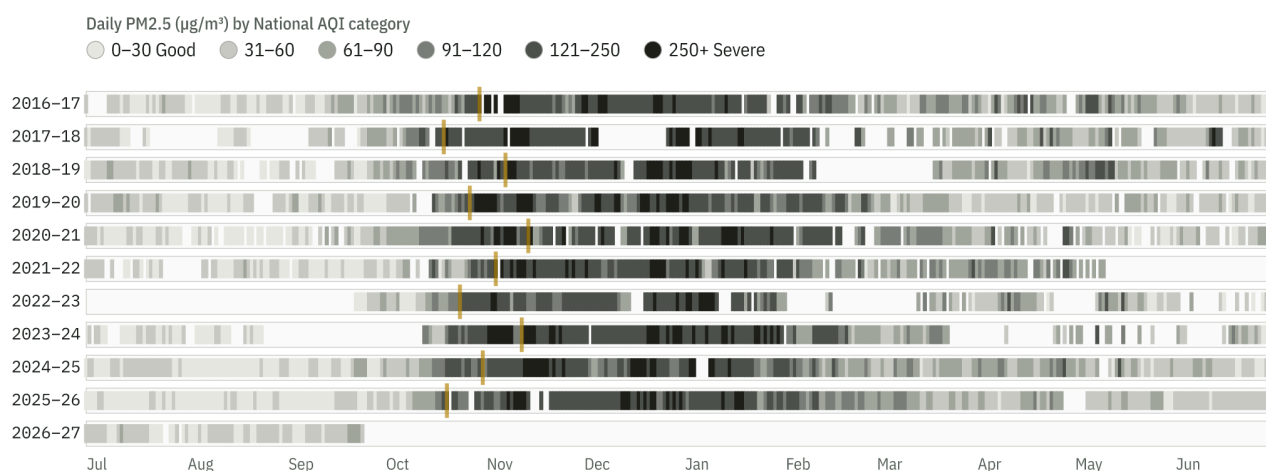


Share of hours with no valid reading at the US Embassy monitor, Diwali nights against ordinary autumn nights.

Weather and the winter gap

The daily weather models reach a median cross-validated R^2 of 0.52 on log PM2.5 across 103 sites (interquartile range 0.28–0.68; 0.82 at the US Embassy). We leave out of the comparison the 37 sites below $R^2 = 0.4$, mostly short records in Punjab and Haryana where holding out whole years leaves the model little to learn from. Across the remaining 66 sites in 23 cities, weather accounts for a median of 62% of the winter-minus-monsoon gap in Delhi-NCR (5 cities, range 61%–68%), 48% in Punjab and Haryana (7 cities, 39%–62%), 82% in the rest of the Gangetic Plain (6 cities) and 81% outside the plain (5 cities; Fig. 4). The burning belt stands out: where paddy residue is burned, weather explains only about half of the winter rise, and in Delhi-NCR, downwind of it, about three-fifths. Further east along the plain and in southern and western cities, most of the seasonal swing is the monsoon washing the air clean and the shallow winter boundary layer trapping what is emitted all year. Removing weather shrinks the north–south difference in winter PM2.5 from 45 to 33 $\mu\text{g}/\text{m}^3$, so about 27% of that difference is weather and the rest is emissions.

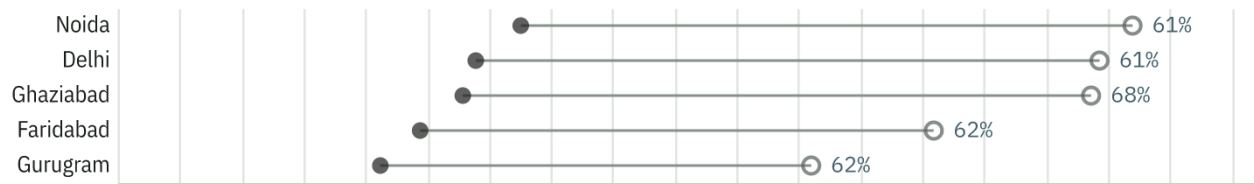
Did the 2020 drop last? In Delhi, largely yes (Figs. 3 and 5). Over the whole record the weather-normalised series at the US Embassy falls by 1.6% a year (Theil–Sen), but the decline is not smooth: the only change point PELT finds in the deseasonalised series is at 2020-01. During the national lockdown, normalised PM2.5 was 14% below its 2016–2019 level. From June 2020 to September 2026 it averaged 11% below that level (one-sided Mann–Whitney $p < 0.001$), and within that later period it fell by only 0.5% a year (95% CI 0.0 to 0.9). The lower level that followed the lockdown held, but little further progress followed it. Because the normalisation model includes a smooth time trend, it may spread part of a sharp step over neighbouring months; the step and the slope should be read together.



