Agricultural Residue Burning in Punjab, India: Quantitative Assessment of Emissions, Air-Quality Degradation and Human-Health Impacts

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Abstract: Agricultural residue burning is a major seasonal source of air pollution in Punjab, India, particularly within the rice–wheat cropping system. Open-field burning releases $PM_{2.5}$, PM_{10}, CO, NO_x, SO_2, NH_3, CH_4, CO_2 and other pollutants, contributing to regional air-quality deterioration and human exposure. This study synthesises recent evidence on residue-burning trends, emissions, air quality, health impacts and sustainable management options in Punjab. Official data indicate that paddy-season fire incidents declined from 71,304 in 2021 to 5,114 in 2025. However, satellite-based estimates for 10 October–30 November 2022 reported approximately 14,700 km² of burned crop area and emissions of 54.28 Gg $PM_{2.5}$, 62.1 Gg CO, 25.63 Gg CH_4 and 1,100.3 Gg CO_2. National modelling has estimated 44,000–98,000 premature deaths annually in India associated with particulate exposure from agricultural-residue burning, with Punjab identified as the largest state-level contributor. Rural Punjab studies have also reported substantial seasonal variation in $PM_{2.5}$ concentrations. The findings highlight the need for integrated residue management, biomass utilisation, improved monitoring and targeted air-quality and health interventions to reduce the environmental and public-health impacts of open-field burning.

Keywords: Agricultural residue burning; paddy straw; Punjab; $PM_{2.5}$; air pollution; human health; biomass energy; crop residue management; Indo-Gangetic Plain.

1. Introduction

Agricultural production is an essential component of Punjab's economy and food-security system. The state is particularly important for rice and wheat production, with the rice–wheat rotation dominating large areas of cultivated land. However, intensive agriculture and mechanised harvesting have also created a major residue-management challenge. Following mechanical harvesting of paddy, a substantial quantity of straw and stubble remains in the field. The short period available between rice harvesting and wheat sowing creates strong pressure for rapid field clearance.Open-field burning provides a rapid method of removing the remaining residue. However, combustion transfers a potentially valuable biomass resource into the atmosphere in the form of particulate matter and gaseous emissions. The Indian Council of Agricultural Research notes that the interval between rice harvesting and wheat sowing in the region can be only approximately 20–25 days, which contributes to the persistence of residue burning [1].

The environmental significance of the problem extends beyond individual agricultural fields. Smoke generated from agricultural fires can affect rural populations close to the source and can also be transported across the Indo-Gangetic Plain. During October and November, atmospheric conditions can favour the accumulation of particulate matter near the surface. Atmospheric modelling has demonstrated that the timing of agricultural fires can substantially influence downwind $PM_{2.5}$ concentrations [2]. The scale of the problem has nevertheless changed considerably in recent years. According to the Commission for Air Quality Management (CAQM), Punjab recorded 5,114 farm-fire incidents during the 2025 paddy-harvesting monitoring period, compared with 71,304 incidents in 2021. This represents a reduction of approximately 93% [3].

The decline in fire counts is an important achievement, but fire counts alone do not fully describe the atmospheric or health burden. The quantity of biomass burned, combustion characteristics, timing, meteorological conditions, pollutant dispersion and population distribution all influence actual exposure.

The objective of this paper is therefore to provide an integrated assessment of agricultural residue burning in Punjab by examining:

- Analyse the recent temporal trends in paddy-residue burning incidents in Punjab, India.
- Characterise the magnitude and composition of emissions associated with agricultural-residue burning, with particular emphasis on particulate matter and major gaseous pollutants.
- Examine the association between agricultural-residue burning and ambient $PM_{2.5}$ concentrations during the post-monsoon period.
- Assess the potential respiratory and cardiovascular health risks associated with exposure to air pollutants generated from agricultural-residue burning.
- Examine the regional transport and atmospheric dispersion of agricultural-fire emissions across Punjab and the wider Indo-Gangetic Plain.
- Review sustainable residue-management and biomass-utilisation options that can reduce open-field burning and facilitate the conversion of agricultural residues into value-added energy resources.

