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Assessing public health risks from crop residue burning: a spatiotemporal case study in Telangana, India

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Abstract

The escalating practice of rice-residue burning in agricultural regions has become a critical environmental and public health concern, necessitating a comprehensive assessment of its impact. With increasing evidence linking crop residue burning to air pollution, health risks, and socio-economic burdens, there is an urgent need to quantify its effects on burned areas, pollutant emissions, and associated health outcomes. This study analyzes the spatial distribution of burned areas, PM2.5 emissions, and their associated health impacts, including asthma cases, premature deaths, Years of Life Lost (YLLs), and Disability-Adjusted Life Years (DALYs). The data reveals alarming increases in burned areas, with regions like Makloor, Papannapet, and Armoor showing substantial rises. Emerging hotspots such as Dubbak and Athmakur (M) demonstrate exponential growth in burned hectares and corresponding health impacts, underscoring the urgent need for targeted interventions. Urban centers like Ghatkesar and Shamirpet face disproportionate health burdens due to high population exposure and regional pollutant transport. These findings highlight the critical need for comprehensive strategies, including promoting alternative residue management practices, strengthening regulations, and enhancing public awareness, to effectively mitigate the adverse effects of crop residue burning.

Introduction

Agricultural practices are integral to global food security and economic development, yet they are increasingly recognized as significant contributors to environmental degradation and public health challenges (Gadde et al. 2009). Among these practices, crop residue burning has emerged as a particularly concerning issue due to its severe impact on air quality and human health (Jain et al. 2014). This practice, commonly employed in regions with intensive rice farming, releases substantial amounts of pollutants such as particulate matter (PM2.5, PM10), carbon monoxide (CO), nitrogen oxides (NOx), sulphur dioxide (SO2), and volatile organic compounds (VOCs) into the atmosphere (Pandey et al. 2014). These pollutants have been linked to a range of adverse health outcomes, including respiratory and cardiovascular diseases, which collectively impose a significant burden on public health systems worldwide(Murray et al.2020).

The global significance of air pollution as a public health challenge cannot be overstated. According to the World Health Organization (WHO), air pollution contributes to approximately 7 million premature deaths annually, with agricultural burning being a notable contributor in many developing regions (https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health). Disability-Adjusted Life Years (DALY), a comprehensive metric that combines years of life lost due to premature mortality and years lived with disability, provides a valuable tool for quantifying this burden (Brauer et al. 2016). Understanding the relationship between agricultural practices like crop residue burning and DALY metrics is critical for addressing the intertwined challenges of environmental sustainability and public health(Bhuvaneshwari et al. 2019).

The consequences of crop residue burning in India are far-reaching. Studies have shown that the practice contributes up to 40% of the total particulate matter emissions in certain regions during peak burning periods(Lan et al. 2022). The resulting haze not only affects urban centres like Delhi but also disproportionately impacts rural populations who

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are directly exposed to open-field burning. Respiratory and cardiovascular diseases linked to air pollution have surged in these areas, placing an immense burden on healthcare systems and reducing overall quality of life(Chakrabarti et al. 2019). Moreover, the temporal variability of burning, often concentrated during specific post-harvest periods, creates fluctuating exposure patterns that complicate efforts to effectively assess and mitigate its health impacts(Singh et al. 2024).

Despite these challenges, there is growing recognition of the need for sustainable alternatives. Initiatives such as promoting bioenergy production, incorporating residues into soil, or using them as animal feed have been proposed to reduce reliance on burning. However, the adoption of these alternatives remains limited, particularly in resource-constrained regions where immediate economic pressures often outweigh long-term environmental considerations (Gupta et al. 2022; Meena et al. (Meena 2024); Shyamsundar et al. 2019).

This gap is particularly pronounced in regions like India, where agricultural expansion and intensive farming practices have led to increased residue burning. For instance, the Kaleshwaram command area in Telangana, India, has experienced significant agricultural intensification in recent years, accompanied by a rise in crop residue burning. However, the spatial and temporal dynamics of health impacts in this region remain poorly understood, limiting the development of targeted interventions to mitigate both environmental degradation and associated health risks.

To address these gaps, this study aims to comprehensively analyze and quantify the impact of crop residue burning on Disability-Adjusted Life Years (DALY) in the Kaleshwaram command area of Telangana, India. By integrating geospatial analysis of burn areas with health impact assessments, this study offers a novel approach to understanding the link between agricultural practices and measurable health burdens. The findings will not only enhance our understanding of the magnitude of health impacts in India but also inform the development of targeted policy interventions to promote sustainable agricultural practices and improve public health outcomes.

Materials and methods

Study area

The Kaleshwaram Lift Irrigation Project (KLIP) is a transformative initiative in the Indian state of Telangana and serves as the central focus of this study. Recognized as the world's largest multi-stage lift irrigation project, KLIP is designed to irrigate approximately 1.875 million hectares of drought-prone agricultural land across 13 districts. By lifting water from the Godavari River at Medigadda (near Kaleshwaram town), the project ensures water availability for regions historically vulnerable to erratic rainfall. It comprises 7 links, 28 segments, and an expansive canal network stretching over 1,800 km, benefiting 118 notified mandals/blocks. KLIP aims not only to enhance agricultural productivity but also to ensure year-round water supply for irrigation, drinking, and industrial purposes particularly in regions previously dependent on rainfed agriculture.

The project area primarily lies in the northern and northeastern parts of Telangana, integrating various agro-climatic zones and hydrological systems. These areas, once characterized by frequent droughts and low agricultural yields, are now undergoing a significant shift in land use and cropping intensity due to the assured water availability from KLIP.

Telangana, located in southern India, lies between 15°46′ and 19°47′ N latitude and 77°16′ and 81°43′ E longitude, and ranks as the 12th largest state in both geographical area and population. It is bordered by Maharashtra to the north and northwest, Karnataka to the west, Chhattisgarh to the northeast, and Andhra Pradesh to the south and east (Fig. 1). The state occupies a major portion of the Deccan Plateau, characterized by semi-arid climatic conditions and shallow to moderately deep soils.

