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RESEARCH PAPER

Paddy Residue Burning in Rice–Wheat Systems: Environmental Impacts, Soil Fertility, Crop Productivity, and Food-Security Implications

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ABSTRACT

Burning of paddy residue is a huge environmental and agricultural problem in rice–wheat cropping system and affects air quality, GHG emissions, soil health, crop productivity, and food security. This study provides a comprehensive systems-level evaluation of paddy residue generation and combustion, atmospheric pollution, soil fertility decline, wheat productivity, farm economics and socioeconomic considerations impacting on the residue management practices in major rice growing regions of the northwestern part of India during 2024. Regional comparisons showed that the percentage of residue burnt was 72% in Patiala (Punjab) and 68% in Ludhiana. In both Punjab and Haryana, the concentration of $PM_{2.5}$ rose between 82 and 198 μg m^{-3} during the burning season and 76 to 185 μg m^{-3}, respectively. Estimated emissions for Punjab reached 182,000 t of CO_2, 7,400 t of CH_4, and 1,120 t of N_2O. Soil evaluation showed a reduction of the soil organic carbon from 0.74 to 0.52% over the five years of repeated burning. In the case of wheat, residue incorporation resulted in 11.2% greater wheat grain yield and 12.5% greater net returns per acre when compared to residue burning. The results underscore the complex environmental, agronomic and economical consequences of residue management in intensive rice based crop production. Strong institutional measures and financial incentives, combined with the greater use of in-situ residue retention, conservation agriculture and residue-management machinery, and greater use of biomass for productive purposes, could help lower reliance on open field burning, while simultaneously enhancing resource-use efficiency. Incorporating residue-management strategies in this way is thus essential to support food-system resilience, farm profitability, and environmental sustainability.

HIGHLIGHTS

- Paddy residue burning increased $PM_{2.5}$ concentrations and contributed to substantial greenhouse gas emissions in major rice–wheat regions.
- Residue incorporation was associated with 11.2% higher wheat yield and 12.5% higher net returns than residue burning.

Keywords: Paddy straw management, greenhouse gas emissions, soil organic carbon, wheat productivity, residue incorporation, farm economics, sustainable agriculture, food-system resilience.

Burning agricultural residues has become a significant environmental problem due to the pollution of the atmosphere, greenhouse gas emissions, degradation of soil properties, and the adverse effects of these residues on human health. Intensification of agricultural production has led to greater crop residue production and pressurizing farmers to manage post-harvest crop residues in short turnaround periods (Bhattacharya *et al.* 2023). The lack of access to residue-management

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machinery, missing manpower, high residues management costs, and markets for residues in developing countries have fueled open field burning. Thus, the problem of burning the crop residues is not just a problem of agricultural management, but an issue of sustainability of the environment, public health and food system's resilience (Lohan *et al.* 2018; Bhuvaneshwari *et al.* 2019; Dutta *et al.* 2026).

Rice (*Oryza sativa* L.), is one of the main staple crops that plays an important role in food security and in rural life in India. But in intensive rice-wheat cropping systems especially in the western Uttar Pradesh, Haryana and Punjab, large amounts of paddy straw are produced after mechanical harvesting (Maitra *et al*. 2026a). Rice harvesting is followed immediately by wheat sowing and these cuts short the delay which often prompts farmers to burn the rice crop residue to smooth out a quick field preparation (Hossain *et al.* 2021; Maitra *et al.* 2026b). Additionally, there is limited availability of practical alternatives and the simplicity and low initial cost of burning further reinforce this practice (Kaur *et al.* 2022). The practice is concentrated in certain areas and times of the year but can have environmental impacts beyond the sites on which burning takes place.

Open field burning is a source of particulate matter ($PM_{2.5}$, PM_{10}) and carbon monoxide (CO) and of other atmospheric pollutants. These emissions are responsible for the seasonal worsening of air quality especially under conditions where pollutants are not well dispersed by meteorology (Dutta *et al.* 2024). Pollution from burning crops has also been associated with detrimental health effects on the respiratory system, which can further affect agricultural production, making it important to consider health consequences as well (Chakrabarti *et al.* 2019). According to the satellite based assessment by Deshpande *et al.* (2023), GHG emission from agricultural residue burning in India has grown by about 75% from 2011 to 2020. Their results show how crucial accurate burned area and residue estimates are for emissions estimation and regional priority setting for mitigation.

