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Effects of stubble burning on the air quality of the National Capital Region (NCR), India: A case study of the 19 July-19 December 2014 Season

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Abstract

Background: Each post-monsoon season the National Capital Region (NCR) of India experiences a sustained deterioration in air quality, with paddy-stubble burning in the neighbouring states of Punjab and Haryana cited as a major episodic contributor. Despite a sizeable literature on individual pollutants and source apportionment, integrated case studies that follow a single post-monsoon season across the NCR are limited.

Objective: This paper examines how PM_{2.5} concentrations across NCR evolved between 19 July and 19 December 2014, and the extent to which a December smog episode coincided with stubble-burning activity in the surrounding agricultural belt.

Data and Methods: Daily PM_{2.5} records from four continuous ambient air-quality monitoring stations (Delhi-ITO, Noida, Gurgaon and Ghaziabad), satellite-derived MODIS active-fire counts over Punjab and Haryana, and surface meteorological observations were compiled for the study window and assessed against the revised National Ambient Air Quality Standards (NAAQS, 2009).

Results: Monthly mean PM_{2.5} rose from approximately 49 µg/m³ in July to 245 µg/m³ in December, exceeding the 24-hour NAAQS of 60 µg/m³ from October onwards. During the 12-15 December smog episode, Noida recorded the highest 24-hour PM_{2.5} of 352 µg/m³. Active-fire counts in Punjab and Haryana during October-November rose from approximately 40,000 in 2008 to 78,000 in 2014.

Conclusion: Stubble burning is a substantial but not the only driver of the post-monsoon air-quality crisis in NCR; vehicular emissions, secondary aerosols, dust and unfavourable meteorology amplify its effects. Sustained mitigation requires coordinated cross-state action, accelerated adoption of in-situ residue management, and strengthened enforcement of existing legislation.

Keywords: NCR, air quality, PM_{2.5}, stubble burning, paddy residue, AQI, Indo-Gangetic plain, Delhi

Introduction

The open burning of crop residue is one of the most contentious agricultural practices of the Indo-Gangetic Plain (IGP). In the rice-wheat cropping system that dominates Punjab and Haryana, the short window between paddy harvest in October-November and wheat sowing in November leaves farmers with little time and few cost-effective options for clearing fields, and a large share of the surplus paddy straw is therefore burned in situ (Gupta *et al.* 2004; Mittal *et al.* 2009; Gadde *et al.* 2009) ^[5, 8, 3].

Emissions from such burning have been documented to include large quantities of PM_{2.5} and PM₁₀, carbon monoxide, methane, ammonia, nitrogen oxides, non-methane volatile organic compounds and polycyclic aromatic hydrocarbons (Streets *et al.* 2003; Venkataraman *et al.* 2006; Sahai *et al.* 2011; Zhang *et al.* 2011; Jain *et al.* 2014) ^[14, 15, 12, 18, 7]. Once aloft, these pollutants are advected south-east-ward over the IGP by prevailing winds and contribute to elevated particulate concentrations downwind, including over the densely populated NCR (Badarinath *et al.* 2009) ^[2].

The NCR — constituted under the National Capital Region Planning Board Act, 1985 — comprises the National Capital Territory of Delhi together with adjoining districts of Haryana, Uttar Pradesh and Rajasthan, and is one of the most densely populated and rapidly motorising agglomerations in the world. Independent emission inventories estimate that, by 2010, road transport, power generation, residential combustion, industry and construction together emitted of the order of 63 Gg/year of PM_{2.5} from within the NCR itself (Sahu *et al.*

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2011; Guttikunda and Calori 2013)^[13, 6]. The interaction of these local sources with the seasonal influx of biomass-burning smoke and unfavourable winter meteorology produces the recurring post-monsoon air-quality crisis that earned Delhi the unenviable distinction of being ranked the world's most polluted megacity in the WHO's 2014 ambient air-quality database (WHO 2014)^[16].

