

# Paddy to Pollution: Assessing the Environmental Cost of Stubble Burning and Policy Effectiveness in Punjab and Haryana

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## Abstract

Stubble burning in Punjab and Haryana constitutes an agricultural crisis with catastrophic environmental consequences, releasing hazardous pollutants that degrade air quality, exacerbate climate change, and endanger public health. This comprehensive study quantifies environmental costs using satellite data (2002–2025), economic loss assessments, and policy evaluations. Findings reveal that 84 million tonnes (Mt) of India's annual agricultural residue is burned, emitting 3.4 Mt of CO, 91 Mt of CO<sub>2</sub>, and 1.2 Mt of PM<sub>2.5</sub>, with Punjab and Haryana contributing 30.5 Mt annually (Chauhan *et al.*, 2024). Post-monsoon burning peaks in November due to groundwater preservation policies compressing harvest windows, increasing Delhi's PM<sub>2.5</sub> by 23–26% (Singh & Kumar, 2025). Policy analysis demonstrates underutilization of Crop Residue Management (CRM) machinery despite subsidies, with only 36% adoption due to financial and technical barriers. Viable alternatives like biomass energy generation could avert USD 120 million in annual losses while restoring soil health through agroecological principles (Altieri & Nicholls, 2023). The study recommends integrated solutions combining varietal diversification, ex-situ market incentives, and stricter enforcement to transition toward zero-burn agriculture by 2030.

## Keywords

Stubble burning, Air pollution, Crop residue management, Agricultural policy, Particulate matter, Punjab-Haryana, Environmental health, Biomass valorization

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## INTRODUCTION

India's agricultural heartland, Punjab and Haryana, generates 352 Mt of crop residue annually, dominated by rice (43%) and wheat (21%) (Chauhan *et al.*, 2024). Farmers burn approximately 23.86% (84 Mt) of this residue to clear fields for sequential planting, releasing pollutants linked to severe air quality deterioration across Northern India (Gupta *et al.*, 2024). This practice peaks during October–November, coinciding with Delhi's "pollution season," where stubble burning contributes 30–50% of PM<sub>2.5</sub> concentrations (Sarkar *et al.*, 2024). The *Punjab Preservation of Subsoil Water Act (2009)*, while reducing groundwater depletion by 29.2 mm/yr, inadvertently intensified pollution by delaying harvesting and compressing the burning window (Government of Punjab, 2024). Despite the *National Policy for Management of Crop Residue (2014)*, paddy residue burning increased by 21% since 2010 due to policy

implementation gaps and behavioral lock-ins (Singh & Kumar, 2025).

The environmental crisis demands urgent interdisciplinary solutions. Recent studies highlight agroecology's potential in repurposing agricultural waste through circular economy models (Altieri & Nicholls, 2023). Traditional practices like in-situ incorporation align with ecological principles by enhancing soil organic carbon and microbial diversity (Patel *et al.*, 2024). This research evaluates three dimensions:

- **Environmental and health costs** of stubble burning using geospatial and epidemiological data
- **Policy efficacy analysis** of technological, economic, and regulatory interventions
- **Agroecological alternatives** for sustainable residue management within planetary boundaries

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## METHODOLOGY

### Data Collection and Analysis

- **Environmental Metrics:** NASA MODIS satellite fire counts (2002–2025) quantified spatiotemporal burning trends. HYSPLIT atmospheric transport simulations modeled PM<sub>2.5</sub> dispersion pathways (Chauhan *et al.*, 2024). Emission factors from field experiments established that burning 1 tonne of rice straw releases 1.5 kg PM<sub>2.5</sub>, 60 kg CO, and 0.2 kg N<sub>2</sub>O (Gupta *et al.*, 2024).
- **Economic and Health Costs:** WHO mortality data and disability-adjusted life years (DALYs) linked to PM<sub>2.5</sub> exposure; crop residue valorization potential calculated via benefit-cost ratios (BCR) (World Bank, 2023). Primary surveys with 1,478 farmers across 11 Punjab districts assessed CRM adoption barriers (Singh & Kumar, 2025).
- **Agroecological Assessment:** Soil health parameters (organic carbon, microbial biomass) compared burned fields versus CRM-managed plots using ISO 14240-1 protocols (Patel *et al.*, 2024).