Telangana receives an average annual rainfall of 713 mm, with spatial variability ranging from 700 mm to 1500 mm. The southwest monsoon accounts for nearly 80% of this precipitation, while the northeast monsoon contributes the remaining 20% (MOSPI (MOSPI 2016)). Rainfall distribution and variability play a critical role in shaping the state's agricultural practices.

Agriculture in the KLIP command area follows the seasonal cropping cycles of Kharif (monsoon) and Rabi (winter). In regions receiving KLIP irrigation, paddy (rice) is the dominant crop, along with maize, cotton, and soybeans. Rainfed tracts outside the command area continue to rely on monsoon and primarily grow millets and pulses. The Godavari and Krishna River systems are the major water sources traversing Telangana, but it is the augmentation of these resources through projects like KLIP that is significantly transforming the agrarian landscape of the state.

Health impact modelling

This study focuses on quantifying the adverse health effects of crop residue burning, with particular emphasis on premature mortality and new asthma cases attributable to exposure to fine particulate matter ($PM_{2.5}$) (Fig. 2). The modelling framework integrates region-specific parameters, dose-response relationships, and established epidemiological

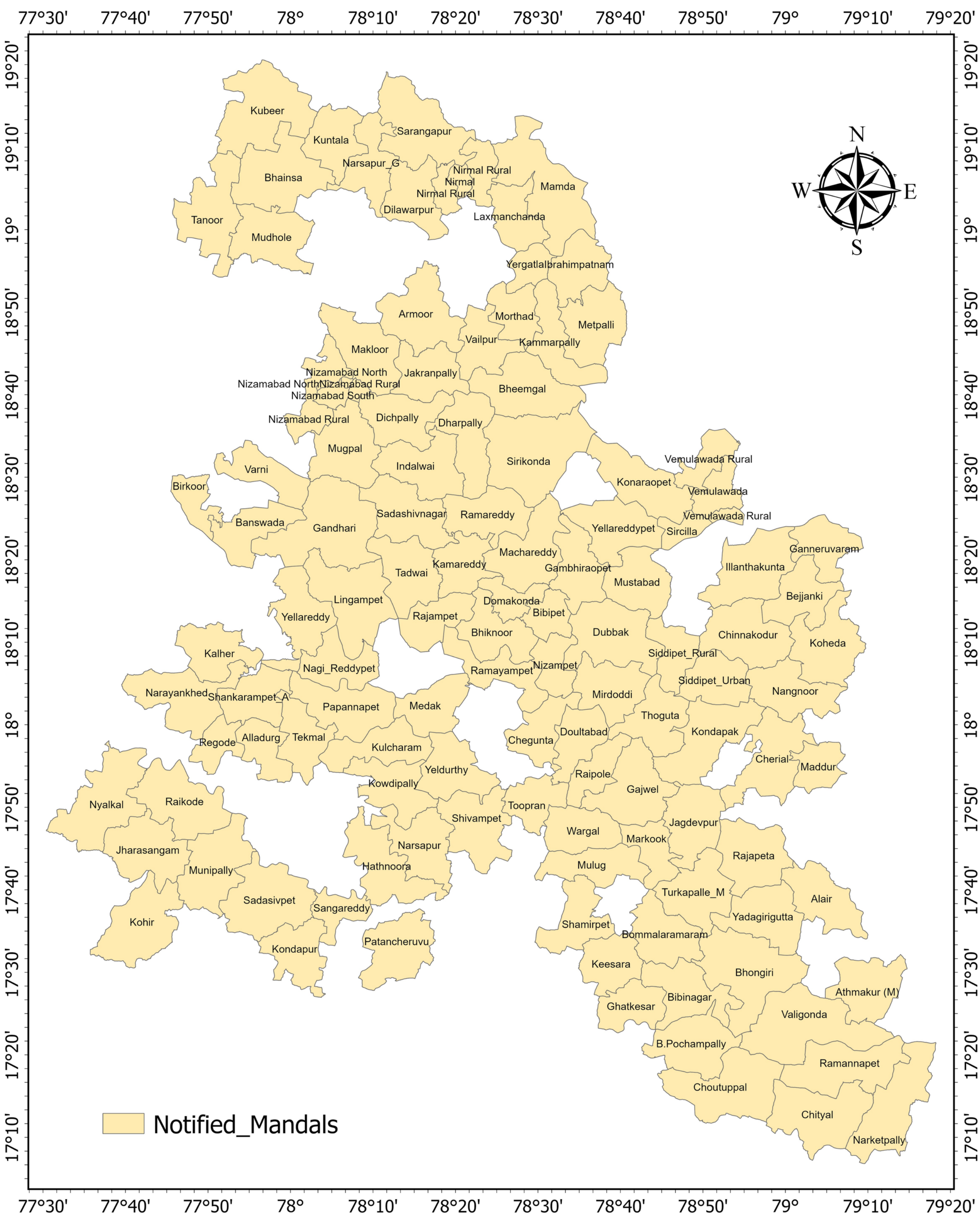

Fig. 1 The study area shows the notified blocks of Telangana

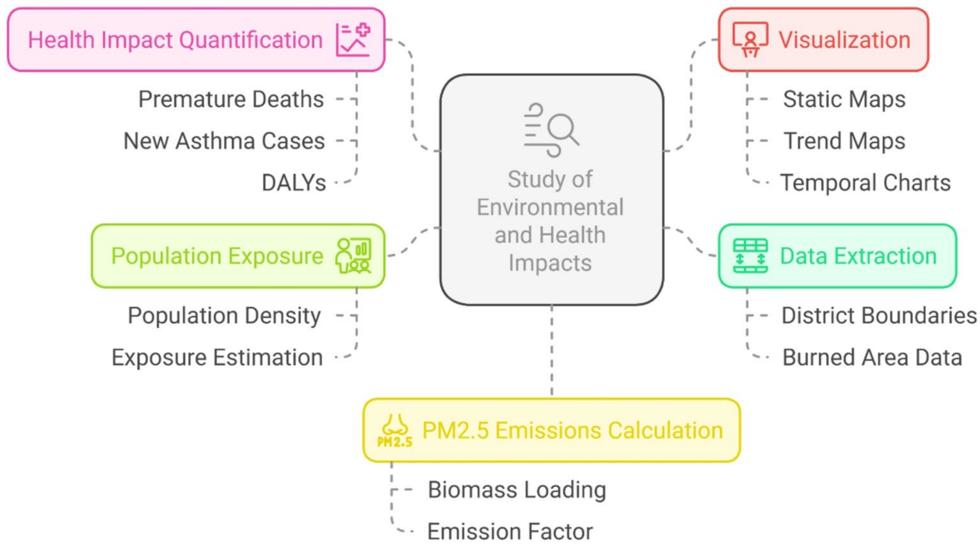

Fig. 2 Methodology for assessing health impact

models to estimate the disease burden resulting from agricultural burning.

Crucially, health impact modelling is tightly integrated with the geospatial analysis of burned areas. Building on methodologies developed in our previous works (Panjala et al. 2024, 2025), the study leverages satellite-derived burned area data and machine learning algorithms to accurately identify residue burn pixels and map emission sources. In these earlier studies, classified burn areas were validated using both classified burn areas and ground-based observations collected during the residue burning period. This field-level validation provided spatial confirmation of burn signatures and supported threshold calibration for spectral indices. This integration allows for detailed temporal and spatial assessments of health risks, highlighting periods and regions of elevated vulnerability to emissions-related health impacts.

Exposure assessment

The foundation of health impact modelling lies in assessing population exposure to PM2.5 emissions (Table 1). Using high-resolution population density data (WorldPop dataset) and Mandal-level boundaries, the study calculates the number of people exposed to elevated PM2.5 concentrations due to crop residue burning. Population counts are aggregated for each Mandal, ensuring localized variations in population distribution are accounted for.

PM2.5 concentrations are derived from burned area metrics using the following formula:

Table 1 Table showing the health impact parameters and values

Parameter	Value (Telangana)	Description	Reference
Biomass Loading (Tons/Ha)	6	The amount of biomass per hectare in Telangana's agricultural fields.	(Manojkumar and Srimuruganandam 12)
Combustion Efficiency	0.9	Fraction of biomass burned in Telangana's farming practices.	(Apoorva Pandey et al. 17)
PM2.5 Emission Factor	0.05	Fraction of burned biomass emitted as PM2.5.	(Apoorva Pandey et al. 17)