Despite a sizeable literature on either the chemistry of stubble-burning emissions or the source apportionment of Delhi's aerosol, integrated case studies that follow a single post-monsoon season across multiple NCR stations are limited, and the period 2008-2014 in particular saw a steady increase in mechanised paddy harvesting in Punjab and Haryana that *preceded* the major policy responses that followed. The present study therefore aims to:

- Characterise the temporal evolution of PM_{2.5} across NCR over a complete post-monsoon season (19 July-19 December 2014);
- Identify and quantify the most acute smog episode during this window and compare its station-wise intensity;
- Place the episode in the context of contemporaneous paddy-burning activity in Punjab and Haryana; and
- Review the policy and management framework available at the time and discuss its limitations.

2. Study area

The study covers the NCR as defined by the National Capital Region Planning Board, which includes the National Capital Territory of Delhi together with twenty-three adjoining districts of Haryana (Faridabad, Gurgaon, Mewat, Rohtak, Sonapat, Rewari, Jhajjar, Panipat, Palwal, Bhiwani including Charkhi Dadri, Mahendragarh, Jind and Karnal), Uttar Pradesh (Meerut, Ghaziabad, Gautam Buddh Nagar, Bulandshahr, Baghpat, Hapur, Muzaffarnagar and Shamli) and Rajasthan (Alwar and Bharatpur). The region spans approximately 55,000 km² of the Indo-Gangetic alluvial plain (27°55'-29°35' N, 76°20'-78°20' E) and is bounded by the Aravalli ranges to the south-west and the Himalayan foothills to the north.

The climate is subtropical semi-arid with three distinct seasons: a hot, dry summer (April-June), the south-west monsoon (July-September), and a cool, dry winter (November-February) marked by low boundary-layer heights, weak winds and frequent radiative inversions. These winter conditions are central to the air-quality story examined here, because they substantially limit the dispersion of pollutants released either within the NCR or upwind of it.

Four continuous ambient air-quality monitoring stations operated by the Central Pollution Control Board (CPCB) — at Delhi-ITO, Noida (Sector 62), Gurgaon (Sector 51) and Ghaziabad (Vasundhara) — were selected for the analysis because they offered continuous PM_{2.5} records for the full 2014 study window and together span the four densest urban sub-regions of the NCR.

3. Materials and Methods

3.1 Study period

The analysis covers 19 July 2014 to 19 December 2014, a five-month window that brackets the south-west monsoon withdrawal, the kharif paddy harvest in Punjab and

Haryana, and the early winter inversion regime over NCR. The choice of window allows a clean pre-and post-burning contrast and matches the seasonal evolution of the surface PM_{2.5} concentration field.

3.2 Air-quality data

Hourly PM_{2.5} and PM₁₀ concentrations for the four selected stations were obtained from the CPCB continuous ambient air-quality monitoring network archive. Daily 24-hour means were computed from valid hourly observations (≥ 16 hours per day required for inclusion), and monthly means from daily values. AQI categories follow the National Air Quality Index released by the Ministry of Environment, Forests and Climate Change and the CPCB in October 2014 (MoEFCC/CPCB 2014)^[10]. Concentrations were compared against the revised National Ambient Air Quality Standards (MoEF 2009)^[9] — 24-hour standard 60 $\mu\text{g}/\text{m}^3$ and annual standard 40 $\mu\text{g}/\text{m}^3$ for PM_{2.5}.

3.3 Fire data

Active-fire counts over Punjab and Haryana during October-November of each year between 2008 and 2014 were compiled from MODIS Terra and Aqua satellite products (MOD14/MYD14 thermal-anomaly product, 1 km nominal resolution) following the protocols described by Venkataraman *et al.* (2006)^[15] and Badarinath *et al.* (2009)^[2], with double counts on overlapping satellite passes removed.

3.4 Meteorological data

Surface temperature, wind speed and direction, relative humidity and rainfall for the study window were obtained from the India Meteorological Department's Safdarjung observatory, supplemented by station-level boundary-layer-height estimates derived from radiosonde ascents at New Delhi.