### Analytical Frameworks

- **Counterfactual Analysis:** Compared pre-2010 and post-2010 burning patterns to isolate policy impacts.
- **Stakeholder Cost-Benefit Analysis:** Contrasted burning costs (health, soil degradation) against CRM alternatives using net present value (NPV) calculations over 10-year horizons.
- **Policy Implementation Gap Analysis:** Evaluated administrative structures using the 5C framework (Capacity, Coordination, Compliance, Community, Capital) (CEEW, 2024).

## ENVIRONMENTAL AND HEALTH IMPACTS

### Emission Loads and Air Quality

Punjab and Haryana's 30.5 Mt annual residue burning releases 149 Mt CO<sub>2</sub>, 3.4 Mt CO, and 1.28 Mt PM<sub>2.5</sub> (Chauhan *et al.*, 2024). November burning peaks correlate with atmospheric inversions in the Indo-Gangetic Plain, trapping pollutants and elevating Delhi's PM<sub>2.5</sub> to 480 µg/m<sup>3</sup> (severe category). HYSPLIT simulations confirmed 42% of Delhi's pollution burden originates from Punjab-Haryana fires during peak episodes (Sarkar *et al.*, 2024). The shift to late harvesting under groundwater policies concentrated 78% of burning within 15 days (November 1–15), increasing emission intensity by 34% compared to pre-2009 patterns (Government of Punjab, 2024).

### Health and Economic Burden

Epidemiological models attribute 66,200 annual premature deaths in India to stubble fire-related PM<sub>2.5</sub> (Sarkar *et al.*, 2024). Hospital admissions for acute respiratory infections increase threefold during burning episodes, with children and elderly disproportionately affected. Economic losses from health impacts (USD 30 billion/year) and soil nutrient depletion (USD 3.2 billion/year) exceed Punjab's annual agricultural budget (World Bank, 2023).

### Soil Degradation

Burning elevates topsoil temperature to 42.2°C, eliminating microbial communities and reducing dehydrogenase activity by 89% (Patel *et al.*, 2024). Each burning episode depletes 5.5 kg nitrogen, 2.3 kg phosphorus, and 1.2 kg sulphur per tonne of residue - equivalent to 143 kg/ha of NPK fertilizers (Singh & Kumar, 2025). Long-term soil carbon stocks decline by 0.8%/year in continuously burned fields, accelerating desertification in semi-arid zones.

### Policy Effectiveness Analysis

Table 1: Policy Interventions and Outcomes (2014–2025)

Policy/Initiative	Key Provisions	Outcomes	Limitations
<b>Subsoil Water Acts (2009)</b>	Delayed paddy transplanting to June 10	Groundwater depletion ↓29.2 mm/yr (post-2013)	Compressed harvest window ↑ Nov burning 21%
<b>CRM Machinery Subsidies</b>	50–80% subsidies for Happy Seeders	43,452 Super Seeders deployed; 100% technical coverage	64% avoid rentals; 30% practice partial burning
<b>Ex-situ Incentives</b>	INR 1,200/acre for biomass removal	33% adoption in Punjab	69% provided straw free; underdeveloped markets
<b>Air Quality Commission</b>	Ban on stubble burning (GSR 135)	22% conviction rate; 73% non-compliance	Inadequate monitoring staff (1 officer/15,000 ha)

### Adoption Barriers

- Financial:** Smallholders (<2 ha) cannot afford CRM rentals (INR 1,500/acre) despite subsidies. Annualized costs represent 34% of marginal farmer income (CEEW, 2024).
- Technical:** Long-duration varieties like PUSA 44 (grown by 36% of farmers) generate 25% higher residue volumes, exceeding CRM machinery capacity (Singh & Kumar, 2025).
- Behavioral:** 58% of farmers believe burning controls pests; 42% cite time pressures for wheat sowing.
- Institutional:** Custom Hiring Centers (CHCs) supply only 3% of machinery; 82% of rentals rely on informal networks with exploitative pricing (CEEW, 2024).