Baseline Mortality Rate	0.007	Annual mortality rate per person in Telangana due to air pollution.	(Anamika Pandey et al. 16)
Relative Risk (per 10 µg/m³)	1.06	Increase in mortality risk per 10 µg/m³ increase in PM2.5.	(Anamika Pandey et al. 16)
Asthma Incidence Rate	50	New asthma cases per 100,000 people per 10 µg/m³ increase in PM2.5.	(Sharma and Jain 21)
Life Expectancy Loss Per Death	10	Average years of life lost per premature death in Telangana.	(Anamika Pandey et al. 16)
Asthma Duration (Years)	5	Average duration of asthma cases related to pollution exposure.	(Sharma and Jain 21)

$$PM2.5\,Increase\,\left(\mu\,\frac{g}{m^3}\right) = \frac{PM2.5\,Emissions\,\,(Tons) * 10^6}{Mandal\,\,Area\,\,(Km2) * 10^6}$$

Where:

PM2.5 Emissions (Tons) is calculated as:

$$PM2.5\,Emissions\,\,(Tons)\,\,=Burned\,Area\,\,(Ha) \times\,Biomass\,Loading\,\,(Tons/Ha) \times\,Combustion\,Efficiency \times\,PM2.5\,Emission\,Factor$$

This step ensures that PM2.5 exposure is normalized over Mandal areas, providing a spatially explicit representation of air pollution levels.

Premature deaths are estimated using baseline mortality rates and relative risk functions based on PM2.5 exposure. The formula used is:

$$Premature\,Deaths = Population\,Exposed \times Baseline\,Mortality\,Rate \times\,\left((Relative\,Risk)^{(PM2.5\,Increase/10)} - 1\right)$$

New asthma cases are calculated using asthma incidence rates and PM2.5 exposure levels. The formula is:

$$New\,Asthma\,Cases = Population\,Exposed \times (PM2.5\,Increase/10) \times\,(Asthma\,Incidence\,Rate/100000)$$

DALYs provide a holistic measure of the disease burden by combining Years of Life Lost (YLL) due to premature deaths and Years Lived with Disability (YLD) associated with asthma cases. The formulas used are:

Years of Life Lost (YLL) :

$$YLL = Premature\,Deaths \times\,Life\,Expectancy\,Loss\,per\,Death$$

Years Lived with Disability (YLD) :

$$YLD = New\,Asthma\,Cases \times\,Asthma\,Duration\,(Years) \times\,Disability\,Weight\,for\,Asthma$$

Total DALYs: $DALY = YLL + YLD$

Results and discussion

Spatial distribution of burned areas in 2019 and 2023: population exposure to PM2.5 emissions, concentrations, and changes

The spatial distribution of burned areas from 2019 to 2023 reveals significant variations across different mandals, with several regions showing alarming increases in rice-residue burning (Fig. 3). Makloor Mandal consistently exhibits the highest burned area, escalating substantially from 6771.6 hectares in 2019 to 8850.3 hectares in 2023. This represents a concerning 30.7% increase over four years. Other mandals such as Papannapet and Armoor also show substantial increases, with Papannapet's burned area surging from 3325.5 hectares to 8526.9 hectares (a 156.4% increase) and Armoor's increasing from 5194.3 hectares to 7862.9 hectares (a 51.4% increase). Notably, some mandals that had relatively small, burned areas in 2019 demonstrate dramatic percentage increases by 2023. For instance, Dubbak experiences an extraordinary increase from 378.7 hectares to 4612.8 hectares (a staggering 1118.7% increase), while Mirdoddi grows from 255 hectares to 3324.2 hectares (a remarkable 1203.6% increase). Additionally, Athmakur (M) shows one of the most extreme changes, jumping from 114.7 hectares to 2888.1 hectares (an astonishing 2418.5% increase).