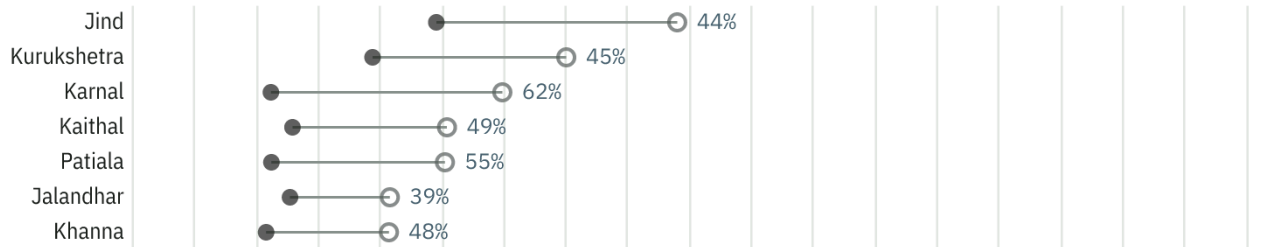
Daily mean PM2.5 at the US Embassy, one strip per season from July to June, shaded by India's National AQI category. Marigold ticks mark Diwali.

Delhi-NCR

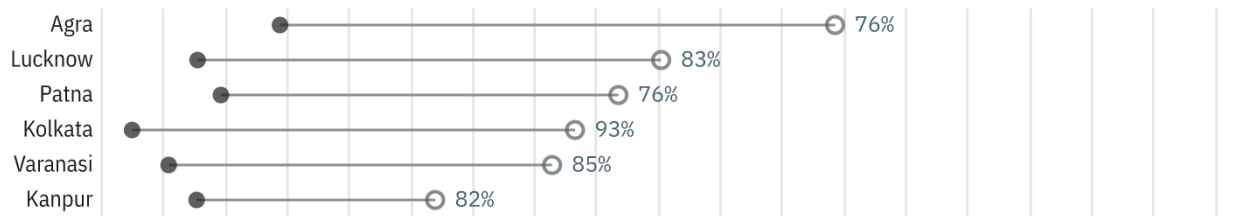
Filled: weather removed. Open: observed. Number: share of the gap due to weather.