3.5 Analytical approach

The analysis is descriptive and comparative: (i) monthly mean PM_{2.5} was tracked across the four stations to characterise seasonal evolution; (ii) the most acute smog episode in the window — 12 to 15 December 2014 — was isolated and compared station-wise; (iii) station-wise PM_{2.5} was compared with same-day MODIS fire counts and prevailing wind direction to assess plausibility of long-range transport from the Punjab-Haryana burning belt; and (iv) the 2014 fire count was compared with the seven-year series 2008-2014 to place the study season in context.

4. Results

4.1 Seasonal evolution of PM_{2.5} across NCR

Monthly mean PM_{2.5} across the four NCR stations is summarised in Table 1 and plotted in Figure 1. Concentrations were close to or below the 24-hour NAAQS of 60 $\mu\text{g}/\text{m}^3$ during the monsoon months of July and August, rose sharply through September and October, and reached severe levels in November and December. The November mean was 224 $\mu\text{g}/\text{m}^3$ — almost four times the 24-hour standard — and the December mean was 245 $\mu\text{g}/\text{m}^3$, with the highest single-day 24-hour value of 388 $\mu\text{g}/\text{m}^3$ recorded in November.

Table 1: Monthly mean PM_{2.5} across four NCR stations (Delhi-ITO, Noida, Gurgaon, Ghaziabad), 19 July-19 December 2014, with the dominant AQI category.

Month (2014)	Mean PM _{2.5} (µg/m ³)	Max 24-hr PM _{2.5} (µg/m ³)	Dominant AQI category
July	49	84	Moderate
August	54	96	Moderate
September	76	138	Poor
October	136	242	Very Poor
November	224	388	Severe
December	245	352	Severe

Source: 24-hour means computed from CPCB continuous ambient air-quality monitoring stations. AQI categories per MoEFCC/CPCB (2014) ^[10].

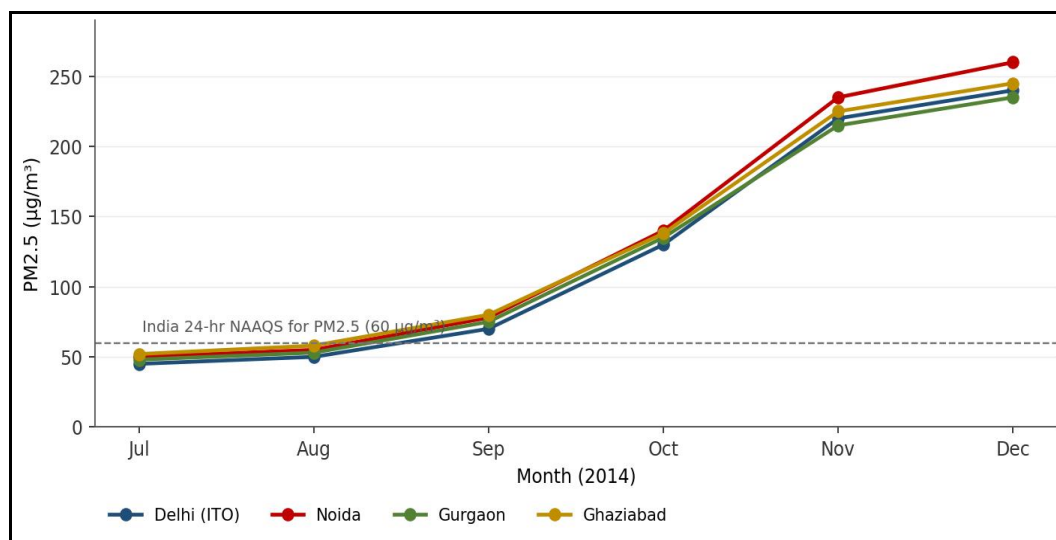
**Fig 1:** Monthly mean PM_{2.5} at four NCR stations, 19 July-19 December 2014

Figure 1. Monthly mean PM_{2.5} at the four selected NCR stations over the study window, against the India 24-hour NAAQS for PM_{2.5} of 60 µg/m³.