These substantial increases indicate expanding rice-residue burning practices across multiple regions, particularly in previously low-burning mandals. The data demonstrates not only an overall increase in burned areas but also the emergence of new hotspots, highlighting potential shifts in agricultural practices or enforcement challenges. Several mandals demonstrated consistently high burning activity across both years, including Yellareddypet, Sirikonda, and Metpalli, suggesting that rice-residue burning remains a persistent issue in these regions.

The PM2.5 concentration data reveals notable increases across most mandals. Nizamabad South experienced the highest concentration increase from 0.99 µg/m³ to 1.61 µg/m³ (a 62.6% increase), while Bibinagar showed one of the lowest increases from 1.05 µg/m³ to 1.67 µg/m³. Urban areas generally demonstrate higher concentration increases compared to rural counterparts. For example, Ghatkesar's concentration rose from 0.32 µg/m³ to 0.91 µg/m³ (nearly a threefold increase), and Shamirpet's concentration increased from 0.27 µg/m³ to 0.80 µg/m³ (almost tripling). Significant changes are observed in mandals with rapid expansion of burned areas; Papannapet shows an increase from 4.39 µg/m³ to 11.26 µg/m³ (a 156.5% increase), and Dubbak jumps from 0.42 µg/m³ to 5.16 µg/m³ (a remarkable 1128.6% increase).

Regarding population exposure and PM2.5 emissions, the data shows a clear correlation between burned areas and PM2.5 emissions (Fig. 4). For example, Makloor's PM2.5 emissions increased from 1828.3 tons to 2389.6 tons, paralleling its increased burned area. Papannapet follows a similar trend, with emissions rising from 897.9 tons to 2302.3 tons, and Armoor from 1402.5 tons to 2123.0 tons. Urban centers with high population exposure, like Ghatkesar (199,645 people exposed) and Shamirpet (132,306 people exposed), show particular concern despite their relatively smaller burned areas locally. Across all mandals, total PM2.5 emissions increased from approximately 18,000 tons

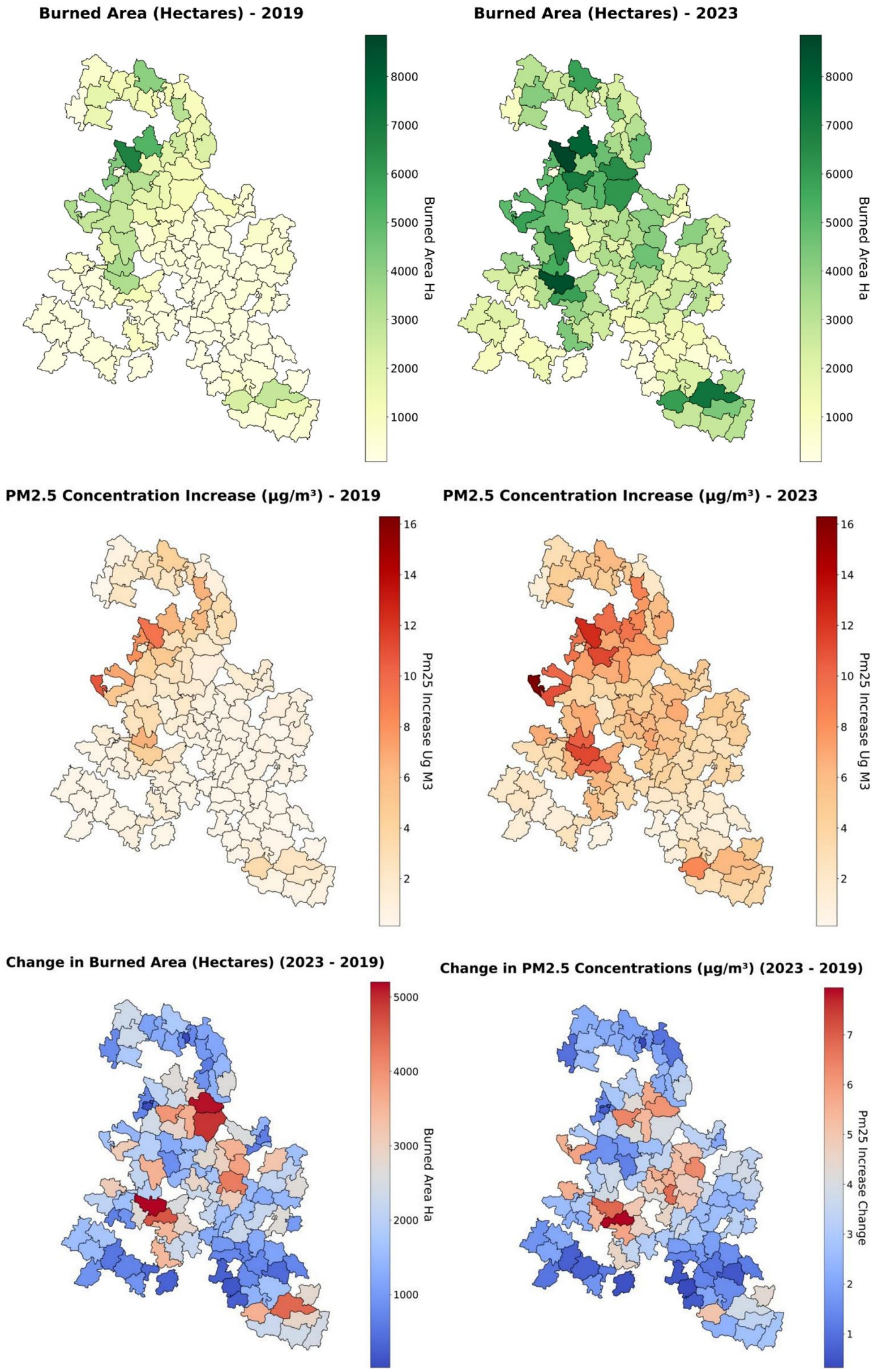

Fig. 3 Spatial distribution of Burned area, and PM2.5 concentrations and their changes

in 2019 to over 23,000 tons in 2023, representing a significant 28% increase.