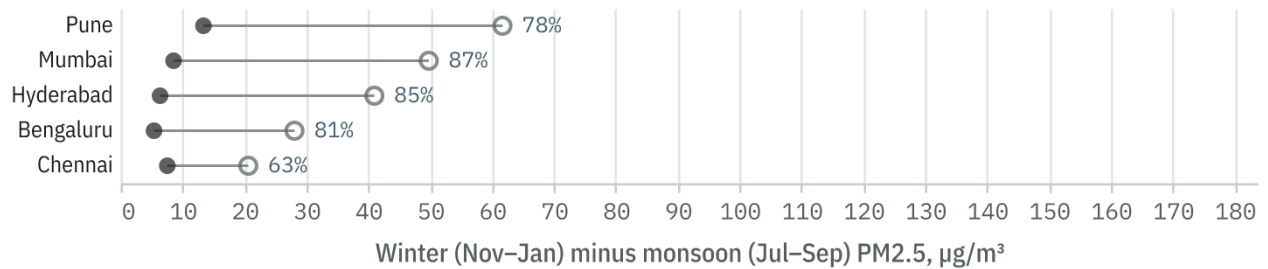
Punjab and Haryana



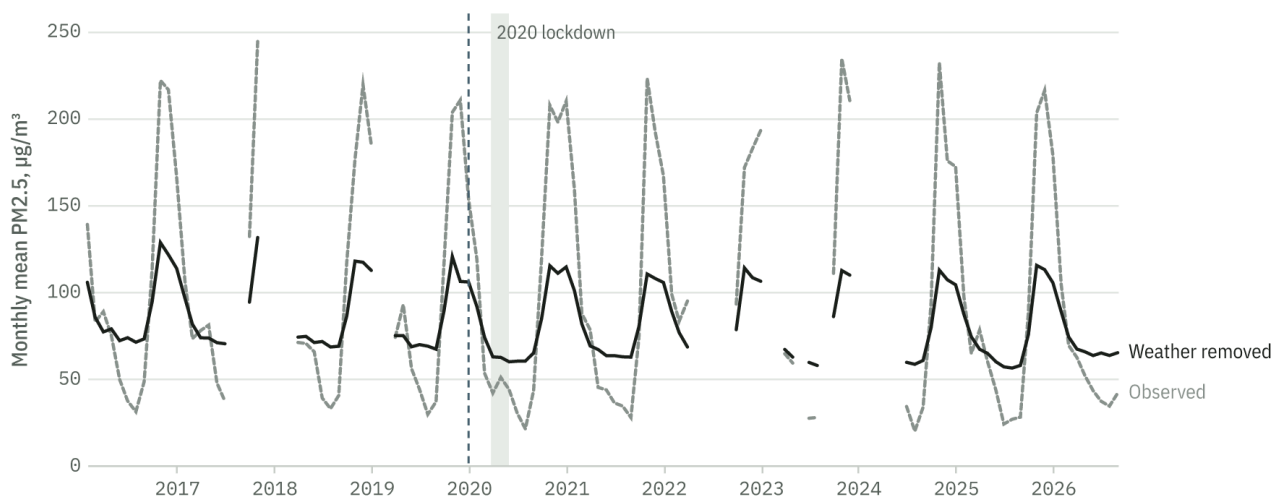
Rest of the Gangetic Plain



Outside the plain



Winter (Nov–Jan) minus monsoon (Jul–Sep) PM_{2.5} by city, as observed (open circle) and after removing weather (filled). The number is the share of the gap that weather accounts for.



Monthly PM_{2.5} at the US Embassy, observed and weather-normalised. The dashed line marks the change point found in the deseasonalised normalised series; the shaded band is the 2020 national lockdown.

Diwali

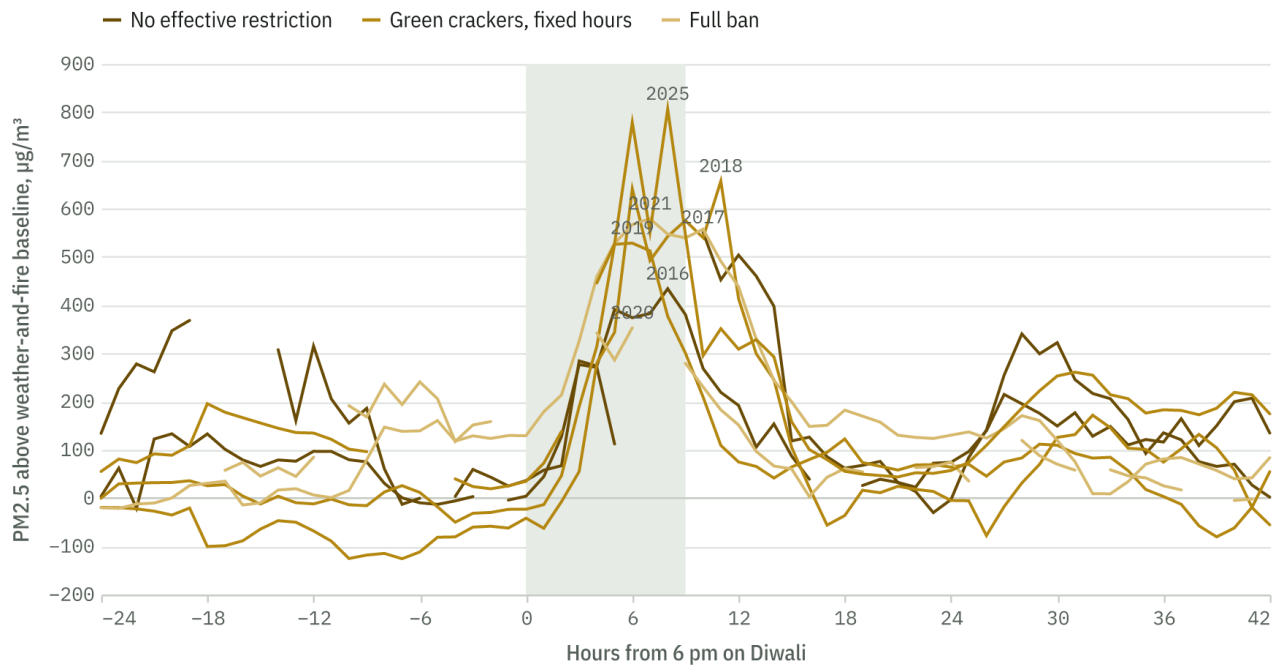
In every year with data, Diwali night rises far above the weather-and-fire baseline (Fig. 6). In the CPCB network median the excess ranged from 127 to 392 $\mu\text{g}/\text{m}^3$ (mean 289), against a 99th percentile of 193 $\mu\text{g}/\text{m}^3$ across 211 ordinary nights; 6 of 7 Diwali nights exceeded it (Fig. 7).