## AGROECOLOGICAL ALTERNATIVES

### In-situ Management

- Bioenzyme Decomposers:** PUSA decomposer (fungal consortium) decomposes residue in 25 days, increasing soil organic carbon by 0.4% and saving INR 1,200/acre in fertilizers (Patel *et al.*, 2024). Adopted on 8% of burned area in 2024.
- Direct Seeding:** Happy Seeder technology maintains yields while reducing operational costs by 24% and soil erosion by 8 t/ha (Singh & Kumar, 2025).

### Ex-situ Valorization

- Biomass Power Plants:** 11 operational plants utilize 1.8 Mt residue annually, generating 1,350 MW at INR 5.4/kWh. Benefit-cost ratio (BCR) of 1.8 when located <15 km from farms (World Bank, 2023).

- Biochar Production:** Pyrolysis at 450°C yields 30% biochar with carbon sequestration potential of 2.8 tC/ha. Market value: INR 8,000/tonne for soil amendment (Altieri & Nicholls, 2023).

### Integrated Diversification Models

- Paddy Diversification:** Short-duration PR 126 rice reduces residue by 37% and enables timely sowing. Adopted by 58% of surveyed farmers when seeds are subsidized (Singh & Kumar, 2025).
- Agroforestry Systems:** Poplar-wheat intercropping utilizes 45% residue for fodder, generating additional INR 28,500/ha from timber (Altieri & Nicholls, 2023).

## DISCUSSION: TOWARD A ZERO-BURN FRAMEWORK

The policy failure stems from fragmented governance: agricultural subsidies incentivize paddy, environmental regulations lack enforcement, and industrial policies neglect biomass supply chains. Successful Punjab villages (e.g., Chaina) achieved zero-burning through:

- Technical Bundling:** Super Seeders with bioenzyme sprays
- Economic Incentives:** Direct benefit transfers (DBT) of INR 2,500/acre for verified non-burning
- Community Governance:** Farmer cooperatives managing rental hubs with mobile apps (CEEW, 2024)

Agroecological principles must guide transition strategies. *Diversification* through rice-alternatives (cotton, maize) reduces residue burden while enhancing farm resilience (Altieri &

Nicholls, 2023). *Circularity via biomass valorization creates rural livelihoods - 1 Mt residue supports 1,200 jobs in bioeconomy sectors* (World Bank, 2023). However, scaling requires addressing structural inequalities: marginal farmers (<2 ha) constitute 72% of burners but receive only 11% of subsidies (Singh & Kumar, 2025).

## CONCLUSION AND POLICY RECOMMENDATIONS

Stubble burning epitomizes the conflict between productivity-focused agriculture and environmental sustainability. Eliminating the practice requires systemic reforms:

- **Agricultural Policy:** Replace PUSA 44 with short-duration varieties; introduce paddy diversification index (PDI) for block-level monitoring
- **Environmental Governance:** Real-time fines via satellite surveillance; Green Tax on paddy procurement to fund CRM infrastructure
- **Industrial Ecosystem:** Biomass procurement mandates for thermal plants (10% co-firing); GST exemptions for bio-based products
- **Community Institutions:** Women-led CHCs with 50% rental subsidies for marginal farmers

Future research should quantify long-term soil carbon recovery under CRM regimes and model decentralized biorefinery networks. Integrating agroecology into Punjab's agricultural extension

system can catalyze India's transition toward carbon-positive farming by 2030.

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**Conflict of Interest:** No Conflict of Interest

**Source of Funding:** Author(s) Funded the Research

**How to Cite:** Kumar, G. (2025). Paddy to Pollution: Assessing the Environmental Cost of Stubble Burning and Policy Effectiveness in Punjab and Haryana. *Journal of Sustainable Agriculture and Environmental Innovations*, 1(1), 01-04.