The findings highlight several critical points. First, the spatial distribution shows not only an overall increase in burned areas but also the emergence of new hotspots, particularly in previously low-burning mandals. Second, the significant increases in PM2.5 emissions and concentrations, especially in urban centers, suggest compounding effects of population density and background pollution levels. Third, mandals like Dubbak and Athmakur (M)

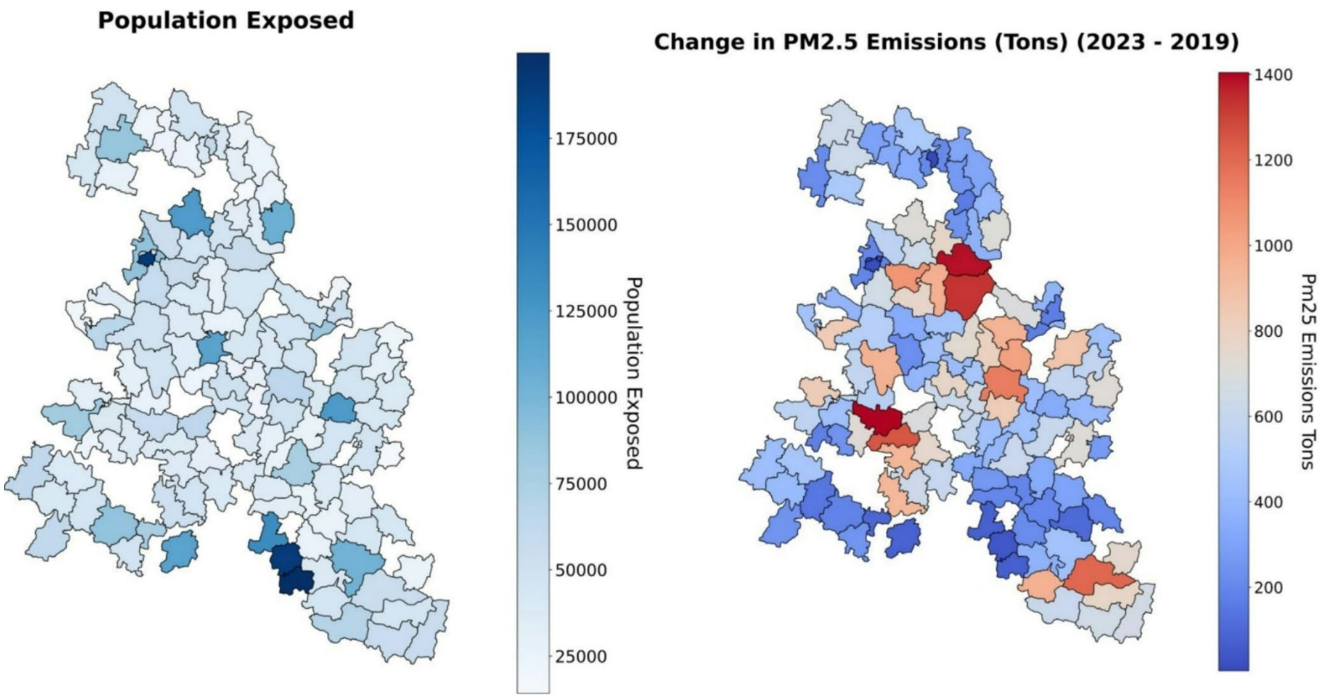

Fig. 4 Spatial distribution of population exposed and change in PM2.5 emissions

demonstrate extreme percentage increases in both burned areas and PM2.5 concentrations, indicating potential shifts in agricultural practices or enforcement challenges. Fourth, urban areas face disproportionate impacts despite having smaller burned areas locally, suggesting regional transport of pollutants and cumulative effects of surrounding agricultural burning. Finally, the consistent pattern of increasing burned areas, emissions, and concentrations across most mandals underscores the need for coordinated regional interventions rather than localized approaches. These results emphasize the urgent need for targeted intervention strategies that address both high-burning regions and rapidly emerging hotspots. The data suggests that current mitigation efforts are insufficient to control the expanding practice of rice-residue burning and its associated air quality impacts. Implementing alternative residue management practices, improving farmer awareness, and enforcing stricter regulations in high-risk areas should be prioritized. The significant changes in PM2.5 concentrations across different regions provide crucial evidence for policymakers to develop targeted interventions and allocate resources effectively to address this pressing environmental issue.

Health impacts due to crop residue burning

The data reveals significant increases in asthma cases across most mandals from 2019 to 2023. Makloor Mandal shows the highest absolute increase, rising from 25.62 cases in 2019 to 33.49 cases in 2023. Papannapet follows with an increase from 12.26 to 31.45 cases. Notably, several mandals demonstrate substantial percentage increases, such as Dubbak, which jumps from 1.37 to 16.63 cases (a 1118.7% increase), Athmakur (M) increasing from 0.23 to 5.75 cases (a 2404.3% increase), and Mirdoddi rising from 1.03 to 13.44 cases (a 1204.9% increase). Urban centers with high population exposure show particular concern; for instance, Ghatkesar experiences an increase from 3.20 to 9.10 cases, Shamirpet from 1.76 to 5.28 cases, and Nizamabad South from 9.36 to 15.27 cases. Across all mandals, total new asthma cases increased significantly, reflecting both increased burned areas and population exposure.