2. Methodology

This study follows an integrated secondary-data assessment framework for agricultural-residue burning in Punjab, India, covering the 2021–2025 period and the post-monsoon paddy-harvesting season (see figure 1).Relevant data are compiled from CAQM, MODIS/VIIRS and Sentinel-2 satellite observations, agricultural sources, CPCB/PPCB air-quality records, meteorological information and published health studies. The collected information is systematically screened, aligned and integrated to assess fire activity, burned area, residue generation and associated pollutant emissions.The environmental impacts are evaluated through $PM_{2.5}$ concentrations, meteorological conditions and regional atmospheric transport, using evidence from published modelling studies.The health dimension is assessed by examining population exposure and reported respiratory and cardiovascular impacts associated with particulate pollution.Finally, in-situ and ex-situ residue-management and biomass-utilisation pathways are evaluated to identify mitigation options and formulate evidence-based policy recommendations.

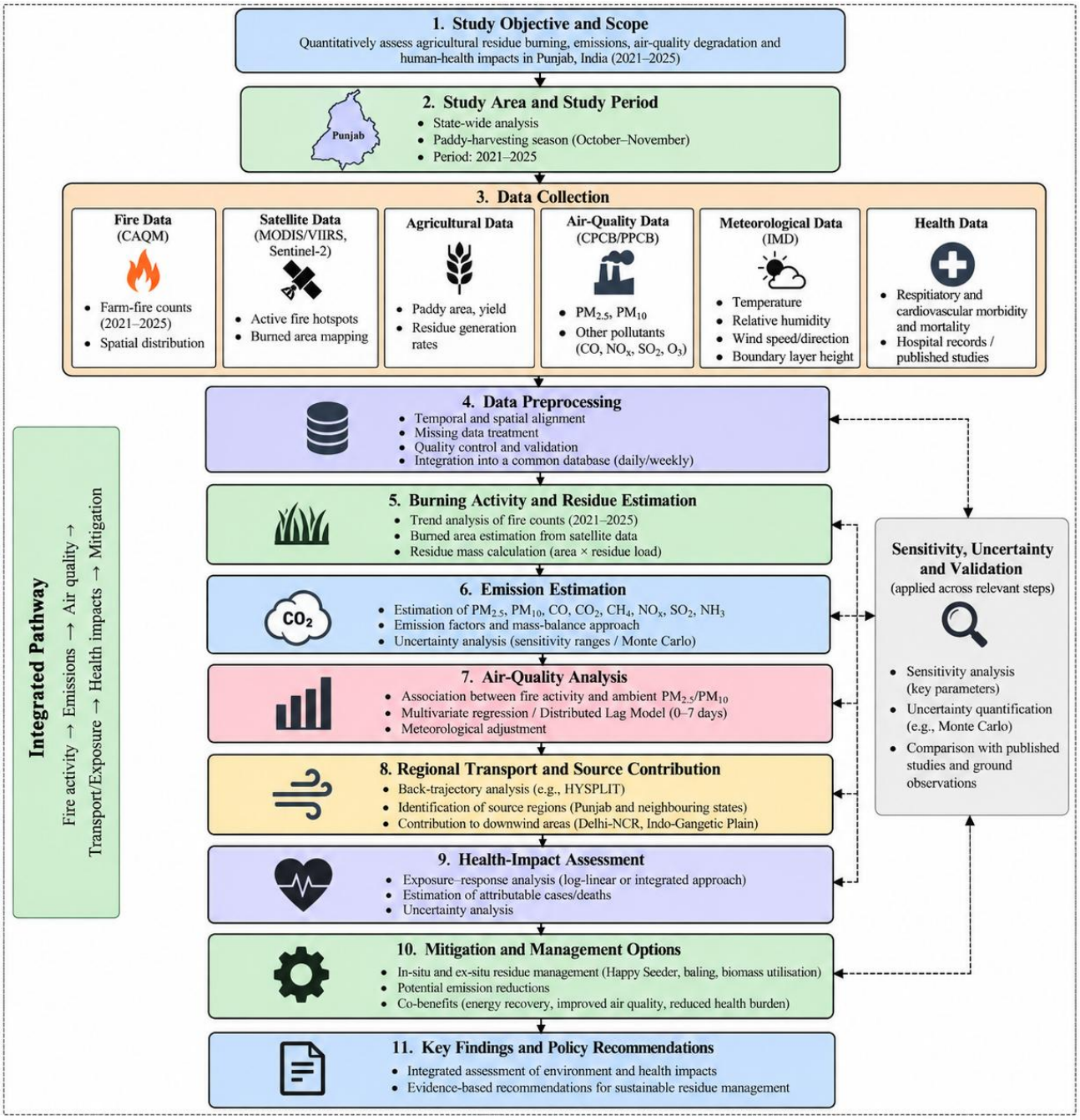

Figure 1. Methodology Flow chart

2.1 Agricultural Residue Burning in Punjab

Punjab's rice–wheat production system is characterised by intensive cultivation, high cropping intensity and widespread mechanisation. The use of combine harvesters enables rapid paddy harvesting but leaves substantial quantities of straw and stubble distributed across agricultural fields. The short interval between rice harvesting and wheat sowing creates considerable pressure for rapid field preparation, making open-field burning a quick and convenient method of residue removal. However, residue collection