The firecracker rules made no visible difference. The mean excess was 192 $\mu\text{g}/\text{m}^3$ in the two years without a bursting restriction (2016, 2017), 303 $\mu\text{g}/\text{m}^3$ in green-cracker years (2018, 2019, 2025) and 366 $\mu\text{g}/\text{m}^3$ in the full-ban years the network covers (2020, 2021) (Kruskal–Wallis $p = 0.18$). The samples are small and the archive gap removes three full-ban Diwalis, so this is descriptive, but nothing in the record suggests the bans shrank the spike. The smallest excess (128 $\mu\text{g}/\text{m}^3$) came in 2017, when the Supreme Court suspended sales in Delhi-NCR about ten days before an early Diwali (9 and 19 October). The two largest came in 2021, under a full ban (392), and 2025, the first year green crackers were allowed again (386), which also had the fewest farm fires of the decade.

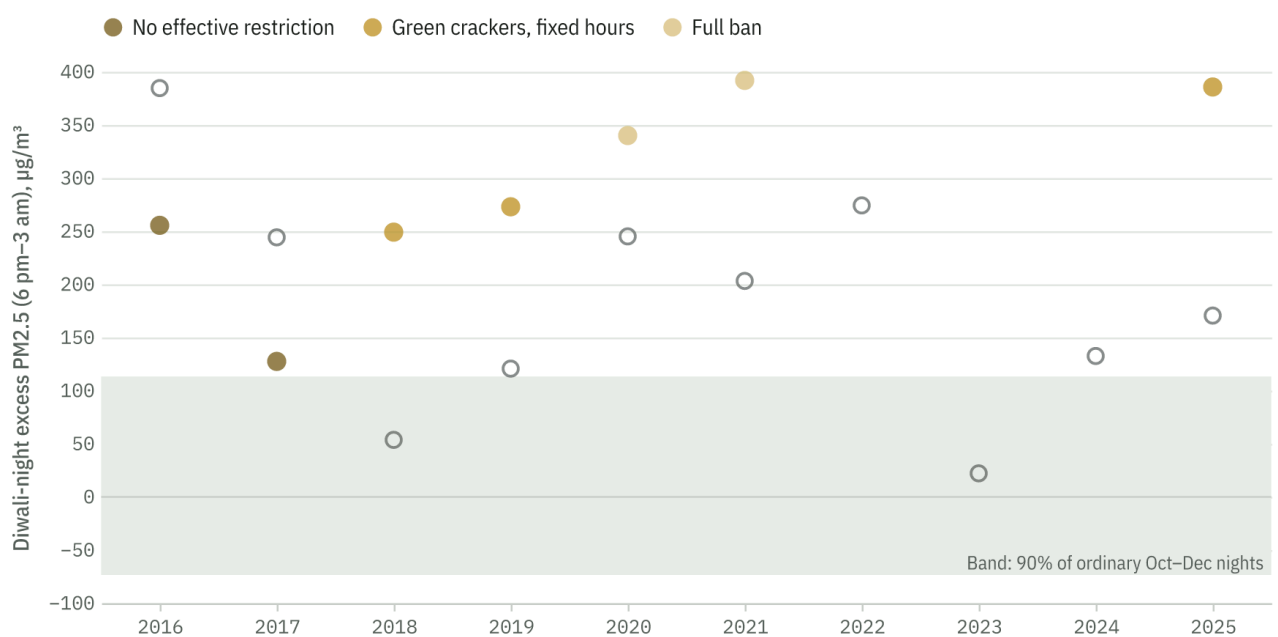
The farm-fire term matters little on Diwali night. Including it in the baseline changed the US Embassy Diwali excess by a median of $-5 \mu\text{g}/\text{m}^3$, and with or without it the excess is unrelated to the fire exposure on Diwali night (Spearman $\rho = -0.31$ and -0.22 , $n = 10$, neither significant). The festival's excess is local; it is not farm smoke being misattributed.

The Diwali evening carries a firework fingerprint at CPCB Delhi sites (Fig. 10). Against the same hours a week earlier, the PM_{2.5}/PM₁₀ ratio rose in 96% of 47 site-years (median 0.41 $\rightarrow$ 0.69, Wilcoxon $p < 0.001$), so the extra particles are fine ones, and SO₂, released by the sulphur in fireworks, rose in 70% (median +37%, $p < 0.001$). The traffic gases moved the other way: NO₂ changed by a median of -8% and CO by -11% , consistent with fewer vehicles on the road on Diwali evening. A rise in fine particles and SO₂ without a rise in NO₂ and CO points to fireworks rather than traffic or a general build-up.