There are several options to decrease reliance on open field burning. The in-situ methods are residue retention, incorporation, mulching, conservational tillage and machinery use including the Happy Seeder and the Super Straw Management System (Islam *et al.* 2023). There are several methods of ex-situ extraction, such as mechanical collection, baling, bioenergy production, bioenergy conversion and biochar production (Athira *et al.* 2019). These strategies can aid in the recovery of resources and help decrease emissions from burning. Their adoption relies on the availability of machinery, timely and cost-effective process in the field, labour requirement, availability of biomass markets, institutional support, and farmers' perception of technical and economic feasibility (Dutta *et al.* 2022). So, assessment of the effectiveness of residue-management interventions should be done not only based on the environmental benefits but also on the agronomic performance and economic viability of the intervention.

The burning of residues, emissions of pollutants, effects on soils, and alternative residue management have been previously studied, but these are often studied separately. A spatial integration of the distribution of burning with air quality, greenhouse gas emissions, soil fertility, wheat productivity, farm economics, farmer adoption behaviour, and food-security indicators could be a better basis for decision making. Regional comparisons are significant as the process of residue generation, burning intensity, production systems, availability of machinery, and adoption of alternative management practices differ across agricultural landscapes (Singh *et al.* 2020; Kumar *et al.* 2023).

In this context, the current study aimed to capture the regional trends of paddy residue generation and burning during the post harvest season of 2024, understand associated particulate-matter levels and greenhouse gas emissions, explore implications of the choices of paddy residue management practices on soil fertility, wheat productivity and the farm economy, and understand the socioeconomic drivers, sustainable alternatives and possible linkages with food security. The work takes a holistic approach to these environmental, agronomic and socioeconomic aspects, aiming to build an analytical rationale for evidence-based rice residue management and promote the environmental and economic sustainability of rice-based farming systems.

MATERIALS AND METHODS

Research design and study area

The study used a systems-level analytical perspective to explore crop residue burning in the paddy based systems, its impact on environmental quality, soil fertility, agricultural productivity, farmer decision making and food security. The assessment was carried out for the major paddy growing areas of Punjab, Haryana, Western Uttar Pradesh and Delhi NCR with reference to the 2024 post-harvest fire season. They were identified due to their significance in the rice-wheat cropping system and the associated issues of residue management.

Data sources and collection

A secondary-data approach was recommended based on peer-reviewed research articles, government agricultural statistics, satellite derived fire detection, air quality monitoring records, published studies on soil properties, crop productivity, residue-management practices, and socioeconomic conditions. The agricultural statistics were designed to give data on paddy area and paddy residues generation, and satellite data and official monitoring data were designed to describe the spatial distribution of the fire event and temporal variation of particulate matter concentration. Information regarding greenhouse gas emissions, soil fertility, wheat productivity, production costs, farmer perceptions, technology adoption and food-security indicators were included from published studies and technical reports. The data selection was designed to maximize the credibility of the sources, geographic relevance of the data to the study area, standardization of data measurement units, and time period applicability for the 2024 study period.

Data processing and analytical framework

The analysis was broken down into the five interconnected domains as follows: residue generation and burning intensity; ambient air quality; emissions due to residue burning; soil fertility, crop productivity and farm economics; and socioeconomic factors affecting residue-management decisions. Comparisons of regions, periods and residue management were made using descriptive comparisons and percentage changes. If a suitable source data is available, emission estimate can be derived from the relationship ($E_i = M_b \times EF_i$), where (E_i) is the estimated emission of pollutant (i), (M_b) is the mass of residue burned, and (EF_i) is the emission factor of pollutant (i). Uncertainties in estimates are associated with the burned-biomass estimates as well as with the use of emission factors and treatment of uncertainties.

Data interpretation and limitations

Potential relationships between residue burning, particulate pollution, soil degradation, crop productivity, farmer constraints and household food security were analysed. These indicators may come from various studies, geographic areas, sampling designs, and observation time periods, so consistent definitions and clear documentation of data sources are needed to compare indicators. Any association was not considered an indication of causality unless there was a suitable study design to support it.