and utilisation require additional machinery, labour, transportation and storage infrastructure. Government documentation identifies mechanised harvesting, labour shortages, transportation costs, inadequate storage facilities and limited economically viable alternatives among the major factors contributing to continued crop-residue burning [4]. Therefore, agricultural-residue burning should be understood not only as a field-level management practice but also as a broader economic, logistical and supply-chain challenge involving residue collection, transportation, storage, market availability and suitable utilisation technologies.

2.2 Recent trend in farm-fire incidents

The official 2025 CAQM assessment provides evidence of a substantial decline in Punjab's recorded paddy-residue fire incidents. From 71,304 incidents in 2021 to 5,114 incidents in 2025, the number of detected fires decreased by approximately 92.8% (see Table 1).

Table 1. Paddy-season farm-fire incidents in Punjab, 2021–2025 [4]

Year	Fire incidents	Reduction compared with previous year
2021	71,304	—
2022	49,922	30.00%
2023	36,663	26.60%
2024	10,909	70.30%
2025	5,114	53.10%

Figure 2 shows the declining trend demonstrates the effectiveness of increasingly coordinated crop-residue-management interventions. However, fire-count data should not be interpreted as equivalent to total biomass burned because satellite fire detection is influenced by fire size, cloud cover, observation timing and detection characteristics.