The timing follows local custom (Fig. 9). In Delhi the median excess peaks around midnight and stays high until morning. In Mumbai and Hyderabad it peaks between 8 and 11 pm on Diwali. In Chennai the largest peak comes on the evening before Diwali as dated in Delhi, consistent with Deepavali being celebrated on Naraka Chaturdashi in Tamil Nadu; Kolkata, with few years of data, shows peaks on both evenings.



Hourly PM_{2.5} above the business-as-usual baseline (weather, calendar and wind-aware fire index) around Diwali night, CPCB Delhi network median, one line per year coloured by the firecracker rules. Shading marks 6 pm–3 am.



Diwali-night excess PM_{2.5} (6 pm–3 am, above the weather-and-fire baseline) by year. Filled points: CPCB network median, coloured by the firecracker rules. Open circles: US Embassy, with missing hours carried forward. The band covers 90% of ordinary October–December nights in the network median.

Delhi (CPCB network)



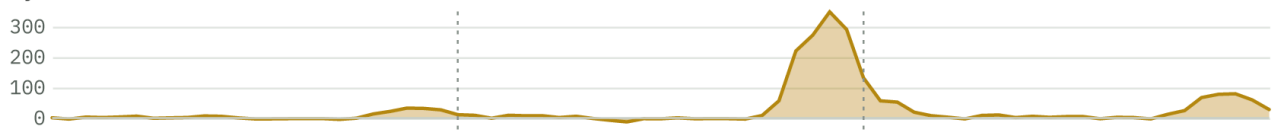
Kolkata



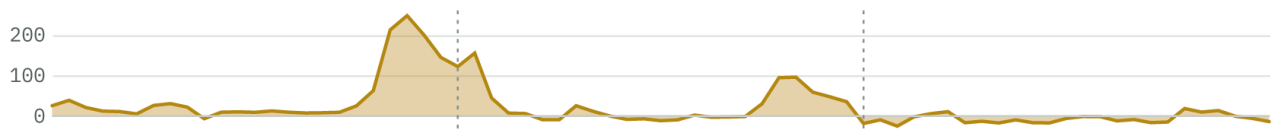
Mumbai



Hyderabad

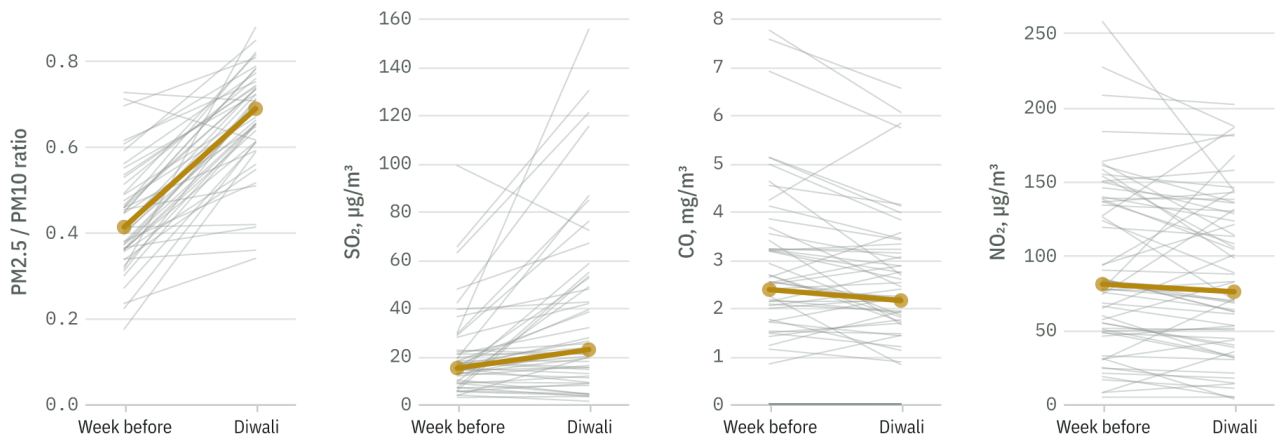


Chennai



Clock time; dotted lines mark the midnights before and after Diwali day

Median hourly excess PM_{2.5} above the baseline around Diwali in five cities (Delhi: CPCB network median; others: US mission monitors). Dotted lines mark the midnights before and after Diwali day as dated in Delhi.



Diwali evening (6 pm–midnight) against the same hours on the five nights a week earlier, at CPCB Delhi sites. Thin lines are site-years; the thick line joins the medians.