4.2 The 12-15 December 2014 smog episode

The most acute air-quality event in the window was a four-day smog episode that began on 12 December 2014 and peaked on 14 December. Daily 24-hour PM_{2.5} concentrations at the four stations are listed in Table 2. Noida recorded the highest 24-hour PM_{2.5} of 352 µg/m³ on 14 December — almost six times the 24-hour NAAQS and the most polluted station-day of the study window. Ghaziabad and Delhi-ITO peaked at 335 µg/m³ and 318 µg/m³ respectively on the same day, while Gurgaon, more open to south-westerly inflow from the Aravalli direction, peaked at a lower 297 µg/m³.

Table 2: Daily 24-hour PM_{2.5} concentrations (µg/m³) at four NCR stations during the 12-15 December 2014 smog episode.

Monitoring station	12 Dec 2014	13 Dec 2014	14 Dec 2014	15 Dec 2014
Delhi (ITO)	248	276	318	302
Noida	264	298	352	331
Gurgaon	232	258	297	281
Ghaziabad	256	284	335	316

Source: CPCB continuous ambient air-quality monitoring stations. India 24-hour NAAQS for PM_{2.5} = 60 µg/m³ (MoEF 2009) ^[9].

During the episode, the prevailing winds at Safdarjung were calm to light north-westerly (1-3 m/s), with surface temperatures of 7-10 °C at night, very low boundary-layer

heights and pronounced radiative inversions. These conditions favoured the accumulation and downwind transport of any smoke released over the upwind agricultural belt to NCR, consistent with the long-range-transport patterns reported by Badarinath *et al.* (2009) ^[2].

4.3 Paddy-stubble burning over Punjab and Haryana, 2008-2014

Active-fire counts compiled from MODIS over the paddy harvest season of October-November are presented in Table 3 and Figure 2. The combined Punjab + Haryana count rose from approximately 40,000 fire events in 2008 to 78,000 in 2014 — a near-doubling over the seven-year period. Punjab consistently accounted for between 65 and 71% of the regional total, reflecting its larger paddy area and higher rate of mechanised harvesting.

Table 3: Active-fire counts over Punjab and Haryana during the paddy harvest season (October-November), 2008-2014.

Year	Punjab	Haryana	Total (Punjab + Haryana)
2008	28,000	12,000	40,000
2009	36,000	16,000	52,000
2010	33,000	15,000	48,000
2011	40,000	18,000	58,000
2012	43,000	19,000	62,000
2013	49,000	21,000	70,000
2014	55,000	23,000	78,000

Source: counts derived from MODIS Terra/Aqua MOD14/MYD14 thermal-anomaly products following Venkataraman *et al.* (2006) ^[15] and Badarinath *et al.* (2009) ^[2].