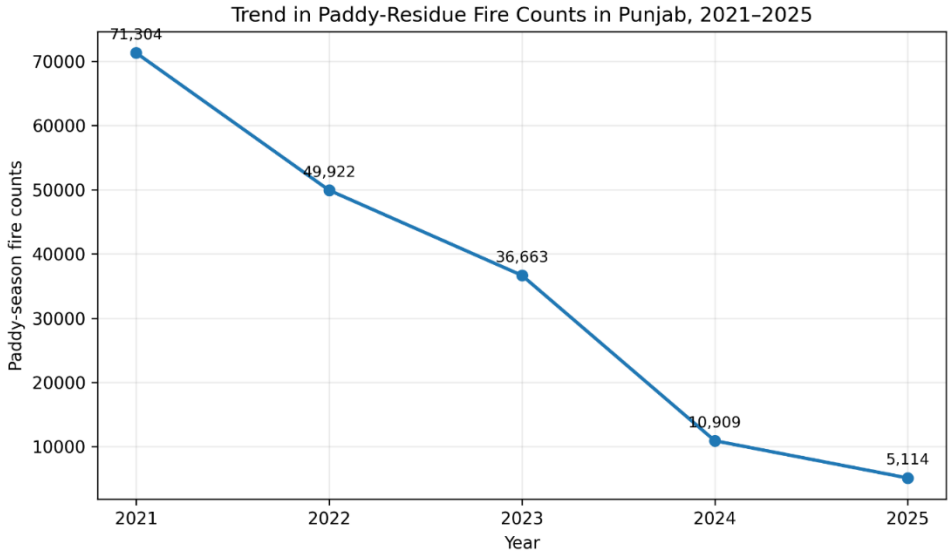

Figure 2. Trend in paddy-residue fire counts in Punjab, 2021–2025

2.3. Emission Characteristics of Agricultural Residue Burning

Open combustion of agricultural residue is generally an uncontrolled combustion process. Emission characteristics vary with biomass composition, moisture content, combustion temperature, oxygen availability and burning conditions.The major pollutants released include $PM_{2.5}$, PM_{10}, CO, NO_x, SO_2, NH_3, CH_4, CO_2 and organic compounds.Fine particulate matter is particularly important because $PM_{2.5}$ can penetrate deep into the respiratory system and is associated with both respiratory and cardiovascular health effects.

A recent study by Ambulkar et al. used VIIRS fire observations and Sentinel-2-derived burned areas to quantify emissions from crop-residue burning during 10 October–30 November 2022 (see Table 2). The study estimated that approximately 14,700 km² of crop area was burned in Punjab during the study period [5].

Table 2. Estimated emissions from crop-residue burning in Punjab during 10 October–30 November 2022

Pollutant	Estimated emissions

$PM_{2.5}$	54.28 Gg
CH_4	25.63 Gg
CO_2	1,100.30 Gg
NH_3	0.83 Gg
SO_2	0.68 Gg
CO	62.10 Gg

The magnitude of these emissions demonstrates why agricultural burning is an important atmospheric source even though individual fires are relatively small. The emissions are concentrated into a relatively short seasonal period, increasing the likelihood of severe episodic pollution. The estimated emissions demonstrate that agricultural-residue burning represents a substantial seasonal source of atmospheric pollution in Punjab. During the period from 10 October to 30 November 2022, approximately 14,700 km² of crop area was burned in Punjab, resulting in estimated emissions of 54.28 Gg of $PM_{2.5}$, 62.10 Gg of CO, 25.63 Gg of CH_4, 1,100.30 Gg of CO_2, 0.83 Gg of NH_3 and 0.68 Gg of SO_2 (see figure 3). The concentration of these emissions within a relatively short post-monsoon period can intensify episodic air-pollution events, particularly when atmospheric dispersion is limited. These findings highlight the importance of agricultural-residue burning as a significant seasonal contributor to regional air-quality degradation in northwestern India.