Premature deaths also show alarming increases across most regions. Makloor experiences an increase from 21.49 to 28.33 deaths, while Papannapet rises from 10.13 to 26.51 deaths, and Armoor from 32.14 to 49.12 deaths. Several mandals demonstrate extreme percentage increases: Dubbak rises from 1.12 to 13.77 deaths (a 1132.1% increase), Athmakur (M) from 0.19 to 4.75 deaths (a 2400.0% increase), and Mirdoddi from 0.84 to 11.14 deaths (a 1226.2% increase). Urban areas, despite having smaller local burned areas, show significant impacts; for example, Ghatkesar increases from 2.61 to 7.44 deaths, Shamirpet from 1.43 to 4.32 deaths, and Nizamabad South from 7.66 to 12.51 deaths.

Years of Life Lost (YLLs) and Disability-Adjusted Life Years (DALYs) exhibit parallel increasing trends (Figs. 5 and 6). Makloor Mandal demonstrates the highest values,

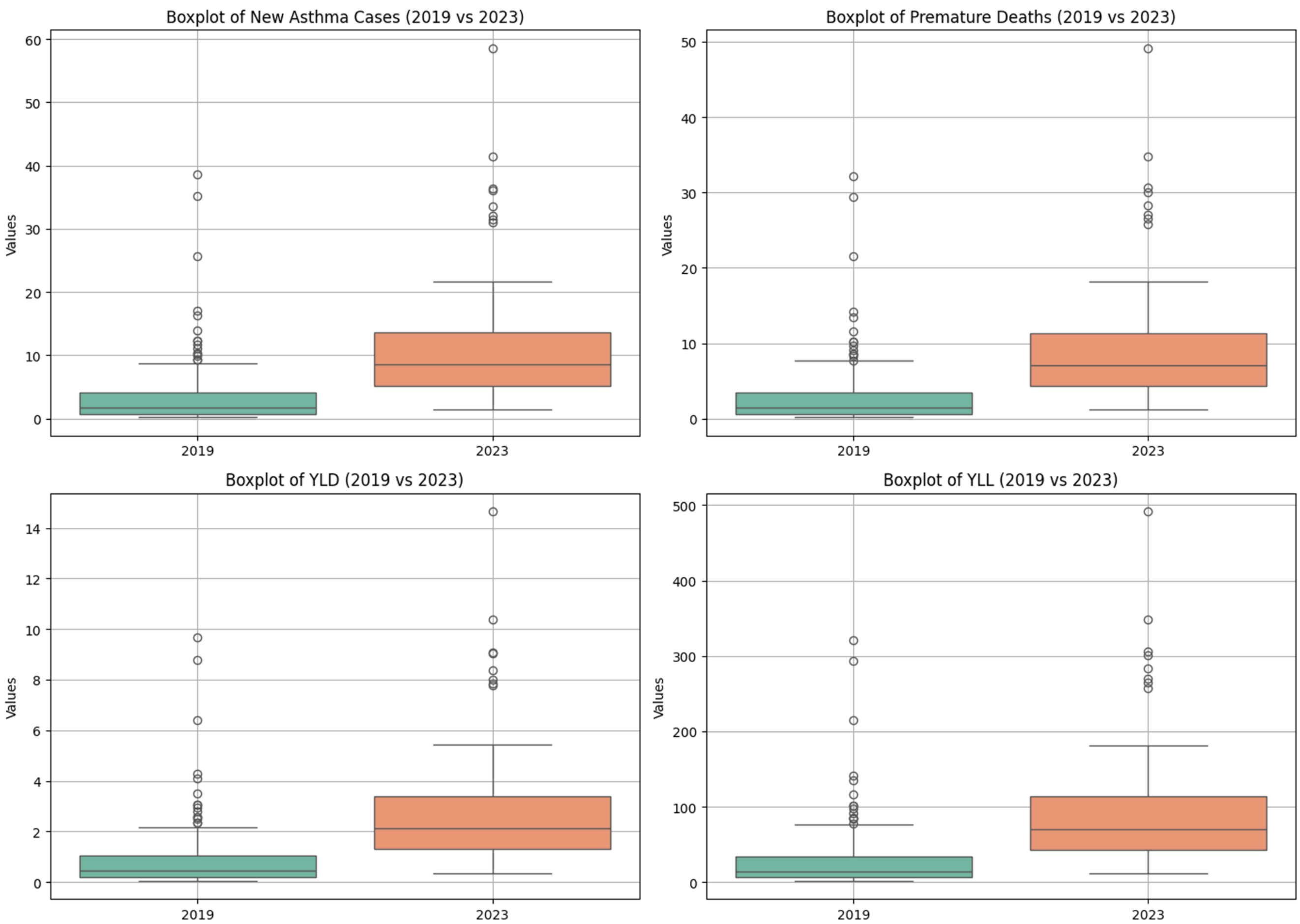

Fig. 5 Box and Whisker Plots for New Asthma cases, Premature deaths, YLD and YLL

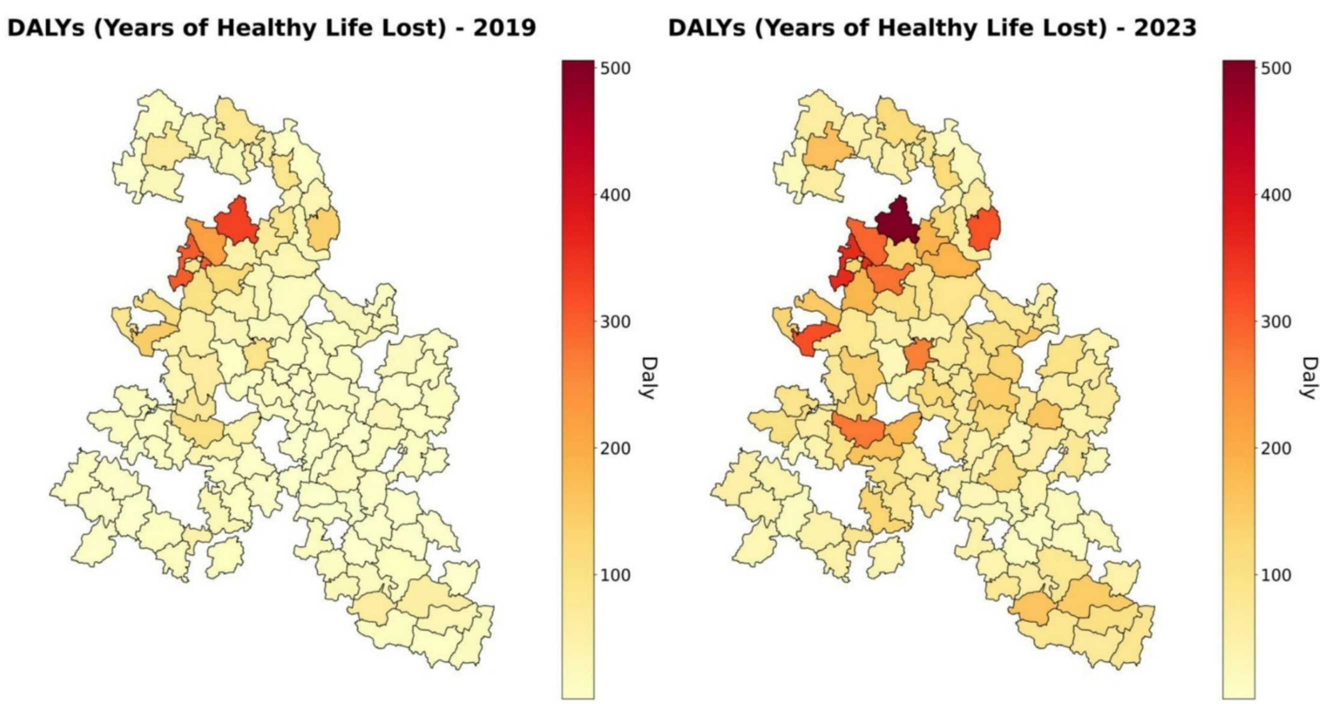

Fig. 6 Spatial distribution of DALYs for 2019 and 2023

with YLLs increasing from 214.89 to 283.27 and DALYs from 221.30 to 291.64. Other significant increases include Papannapet, where YLLs rise from 101.33 to 265.12 and DALYs from 104.40 to 272.99, and Armoor, where YLLs increase from 321.38 to 491.17 and DALYs from 331.05 to 505.80. Percentage increases highlight emerging hotspots: Dubbak shows YLLs jumping from 11.15 to 137.73 (a 1135.2% increase) and DALYs from 11.49 to 141.89 (a 1136.2% increase), while Athmakur (M) experiences YLLs rising from 1.86 to 47.53 (a 2455.4% increase) and DALYs from 1.92 to 48.97 (a 2450.5% increase). Urban areas also show concerning trends, such as Ghatkesar, where YLLs increase from 26.12 to 74.43 and DALYs from 26.92 to 76.70, and Shamirpet, where YLLs rise from 14.34 to 43.16 and DALYs from 14.78 to 44.48.

These health impact metrics demonstrate the growing burden of rice-residue burning on public health. The consistent pattern of increasing asthma cases, premature deaths, YLLs, and DALYs across most mandals underscores the urgent need for effective intervention strategies. The data highlights that even urban areas with smaller local burned areas face significant health impacts, suggesting regional transport of pollutants and cumulative effects. This comprehensive assessment provides crucial evidence for policymakers to prioritize resources and develop targeted interventions to mitigate the health impacts of crop residue burning.