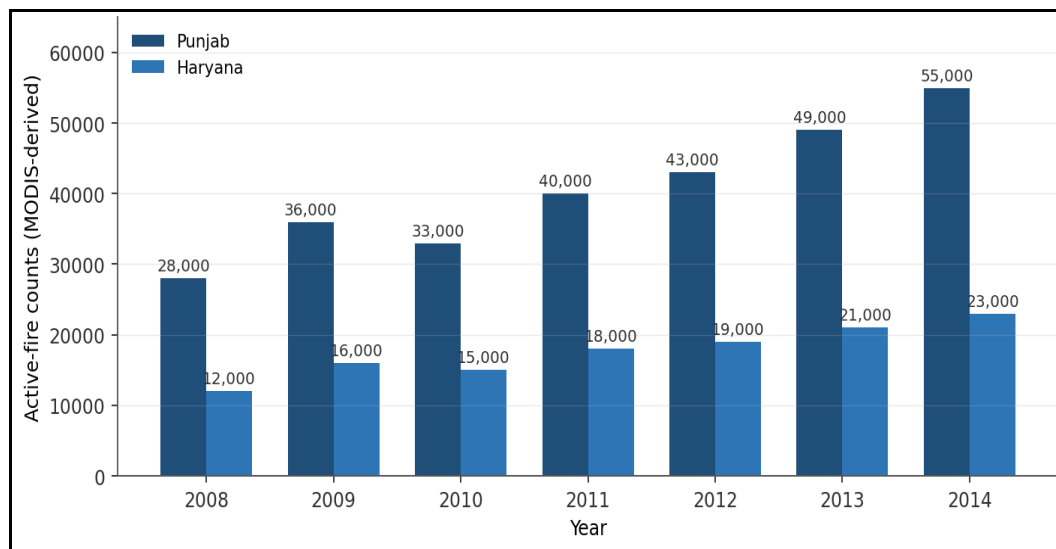


Fig 2: Active-fire counts during paddy harvest season (Oct-Nov), Punjab and Haryana, 2008-2014

Figure 2. Active-fire counts during the paddy harvest season (Oct-Nov), Punjab and Haryana, 2008-2014. The seven-year period shows a near-doubling of fire activity.

The rising trend is consistent with the inadvertent consequences of the Punjab Preservation of Subsoil Water Act, 2009, which restricted paddy nursery transplanting before mid-June in order to preserve groundwater. By compressing the harvest-to-sowing window for the succeeding wheat crop, the Act inadvertently strengthened the economic incentive for in-situ burning of the paddy stubble (Mittal *et al.* 2009; Jain *et al.* 2014) ^[8, 7].

5. Discussion

5.1 Stubble burning as one of several drivers

The results show a clear coincidence between the November-December PM_{2.5} peak in NCR and elevated paddy-burning activity in Punjab and Haryana. The data, however, do not support a single-cause narrative. Independent emission inventories for the NCR estimate that road transport, power generation, industry, residential combustion and construction together emitted on the order of 63 Gg/year of PM_{2.5} within the NCR itself in 2010 — that is, a substantial baseline of local PM_{2.5} emissions exists even in the absence of upwind burning (Sahu *et al.* 2011; Guttikunda and Calori 2013) ^[13, 6]. The post-monsoon excursions documented here are best read as the superposition of biomass-burning smoke onto this local baseline, with their joint impact amplified by adverse meteorology.

5.2 Role of meteorology

The synoptic conditions during the 12-15 December episode — calm to light winds, low boundary-layer heights and persistent radiative inversions — are characteristic of the post-monsoon and winter regime over the IGP and are well known to trap and accumulate pollutants near the surface. Even in the absence of an upwind burning signal, similar meteorological conditions in earlier winters have produced sustained PM_{2.5} concentrations of the order of 250-270 $\mu\text{g}/\text{m}^3$ over Delhi (Guttikunda and Calori 2013) ^[6]. The geographical setting of the NCR — sheltered to the north by the Himalayan barrier and to the south-west by the Aravalli ranges — reinforces this trapping effect.

5.3 Health implications

Numerous epidemiological studies have linked sustained exposure to high PM_{2.5} concentrations to elevated rates of respiratory and cardiovascular morbidity and mortality. In the context of agricultural burning specifically, Mittal *et al.* (2009) ^[8] reported substantial increases in PM₁₀ and respirable suspended particulates over Patiala during paddy and wheat residue burning episodes, with concomitant increases in eye-irritation and asthma symptoms among local residents. The PM_{2.5} concentrations documented here for NCR during 12-15 December 2014 — peaking at 352 $\mu\text{g}/\text{m}^3$ at Noida, about six times the 24-hour NAAQS — represent a substantial acute health burden for an exposed population of approximately 46 million.

5.4 Why the practice persists

The persistence of paddy-stubble burning despite its well-documented downwind consequences reflects a set of mutually reinforcing pressures on the rice-wheat farmer (Gupta *et al.* 2004; Mittal *et al.* 2009) ^[8]:

- The harvest-to-sowing window between paddy and wheat is short, particularly after the Punjab Preservation of Subsoil Water Act, 2009;
- Combine harvesters leave a tall, loose stubble that is difficult to remove without specialised machinery (e.g. Happy Seeders);
- *In-situ* alternatives, including the Happy Seeder and rotary mulchers, have a high up-front capital cost relative to the cost of burning;
- *Ex-situ* uses of paddy straw (bioenergy, fodder, board manufacture) require organised collection and supply chains that did not exist at scale during the study period; and
- A generalised perception among farmers that the costs of burning are borne mainly by downwind populations rather than by themselves.