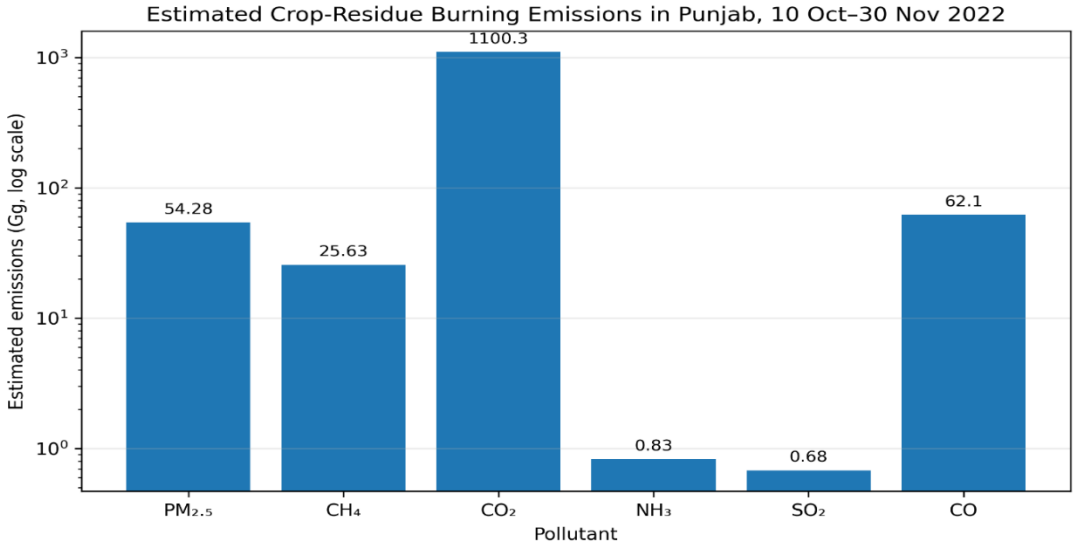

Figure 2. Estimated pollutant emissions from crop-residue burning in Punjab

4. Results and Discussion

4.1 Temporal Trend in Agricultural-Residue Burning

Punjab showed a substantial decline in reported paddy-season farm-fire incidents between 2021 and 2025. The number of detected incidents decreased from 71,304 in 2021 to 49,922 in 2022, 36,663 in 2023, 10,909 in 2024 and 5,114 in 2025, corresponding to an overall reduction of approximately 92.8% over the study period. The sharpest year-on-year reduction occurred between 2023 and 2024, when fire incidents declined by approximately 70.3%, followed by a further 53.1% reduction in 2025. These results indicate substantial progress in residue-burning control and the implementation of crop-residue-management interventions. However, the decline in satellite-detected fire counts should not be interpreted as an equivalent reduction in the quantity of biomass burned, because fire detection is influenced by fire size, cloud cover, observation time and satellite detection characteristics.

4.2 Emission Magnitude and Atmospheric Significance

The available satellite-based assessment for 10 October–30 November 2022 provides evidence of the substantial emission burden associated with agricultural-residue burning in Punjab. Approximately 14,700 km² of crop area was estimated to have been burned, producing approximately 54.28 Gg $PM_{2.5}$, 62.10 Gg CO, 25.63 Gg CH_4, 1,100.30 Gg CO_2, 0.83 Gg NH_3 and 0.68 Gg SO_2. The concentration of these emissions within a relatively short post-monsoon period increases the potential for episodic pollution, particularly when atmospheric dispersion is weak. The results therefore demonstrate that agricultural burning represents an important seasonal emission source and that assessment based solely on fire counts may underestimate its atmospheric significance.

4.3 $PM_{2.5}$ Pollution and Regional Air-Quality Implications

The assessment indicates a substantial disparity between observed rural-Punjab $PM_{2.5}$ concentrations and health-based guideline levels. The reported annual mean concentration of approximately 92 μg/m³ was about 18.4 times the WHO 2021 annual guideline of 5 μg/m³ and approximately 2.3 times India's annual standard of 40 μg/m³. Higher concentrations during the post-monsoon and winter periods are particularly important because these periods coincide with agricultural-residue burning and meteorological conditions that can restrict pollutant dispersion. Nevertheless, the observed annual concentration represents total ambient $PM_{2.5}$ exposure at the study location and cannot be attributed exclusively to crop-residue burning because other emission sources also contribute to ambient pollution.

4.4 Regional Transport and Fire-Timing Effects

The results further demonstrate that the impact of agricultural burning extends beyond individual source locations. Modelling studies over the Indo-Gangetic Plain have identified concentrated agricultural-fire hotspots in Punjab and Haryana and demonstrated substantial $PM_{2.5}$ enhancements associated with crop-residue burning. Fire timing is also an important determinant of pollution exposure. Previous modelling for 2008–2019 estimated that delayed agricultural-fire activity increased smoke-related $PM_{2.5}$ concentrations in downwind locations including New Delhi, Bathinda and Jind, while average smoke-related $PM_{2.5}$ concentrations could have been 11–21% lower without the observed delays. These findings indicate that the environmental impact of residue burning depends not only on the number of fires but also on their timing, burned area, emission characteristics and prevailing meteorological conditions.

4.5 Human-Health Implications

The health evidence indicates that exposure to biomass-burning pollution can affect both respiratory and cardiovascular health. The rural Punjab evidence considered 2,582 deaths and estimated preventable deaths attributable to $PM_{2.5}$ exposure at 246 using a 10 μg/m³ reference concentration and 159 using India's 40 μg/m³ standard. These estimates should be interpreted as population-level health-impact estimates rather than deaths directly attributable to individual agricultural fires. Socioeconomic conditions, healthcare access and other seasonal factors may also influence observed health outcomes.