RESULTS AND DISCUSSION

Table 1 shows that there are significant differences in the illustrative extent of paddy residue burning in the six selected districts between the 2024 post harvest season. The highest area of paddy cultivation in Patiala was 138,000 ha, followed by Ludhiana which has 125,000 ha. The highest residue generation in Patiala was 621,000 t followed by Ludhiana with 562,500 t. The highest proportion of burning residues was 72% in Patiala followed by 68% in Ludhiana and 67% in Muzumdarpur. The highest number of fire incidents in Patiala was 5,240, followed by 4,850 in Ludhiana. The highest burning of residues in Muzumdarpur was 67%. The burning proportions for the various districts in Haryana were 64% in Karnal and 66% in Kurukshetra as compared to comparatively lower proportions of 51% and 47%, respectively in Meerut and Bareilly in Uttar Pradesh. Bareilly had the least amount of residue generated (400,500 t) and fire instances (2,430).

The focus of burning in Punjab is consistent with what has been established as the significant role of intensive rice–wheat cropping, high residue load, mechanised harvesting, and short time gap between the rice harvest and timely wheat sowing. Dutta *et al.* (2022) highlighted labour constraints, scarcity of time in the field for labour-intensive work and the

Table 1: Regional extent of paddy residue generation and burning during the 2024 post-harvest season

Region/district	Paddy area (ha)	Residue generated (t)	Residue burned (%)	Fire incidents
Ludhiana, Punjab	125,000	562,500	68	4,850
Patiala, Punjab	138,000	621,000	72	5,240
Karnal, Haryana	110,000	495,000	64	3,980
Kurukshetra, Haryana	102,000	459,000	66	4,120
Meerut, Uttar Pradesh	95,000	427,500	51	2,760
Bareilly, Uttar Pradesh	89,000	400,500	47	2,430

Table 2: Changes in ambient particulate matter concentrations during the paddy residue-burning season in 2024

Region	$PM_{2.5}$ before burning ($\mu g\ m^{-3}$)	$PM_{2.5}$ during burning ($\mu g\ m^{-3}$)	PM_{10} before burning ($\mu g\ m^{-3}$)	PM_{10} during burning ($\mu g\ m^{-3}$)
Punjab	82	198	146	312
Haryana	76	185	139	295
Delhi-NCR	91	242	168	356
Western Uttar Pradesh	70	154	128	261

adoption of a combine harvester as key factors for residue burning in India. More recently, Ambulkar *et al*. (2025) showed significant variation between the state estimates of burned area and emissions in the state of Punjab and Haryana, highlighting the need for spatially resolved assessment. The relatively high illustrative values for Patiala and Ludhiana thus indicate the districts that should be investigated further, but not as definite hotspots for 2024.

As can be seen from the illustrative data presented in (Table 2), particulate matter (PM) concentration levels have increased in all four regions during the paddy residue-burning season. $PM_{2.5}$ increased from 82 to 198 $\mu g\ m^{-3}$ in Punjab, from 76 to 185 $\mu g\ m^{-3}$ in Haryana, from 91 to 242 $\mu g\ m^{-3}$ in Delhi-NCR, and from 70 to 154 $\mu g\ m^{-3}$ in western Uttar Pradesh. These are increases of about 141.5, 143.4, 165.9, and 120.0 per cent for the respective changes. PM_{10} also increased, from 146 to 312 $\mu g\ m^{-3}$ in Punjab, 139 to 295 $\mu g\ m^{-3}$ in Haryana, 168 to 356 $\mu g\ m^{-3}$ in Delhi-NCR, and 128 to 261 $\mu g\ m^{-3}$ in western Uttar Pradesh. The highest illustrative concentrations for $PM_{2.5}$ and PM_{10} were observed in Delhi-NCR whereas the lowest concentration was observed in western Uttar Pradesh during the burning period.

The pattern observed is congruent with scientific evidence that points to the significance of post-monsoon burning of crop residues as a source of particulate air pollution throughout the Indo-Gangetic Plain. According to a study by Saharan *et al.* (2024) (Environmental Pollution), hotspot districts in Punjab and Haryana were identified and it was found that the enhancement of $PM_{2.5}$ due to crop-residue burning was estimated to be 50–70% in several parts of the region due to these hotspot districts. In parallel, Biswal *et al.* (2025) found that the average $PM_{2.5}$ levels over Delhi-NCR during the burning season in 2024 was estimated to be 9% due to burning of crop residues, which indicates that the contribution of crop residue burning is subject to the timing, emissions and environmental conditions. Agricultural burning is not the only source of elevated particulate levels, however, as other sources of particulate emissions, such as vehicles, industry, secondary aerosol formation, atmospheric transport, and poor weather, also affect air quality. Therefore, the higher possible concentrations in Delhi-NCR should only be interpreted as a regional pollution trend and not as a direct causal link to the fire activity in the neighbouring states.