Overall assessment with prioritization of interventions and recommendations

The comprehensive analysis of rice-residue burning across mandals from 2019 to 2023 reveals a significant escalation in environmental degradation, public health risks, and socioeconomic burdens. The data underscores the urgent need for targeted interventions and strategic planning to address this growing crisis effectively.

Environmental Impact: The spatial distribution of burned areas shows not only an expansion of traditional hotspots but also the emergence of new regions contributing significantly to residue burning. Mandals like Makloor, Papannapet, and Armoor remain major contributors, with burned areas increasing by 30.7%, 156.4%, and 51.4%, respectively. Emerging hotspots such as Dubbak and Athmakur (M) have shown exponential growth in burned hectares, with increases exceeding 1,000%. This geographic spread indicates that residue burning is becoming more widespread, potentially due to shifts in agricultural practices or enforcement gaps. Total PM2.5 emissions increased by approximately 28%, from 18,000 tons in 2019 to over 23,000 tons in 2023. Urban centers like Ghatkesar and Shamirpet, despite having smaller local burned areas, experienced significant concentration increases due to regional transport of pollutants. For instance, Ghatkesar's PM2.5 concentration nearly tripled from 0.32 μg/m³ to 0.91 μg/m³, highlighting the compounding effect of regional pollution on urban air quality.

Health Impact: The health impacts are alarming, with significant increases in asthma cases, premature deaths, Years of Life Lost (YLLs), and Disability-Adjusted Life Years (DALYs). Makloor Mandal reported the highest absolute increase in new asthma cases, rising from 25.62 in 2019 to 33.49 in 2023. Similarly, Papannapet saw an increase from 12.26 to 31.45 cases. Premature deaths also rose significantly, with Makloor experiencing an increase from 21.49 to 28.33 deaths, and Papannapet from 10.13 to 26.51 deaths. YLLs and DALYs followed similar trajectories, increasing by 37% and 38%, respectively. Urban areas with high population densities faced disproportionate health burdens, as seen in Ghatkesar, Shamirpet, and Nizamabad South, which showed alarming increases in premature deaths and DALYs despite smaller local burned areas.