At the national level, modelling estimated approximately 44,000–98,000 premature deaths annually, with a central estimate of approximately 69,000 deaths per year, associated with particulate exposure from agricultural-residue burning. Punjab, Haryana and Uttar Pradesh collectively accounted for approximately 67–90% of the estimated national burden, while Punjab was identified as the largest state-level contributor. These results highlight the wider public-health significance of agricultural burning and support the need for coordinated interventions extending beyond individual farms or districts.

4.6 Implications for Residue Management

The combined results indicate that reducing fire counts is important but should be accompanied by strategies that address the underlying economic and logistical constraints of residue management. In-situ technologies such as Happy Seeder and Super Seeder can reduce the need for open-field burning, while collection, baling, pelletisation, biomass power generation, bio-CNG and other conversion pathways can provide productive uses for collected residue. The transition from residue disposal to biomass utilisation could therefore simultaneously address air-pollution concerns and create opportunities for energy recovery and value-added agricultural products.

4.7 Overall Discussion

Taken together, the findings demonstrate that a reduction in fire incidents does not necessarily imply elimination of the environmental and health burden associated with agricultural-residue burning. The 92.8% decline in detected fires represents substantial progress, but the documented magnitude of burned area and pollutant emissions, elevated rural $PM_{2.5}$ concentrations, regional transport and estimated health burden demonstrate that residue burning remains an important seasonal environmental issue. A more comprehensive assessment should therefore move from simple fire-count monitoring towards an integrated framework linking fire activity → burned area → emissions → $PM_{2.5}$ → atmospheric transport → population exposure → health impacts → mitigation. This integrated perspective provides a stronger basis for evaluating the effectiveness of residue-management policies and identifying sustainable biomass-utilisation pathways.

4. Conclusions

Agricultural residue burning remains an important environmental and public-health issue in Punjab despite the substantial decline in reported farm-fire incidents. Official monitoring shows that Punjab's paddy-season fire count decreased from 71,304 incidents in 2021 to 5,114 in 2025, representing a reduction of approximately 93%. Nevertheless, significant quantities of biomass continue to be burned. Satellite-based analysis for 10 October–30 November 2022 estimated approximately 14,700 km² of burned crop area in Punjab and emissions of 54.28 Gg $PM_{2.5}$, 62.1 Gg CO, 25.63 Gg CH_4 and 1,100.3 Gg CO_2. The health implications are substantial. National modelling has estimated 44,000–98,000 premature deaths annually associated with particulate exposure from agricultural residue burning in India, with a central estimate of approximately 69,000 deaths. Punjab has consistently been identified as the

largest state-level contributor to this estimated burden. Evidence from rural Punjab further indicates that $PM_{2.5}$ concentrations can remain substantially above health-based guideline levels, particularly during post-monsoon and winter periods.

The evidence therefore supports a transition from residue disposal to residue utilisation. In-situ management, biomass collection, pelletisation, briquetting, biomass power generation, anaerobic digestion, bio-CNG and biochar production can provide alternative pathways for managing paddy residue.The most effective long-term strategy is likely to combine technological interventions with economic incentives, reliable biomass markets, improved collection infrastructure, satellite monitoring and health-based air-quality management. Punjab's recent reduction in fire incidents demonstrates that substantial progress is possible; the next objective should be to establish a scalable, economically viable and environmentally sustainable zero-open-burning biomass economy.

Declarations

CRediT authorship contribution statement

Harpreet Kaur Channi: Conceptualization, methodology, investigation, data curation, formal analysis, visualization, writing – original draft, writing – review and editing, and project administration.

Declaration of competing interest

The author declares that there are no known financial or personal relationships that could have influenced the work reported in this paper.

Data availability

The data and information analysed in this study were obtained from publicly available governmental reports, satellite-based observations, and published scientific literature. Additional station-level air-quality and health datasets may be obtained from the relevant government agencies, subject to their data-access requirements.

Acknowledgements

The author has no acknowledgements to declare.

Funding

No external funding was received for this study.

Nomenclature

Not applicable. The manuscript does not introduce a mathematical model or a set of specialised symbols requiring a separate nomenclature table.

Supplementary materials

No supplementary materials are associated with this manuscript.

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