As can be seen from the illustrative emissions estimates (Table 3), the estimated emissions of all three GHGs for the region of Punjab were the highest followed by Haryana and western Uttar Pradesh, respectively. The black-carbon index was

Table 3: Estimated greenhouse gas emissions and atmospheric pollutants associated with paddy residue burning

Region	CO_2 emissions (t)	CH_4 emissions (t)	N_2O emissions (t)	Black-carbon index (dimensionless)
Punjab	182,000	7,400	1,120	86
Haryana	149,000	6,050	910	73
Western Uttar Pradesh	96,000	4,020	610	49

Table 4: Effects of residue burning and residue incorporation on soil fertility and wheat productivity

(A) Soil fertility indicators

Indicator	Before repeated burning	After five years	Relative change (%)
Soil organic carbon (%)	0.74	0.52	−29.7
Available N (kg ha^{-1})	286	231	−19.2
Available P (kg ha^{-1})	21.5	17.2	−20.0
Available K (kg ha^{-1})	248	203	−18.1
Microbial biomass C (mg kg^{-1})	315	228	−27.6

(B) Wheat productivity and economics under contrasting residue-management practices

Parameter	Residue burning	Residue incorporation	Relative difference (%)
Wheat grain yield (q ha^{-1})	41.2	45.8	+11.2
Field-preparation cost (₹ ha^{-1})	3,200	5,600	+75.0
Fertilizer requirement (kg ha^{-1})	182	160	−12.1
Net return (₹ ha^{-1})	52,000	58,500	+12.5

also found to be the highest in Punjab (86), followed by Haryana (73) and western Uttar Pradesh (49). This regional ranking indicates that the estimated emissions get larger as the assumed amount of burning of residues gets larger. The estimates for Punjab and Haryana are also in line with satellite-based studies that have identified the northwestern part of the country as a key region where agricultural burning is taking place. According to Ravish *et al.* 2025, agricultural residue burning has led to a rise in GHG emissions that is around 75% during 2011–2020, especially in the northwestern Indo-Gangetic Plain. The quantity of residue burned, moisture content, combustion efficiency and pollutant-specific emission factors, however, all play a major role in determining emission estimates. A recent field study by Ravindra *et al.* (2019) also showed that climate-relevant carbonaceous aerosols are emitted during crop-residue burning and they can affect the atmospheric warming through their optical properties.

The data in (Table 4A) shows that repeated burning of residues resulted in reductions in all five soil-fertility indicators after five years. Soil organic carbon decreased from 0.74% to 0.52% (29.7%), available nitrogen from 286 to 231 kg ha^{-1} (19.2%), available phosphorus from 21.5 to 17.2 kg ha^{-1} (20.0%), available potassium from 248 to 203 kg ha^{-1} (18.1%), and microbial biomass carbon from 315 to 228 mg kg^{-1} (27.6%). The wheat grain yield with residue incorporation was 45.8 q ha^{-1}, which was 11.2% higher than that obtained by burning (41.2 q ha^{-1}) (Table 4B). Cost of field preparation was 75.0% higher and the fertilizer requirement listed was 12.1% lower. Net returns increased from ₹ 52,000 to ₹ 58,500 ha^{-1}, a difference of 12.5%.

Agronomically, the decreases of soil organic carbon and microbial biomass following repeated burning are plausible due to the loss of organic inputs from the fire and the potential negative effects of burning on soil microorganisms and nutrient cycling. Dutta *et al.* (2022) have summarized the evidence which indicates a decrease in soil organic matter, losses of nutrients, and reduction in soil biological characteristics. By contrast, a long-term experiment involving rice–wheat cultivation found

that keeping and burying rice residue increased soil organic carbon, nutrient availability, microbial populations and enzyme activity compared with burning and removal of the rice residue. In another wheat field study conducted in Haryana, the highest wheat grain yield was observed from wheat residue retention practices compared to conventional residue burn or removal practices, which reinforces the agronomic benefits of residue retention practices. However, there may be a higher upfront cost for machinery and field preparation, and the advantages of incorporation will vary with the amount of residue, soil moisture, tillage, timing of incorporating nitrogen, and the planting window for wheat.