Socio-Economic Implications: High population mandals like Ghatkesar (199,645 people exposed) and Shamirpet (132,306 people exposed) face substantial risks due to their dense populations and baseline pollution levels. The economic costs associated with increased healthcare needs, productivity losses from premature deaths and illnesses, and potential reductions in agricultural yields due to soil degradation from burning cannot be overlooked. Moreover, the emergence of new hotspots in previously low-burning regions suggests that resource allocation for mitigation efforts may need to be re-evaluated to address shifting patterns.

Prioritization of Interventions:

1. High-Impact Regions: Mandals like Makloor, Papannapet, and Armoor require immediate attention due to consistently high burned areas and emissions.High-Impact Regions: Mandals like Makloor, Papannapet, and Armoor require immediate attention due to consistently high burned areas and emissions.
2. Emerging Hotspots: Rapidly increasing burned areas in Dubbak, Athmakur (M), and Mirdoddi necessitate targeted interventions to prevent further escalation.
3. Urban Centers: Urban areas like Ghatkesar and Shamirpet require special focus due to their high population exposure and vulnerability to regional pollution transport.

Recommendations:

1. Alternative Residue Management Practices: Promoting sustainable alternatives such as mechanized straw management, bioenergy production, and composting can reduce reliance on burning.Alternative Residue Management Practices: Promoting sustainable alternatives

such as mechanized straw management, bioenergy production, and composting can reduce reliance on burning.
2. Awareness Campaigns: Farmer education programs highlighting the environmental and health impacts of burning, along with incentives for adopting alternative practices, are critical.Awareness Campaigns: Farmer education programs highlighting the environmental and health impacts of burning, along with incentives for adopting alternative practices, are critical.
3. Stricter Enforcement: Strengthening regulations and enforcement mechanisms, particularly in emerging hotspots, can curb the spread of residue burning.Stricter Enforcement: Strengthening regulations and enforcement mechanisms, particularly in emerging hotspots, can curb the spread of residue burning.
4. Regional Coordination: Addressing regional transport of pollutants requires coordinated efforts across neighbouring districts and states.Regional Coordination: Addressing regional transport of pollutants requires coordinated efforts across neighbouring districts and states.
5. Health System Preparedness: Strengthening healthcare infrastructure in high-impact areas to manage the rising burden of respiratory and cardiovascular diseases is essential.Health System Preparedness: Strengthening healthcare infrastructure in high-impact areas to manage the rising burden of respiratory and cardiovascular diseases is essential.

The overall assessment paints a clear picture of an escalating crisis driven by rice-residue burning. The interplay between environmental degradation, public health risks, and socio-economic costs underscores the urgent need for comprehensive, multi-sectoral interventions. Without decisive action, the trends observed from 2019 to 2023 are likely to worsen, leading to even greater environmental damage, health burdens, and economic losses. The findings provide a robust foundation for policymakers to prioritize resources, develop targeted strategies, and implement effective measures to mitigate the impacts of crop residue burning.

This comprehensive approach, focusing on both high-impact and emerging hotspot regions, alongside regional coordination and awareness campaigns, will be pivotal in addressing the multifaceted challenges posed by rice-residue burning.

Limitations of the study

This study has a few important limitations that should be acknowledged. First, the analysis does not incorporate wind direction, wind speed, or atmospheric dispersion modelling. Pollutant exposure was estimated at the mandal level under the assumption that emissions remained localized. Fine particulate matter such as PM2.5 can be transported beyond administrative boundaries, depending on meteorological conditions. The absence of dispersion modelling may lead to an underestimation or spatial misattribution of health impacts. Future work will incorporate atmospheric transport models such as HYSPLIT or WRF-Chem to simulate pollutant movement and better estimate downwind exposure.

Second, the health impact assessment was limited to asthma incidence and premature mortality, based on available exposure–response functions with strong associations to PM2.5. However, exposure to PM2.5 is also linked to a broader set of chronic conditions including cardiovascular disease, stroke, and lung cancer. Including these additional endpoints in future work will provide a more complete estimate of the health burden from crop residue burning.

Third, the analysis focused solely on rice residue burning. Rice was selected due to its dominance in the regional cropping system and its disproportionately high contribution to post-harvest burning and emissions. However, other crop residues such as maize, cotton, and sugarcane may also contribute significantly to local air pollution. Future studies will expand the scope to include multiple crops to provide a more comprehensive assessment of agricultural burning and its public health implications.

Conclusion

The study on rice-residue burning across various mandals from 2019 to 2023 reveals a significant environmental, public health, and socio-economic crisis. Burned areas increased substantially in traditional hotspots like Makloor (30.7%) and emerging regions such as Dubbak (exceeding 1,000%), contributing to a 28% rise in PM2.5 emissions, which reached over 23,000 tons by 2023. This has led to severe health impacts, with asthma cases, premature deaths, YLLs, and DALYs showing alarming increases, particularly in high burden mandals like Makloor and emerging hotspots like Dubbak, where DALYs rose by over 1,000%. Urban centers like Ghatkesar and Shamirpet, despite smaller local burned areas, faced disproportionate health risks due to regional pollutant transport, and worsening air quality for dense populations. The socio-economic burden is evident in high population mandals like Ghatkesar (199,645 exposed) and Shamirpet (132,306 exposed), which face mounting healthcare costs, productivity losses, and reduced agricultural yields. These findings highlight the urgent need for targeted interventions, including promoting alternative residue management practices, strengthening regulations, enhancing public awareness, and fostering regional coordination to mitigate the adverse effects of crop residue burning effectively. Without decisive action, the observed trends are likely to worsen, leading to greater environmental damage, health burdens, and economic losses.

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Data availability Data is freely available upon request.

Declarations

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Consent for publication All authors showed consent for publication.

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