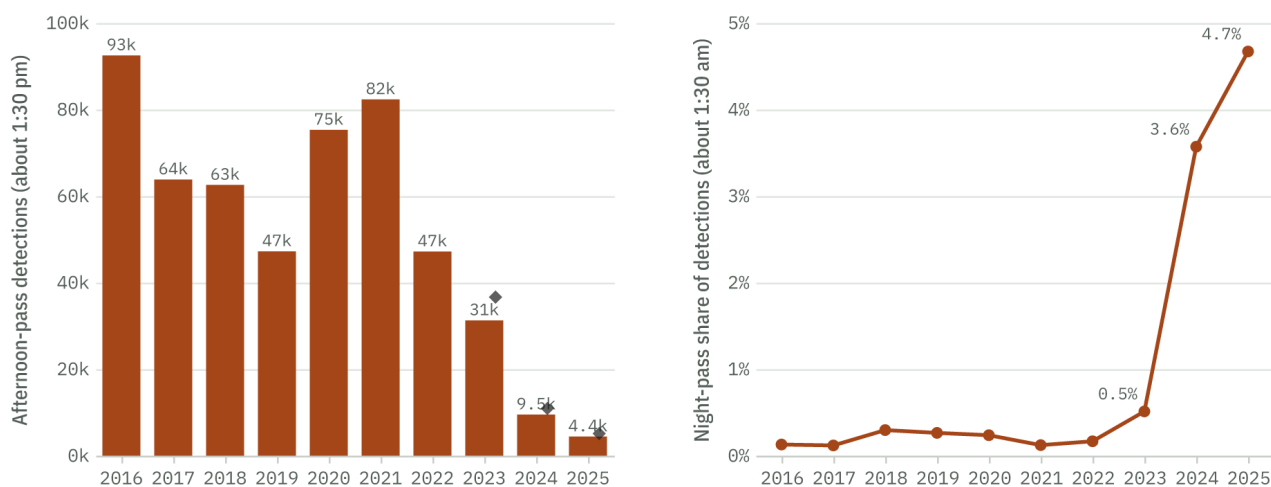
The fire-count paradox

VIIRS detections in Punjab and Haryana during October–November peaked at 100,736 in 2016 and fell to 5,121 in 2025, 94% below 2021 (Fig. 11). The night pass tells a different story. Before 2024 the 1:30 am pass caught 0.2% of detections on average; in 2024 it caught 3.6% and in 2025 4.7%. In Punjab, night-pass detections reached 91 in 2024 and 77 in 2025, against at most 43 in any season from 2016 to 2023, even though daytime detections fell by more than 90%. The rise

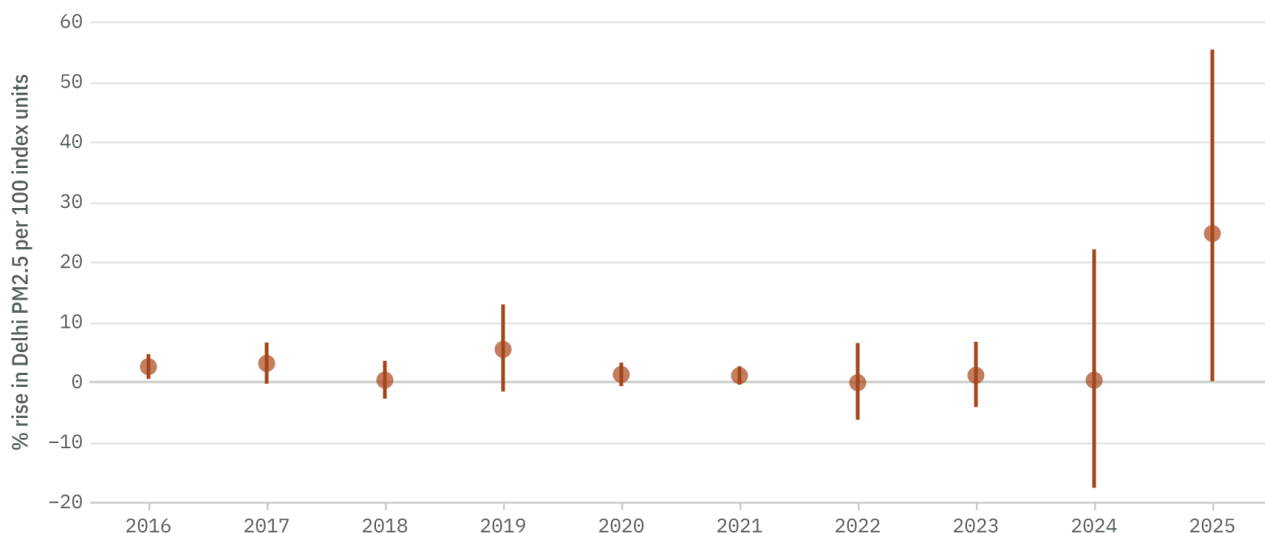
survives removal of fixed heat sources. A satellite that only looks twice a day cannot show when fires start, but more fires still burning at 1:30 am is what a shift of ignition into the evening would produce, and it agrees with geostationary evidence reported elsewhere (iFOREST 2025; NASA Earth Observatory 2025).