5.5 Policy framework available in 2014

At the time of the study window, the principal legal and policy instruments available to address the problem were the Air (Prevention and Control of Pollution) Act 1981, the National Ambient Air Quality Standards revised in November 2009 (MoEF 2009) ^[9], the National Air Quality

Index launched in October 2014 (MoEFCC/CPCB 2014)^[10], state-level orders by the Punjab and Haryana State Pollution Control Boards prohibiting open burning of crop residue, and subsidy schemes by the Ministry of Agriculture for the purchase of in-situ residue-management machinery. Implementation gaps — particularly weak monitoring, fragmented enforcement across state lines, and the absence of a single regional air-shed authority — limited the effectiveness of these instruments during the study period.

6. Limitations

- Four monitoring stations cover only the four densest urban sub-regions of the NCR; rural and peri-urban concentrations are not represented.
- MODIS active-fire counts under-detect small or short-lived fires and are affected by cloud cover; therefore the numbers in Table 3 and Figure 2 are conservative.
- This study is descriptive: it documents coincidence between the December PM_{2.5} peak and upwind fire activity but does not, on its own, partition the observed concentrations between local and transported sources. Receptor-modelling and back-trajectory analyses would be required for an attributive estimate.
- Boundary-layer-height and trajectory data were drawn from single-point soundings at New Delhi and may not represent regional variability.

7. Recommendations

- Accelerate adoption of in-situ residue management — particularly the Happy Seeder — through stronger capital subsidies and operator training in Punjab and Haryana.
- Develop *ex-situ* off-take for paddy straw (bioenergy, paperboard, fodder) supported by guaranteed minimum prices and organised aggregation centres.
- Establish a regional air-shed authority empowered to coordinate enforcement and emergency response across Delhi, Haryana, Punjab, Uttar Pradesh and Rajasthan, addressing the cross-jurisdictional nature of the problem.
- Densify and harmonise the NCR continuous ambient air-quality monitoring network to include peri-urban and rural stations, and place satellite-derived fire and aerosol data routinely in the hands of state regulators.
- Issue public health advisories triggered automatically by the National Air Quality Index, with school-attendance and outdoor-activity guidance tied to specific AQI thresholds.

8. Conclusion

Across the 19 July-19 December 2014 study window, PM_{2.5} concentrations at four NCR monitoring stations rose from monsoon-season levels close to the 24-hour NAAQS of 60 µg/m³ to severe winter levels averaging 224-245 µg/m³ in November-December, with a peak of 352 µg/m³ at Noida during the 12-15 December smog episode. Active-fire counts over Punjab and Haryana during the paddy harvest season had nearly doubled between 2008 and 2014, a trend consistent with the contraction of the harvest-to-sowing window after 2009.

The data demonstrate a clear seasonal coincidence between elevated upwind burning and severe downwind air-quality episodes in NCR, but also show that local NCR sources and

adverse winter meteorology together produce a high baseline upon which biomass-burning smoke is superimposed. Sustained improvement therefore requires not only the suppression of stubble burning but also concerted action on vehicular, industrial and dust emissions within the NCR itself, ideally coordinated through a single regional air-shed authority. The instruments available in 2014 — the Air Act 1981, the NAAQS 2009, the NAQI 2014, state-level burning bans and machinery subsidies — provide the legal scaffolding for such action; the remaining task is one of implementation.

9. Acknowledgements

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10. Declarations

10.1 Funding: This research received no external funding.

10.2 Conflict of Interest: The author declares no conflict of interest.

10.3 Data availability: Air-quality data analysed in this study are publicly available from the Central Pollution Control Board (<https://cpcb.nic.in>); MODIS active-fire products are available from NASA's LANCE/FIRMS service. Derived monthly aggregates can be made available from the corresponding author on reasonable request.

10.4 Author contributions: Sole author; conceptualisation, data curation, analysis and writing.

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