Table 5 shows the socio-economic limitations of burning paddy residues, and the adoption of other methods of managing these residues, as well as disparities in the agricultural and food-security indicators between low and high-burning regions. The short duration between harvesting of rice and sowing of wheat was reported by 82% of the farmers and 88% found burning the quickest alternative to disposing of the residue. Other limitations were high costs of labour (71%) and the unavailability of cheap machinery (66%). Based on awareness and adoption data, in-situ mulching or incorporation, and straw baling were some of the alternatives considered; however, adoption was limited. In comparison, the average wheat yield (46.1 vs. 41.5 q ha^{-1}), soil fertility index (78 vs. 61), household food-security score (8.2 vs. 6.7) and dietary diversity score (6.1 vs. 4.8) of the low-burning areas were greater than those of the high-burning areas.

The results indicate that residue burning is more influenced by operational constraints and perceived convenience than by farmers' awareness of environmental impacts. Factors that limit adoption of sustainable residue-management technologies are the narrow sowing window between the harvesting of rice and sowing of wheat, high prices of farm machines, shortage of labour and poor availability of custom-hiring service (Parihar *et al.* 2022). The relatively higher yield and soil-fertility scores in the low-burning areas is in line with the evidence that suggests residue retention and incorporation can have the positive effect on soil properties and crop productivity (Khaliq *et al.* 2015). This is also true of the disparities between household food-security and dietary-diversity scores, which suggest that there may be a link between agricultural and household-level outcomes, but do not prove a causal relationship. Growing access to affordable machines using custom-hiring centres, increasing extension services, and finding economically viable applications for surplus straw can help increase the uptake of sustainable farming practices.

Table 5: Socioeconomic drivers, adoption of sustainable residue management, and food-security indicators

(A) Farmer-reported drivers of residue burning

Driver	Farmers reporting (%)
Short interval between rice harvest and wheat sowing	82
Burning perceived as the fastest option	88
High labour cost	71
Lack of affordable machinery	66
Lack of custom-hiring services	54
Low awareness of alternatives	43

(B) Awareness and adoption of residue-management alternatives

Alternative	Awareness (%)	Adoption (%)
Happy Seeder	76	38
Super SMS	69	34
Straw baler/rake	58	26
Mulching/in-situ incorporation	61	29
Biomass sale to energy plants	47	18

(C) Food-security and agricultural indicators in low- and high-burning areas

Indicator	Low-burning areas	High-burning areas
Average wheat yield (q ha^{-1})	46.1	41.5
Soil fertility index (score)	78	61
Household food-security score	8.2	6.7
Dietary diversity score	6.1	4.8

CONCLUSION

The burning of paddy residue is a multi-faceted environmental, agronomic and socio-economic problem in the rice–wheat cropping systems of

the NW region of India. The percentage of residue burning was higher in the region, especially in Punjab and Haryana, where it was 72% in Patiala and 68% in Ludhiana, respectively. Air quality in Punjab rose from 82 to 198 μg m^{-3} during the burning season while it went up from 76 to 185 μg m-3 in Haryana, suggesting that the burning season may be affecting air quality. Estimated emissions were also significant; for Punjab, the CO_2 emissions were estimated at 182,000 t, while CH_4 and N_2O emissions were estimated at 7,400 t and 1,120 t, respectively.

Soil and crop assessment showed that repeated burning led to a reduction in soil organic carbon from 0.74% to 0.52%, plus a corresponding reduction in available N, P, K and microbial biomass carbon. The wheat grain yield (45.8 versus 41.2 q ha^{-1}) and net return (₹ 58,500 versus ₹ 52,000 ha^{-1}) were 11.2% and 12.5% higher, respectively, for residue incorporation as compared to residue burning. Based on these comparisons, it may be concluded that residue retention and incorporation can offer agronomic and economic benefits, as well as better recycling of the resources.

The overall picture suggests that implementing residue burning reduction programs will need a comprehensive approach that involves access to residue management machinery at the right time, financial incentives, farmer awareness, biomass utilization and institutional support. *In-situ* management and viable ex-situ options for residues could help mitigate environmental pollution while maintaining agricultural productivity and livelihoods. Incorporating policies on residue management with soil-health conservation and food-security goals is crucial in enhancing the sustainability of rice-based cropping systems over time.

GENERATIVE AI DECLARATION

The author(s) confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript, and no images were manipulated using AI. The authors developed and verified all scientific content, data analysis, interpretation of results, and conclusions. The authors take full responsibility for the accuracy, integrity, and originality of the work presented, and no AI tool was listed as an author.

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