Delhi's weather-adjusted PM_{2.5} responds to the fire index over one to four days rather than on a single day: Spearman ρ is 0.10 on the same day and between 0.16 and 0.17 at lags of one to four days. Per unit of the index, the response was small and fairly stable in 2016–2021 (mean 2.2% per 100 index units) and about ten times larger in 2025 (25%, 95% CI 0 to 55%; Fig. 12). The 2025 interval is wide and only just excludes zero, and 2024 is too uncertain to read, so this is suggestive rather than conclusive. It is, however, what an undercount would produce: if each detected fire stands for more burning than before, each detection goes with more smoke. This offers a second explanation for the weak coupling between counts and Delhi's air reported by Mangaraj et al. (2025), alongside the local controls they discuss. To make the estimate robust to how the data are split, the residuals behind it average predictions over five random cross-fitting splits.

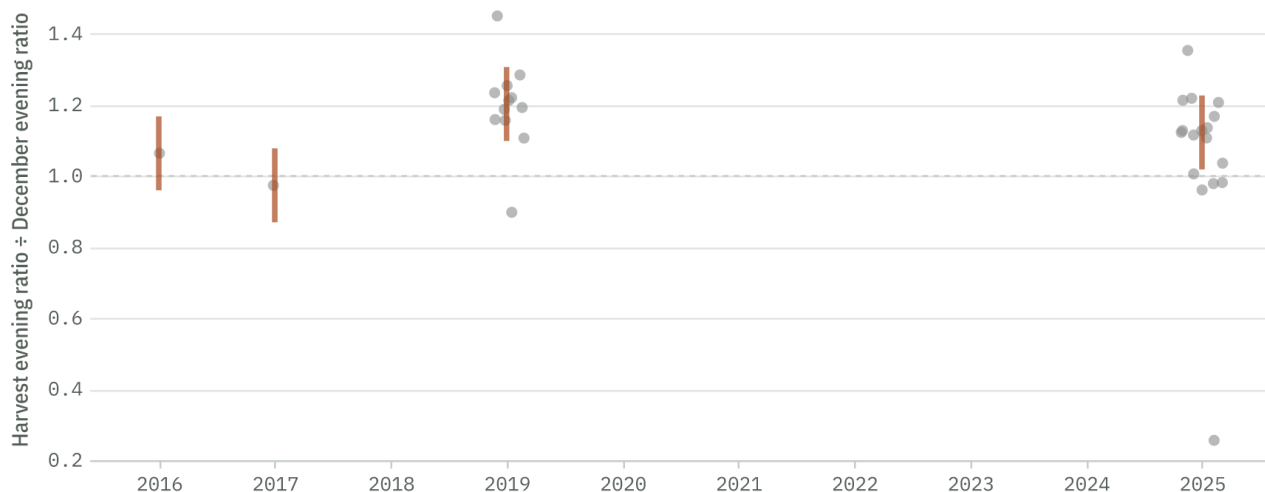
The ground test at 31 site-seasons in Punjab and Haryana does not show the shift (Fig. 13): the harvest-to-December evening ratio had a median of 1.19 before 2022 and 1.12 in 2025 (one-sided Mann-Whitney $p = 0.95$). With the archive gap, the later period rests on few seasons, and 2025 had so little burning that a change in its timing would barely move urban monitors.



VIIRS S-NPP fire detections in Punjab and Haryana, October–November, split by overpass, after removing fixed heat sources. Diamonds mark official Punjab season counts.



Percent change in Delhi’s weather-adjusted PM2.5 per 100 units of the wind-aware fire index, by season, with 95% confidence intervals (HAC standard errors).



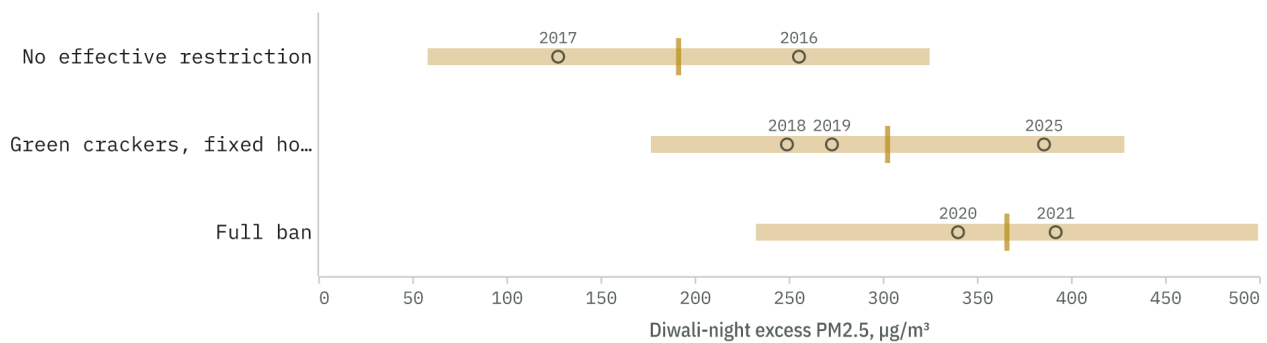
Evening-to-midday PM2.5 ratio in the harvest window divided by the same ratio in December, per monitor and season. Ticks mark the median. Values above 1 mean the evening share rises at harvest.

A forecast for Diwali 2026

Table 1 gives the locked forecast. The record was committed on 2026-10-12 with SHA-256 checksum 0b5f3a06349b1dd1....

FIRECRACKER RULES IN 2026		FORECAST EXCESS (MG/M ³)	80% INTERVAL PAST DIWALIS USED
Full ban		366	233 to 499 2020, 2021
Green crackers, fixed hours		303	177 to 428 2018, 2019, 2025
No effective restriction		192	58 to 325 2016, 2017

Locked forecast of the Diwali-night excess in the CPCB Delhi network median, 8 November 2026.



Forecast Diwali-night excess PM2.5 for 8 November 2026 under each possible firecracker regime, with 80% prediction intervals. Open circles are past Diwalis under the same rules.

Discussion

Fire counts are losing their meaning as a target. Official progress on stubble burning is reported in active-fire counts. Our results add one clear and one suggestive line of evidence that these counts now understate burning: the night pass of the same satellite sees a growing share of fires, and in 2025 each detected fire went with a larger rise in Delhi's PM2.5. Reported declines of 80–90% in counts should not be read as declines of the same size in burning or in its effect on Delhi. Burnt-area mapping and geostationary sensors, which do not depend on a single overpass time, are better suited to tracking progress.

The firecracker bans did not shrink Diwali night. Across the 7 Diwalis the network covers, the weather- and fire-adjusted excess was no lower under a full ban than with green crackers or no bursting restriction. This matches the Supreme Court's own observation in 2025 that air quality differed little between green-cracker and full-ban years (Deccan Herald 2025). It suggests the bans were not effectively enforced, though our data cannot show why. The one low year, 2017, followed a sales suspension ordered about ten days ahead, which may be worth studying as a design that limits supply rather than use.

Monitoring fails when it matters most. The monitor most widely used as Delhi's reference stops reporting during the hours of highest concentration on Diwali night. Studies and dashboards that average whatever hours survive will understate the festival. Reporting the number of missing hours alongside any Diwali figure, and using the network median rather than a single monitor, are simple remedies.

Limitations

The CPCB archive gap from late 2022 to early 2025 removes three Diwalis and three burning seasons from the network record; for these years we rely on the US Embassy monitor, which is censored on Diwali night. The regime comparison rests on two or three Diwalis per regime and is descriptive. The fire-coupling estimate for 2025 rests on one season with very few detected fires. The fire index uses surface winds, while smoke travels at higher levels. Rural Punjab has few monitors, so the ground test uses urban ones, where local sources dominate the evening. Weather normalisation removes the effect of weather on average; it cannot remove every interaction between weather and emissions. Diwali dates and firecracker rules are compiled from secondary reports and should be checked against the original orders.

Conclusions

Separating weather, farm smoke and fireworks with public data and open code is feasible, and the separation changes the story. Diwali adds a large, consistent excess that the firecracker bans have not visibly reduced. The fall in fire counts very likely overstates the fall in burning. And the reference monitor goes dark at the peak. We will score our Diwali 2026 forecast in public after the festival.

Data and code availability

All code, derived tables, figures and the locked forecast are at <https://github.com/krishnav1412/eleven-winters>. The companion website, including a city explorer for the 103 sites with weather-normalised series, is at <https://krishnav1412.github.io/eleven-winters/>. Raw data are public: OpenAQ, NASA FIRMS and ERA5 via Open-Meteo. One command (`ew all`) rebuilds every result from the raw data.

References

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