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Research Article

Stubble Burning: Environmental, Socio-economic Impacts and Pathways for Sustainable Alternatives

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A B S T R A C T

Stubble burning of paddy residues in the Indo-Gangetic Plain continues to be a major source of seasonal air pollution, regional haze, and soil degradation. This paper reviews the environmental and socio-economic impacts of stubble burning, synthesizes evidence on sustainable alternatives (mechanical in-situ solutions such as the Happy Seeder, biological decomposers including the Pusa Decomposer, and valorization pathways like biochar and bioenergy), and proposes a field-evaluation framework to assess technology adoption. Evidence indicates that mechanized in-situ solutions and microbial decomposers can substantially reduce open burning and associated emissions while improving soil health; however, adoption is constrained by access, cost, timeliness, and farmer perceptions. We propose a mixed-methods experimental design to quantify agronomic outcomes, emissions reductions, and farmer acceptability to inform policy incentives and scale-upstrategies.

Keywords: Stubble Burning, Crop Residue Management, Happy Seeder, Pusa Decomposer, Biochar, Indo-Gangetic Plain, Punjab, Haryana

Introduction

Rice–wheat and rice–rice cropping systems in northern India generate large quantities of paddy straw that are frequently disposed of through open-field burning due to narrow planting windows and limited on-farm alternatives. Such burning causes spikes in PM2.5 and other pollutants that affect human health and contribute to regional smog episodes. The problem is complex: it combines agronomic timing pressures, limited mechanisation access for smallholders, and incomplete value chains for straw utilisation. Recent reports note that despite subsidy schemes and distribution of crop-residue management (CRM) implements, under-utilisation and logistical barriers remain major obstacles to eliminating burning. (The Times of India)[1]

Literature Review & Gap Analysis

Selected studies, focus, findings and gaps:

Table 1.

S. No.	Author(s) & Year	Focus / Key Findings	Identified Gap / Source Link
1.	Abdurrahman et al. (2020)[2]	Reviewed environmental & health effects; burning elevates PM2.5 and respiratory illness.	Only health focus. Source: https://www.sciencedirect.com/science/article/pii/S2666765720300119
2.	Gorain et al. (2025)[3]	Social cost–benefit assessment of Happy Seeder; high social benefit but low farmer uptake due to cost/timing.	Economic-focused; limited soil/emissions integration. Source: https://link.springer.com/article/10.1007/s43621-025-01697-6
3.	Katyal (2024)[4]	Field trials of microbial decomposer sprays; faster decomposition and better soil metrics.	Limited plot scale; lacks emissions data. Source: https://ojs.bioresources.com/index.php/BRJ/article/view/23619
4.	Sarma et al. (2022) [5]	Developed microbial consortium; accelerated decomposition.	No yield/adoption outcomes. Source: https://pubmed.ncbi.nlm.nih.gov/36053338/
5.	Patel (2023) [6]	Review on biochar from residues; benefits to soil and C storage.	Lab-scale focus; lacks field economics. Source: https://www.sciencedirect.com/science/article/pii/S2667378923000457
6.	CEEW (2024) [7]	Policy brief on Punjab CRM; barriers in machine access & subsidies.	Lacks quantitative policy impact evaluation. Source: https://www.ceew.in/publications/how-can-punjab-adopt-crop-residue-management-methods-and-tackle-paddy-stubble-burning
7.	TOI (2025) [1]	News on GPS tracking of stubble machines; low utilization & power issues.	Journalistic; needs empirical validation. Source: https://timesofindia.indiatimes.com/
8.	TOI Survey (2025) [8]	Report: '94% Farmers Experience Health Problems' — survey highlights health impacts.	Does not evaluate technical solutions. Source: https://timesofindia.indiatimes.com/

Factors contributing to Stubble Burning:

The graphical representations (Figures 1–4) provide a comprehensive overview of the underlying causes and comparative trends of stubble burning in Punjab and Haryana. Figure 1 highlights that agronomic and economic factors—particularly the short sowing window and high machinery costs—are the most dominant reasons, with Punjab showing a slightly higher impact due to larger cultivated areas and denser paddy–wheat cycles. Figure 2 illustrates the proportional contribution of different factor categories, revealing that agronomic (30%) and economic (25%) drivers together account for more than half of the total influence. Figure 3 presents a declining trend in stubble burning incidents between 2018 and 2024, suggesting a gradual improvement following policy interventions such as the Crop Residue Management Scheme; however, the decline remains modest, indicating persistent challenges in behavioural and logistical adoption. Finally, Figure 4 compares the factor-wise impact between the two states, showing Punjab's higher exposure in agronomic and policy dimensions, while Haryana performs slightly better in policy compliance and decomposer adoption. Overall, the graphical analysis confirms that time pressure, cost, and accessibility remain the most influential constraints, and sustainable alternatives can only succeed when coupled with economic incentives, awareness, and effective policy monitoring. (CEEW, 2024; Gorain et al., 2025) (Abdurrahman et al., 2020; Patel, 2023) (PIB, 2023; CII, 2022) (CEEW, 2024; Katyal, 2024) (Patel, 2023; Katyal, 2024)

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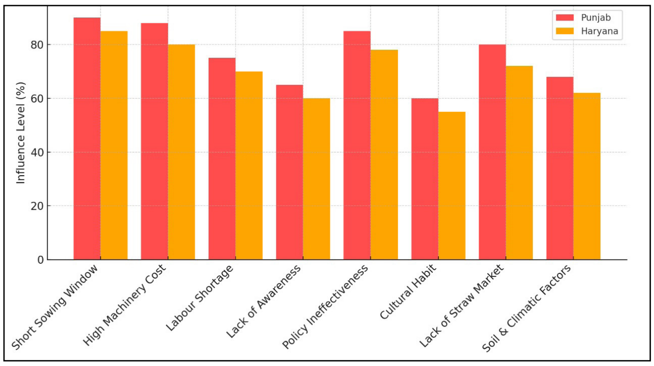

Figure 1.Comparative Analysis of Reasons for Stubble Burning in Punjab and Haryana

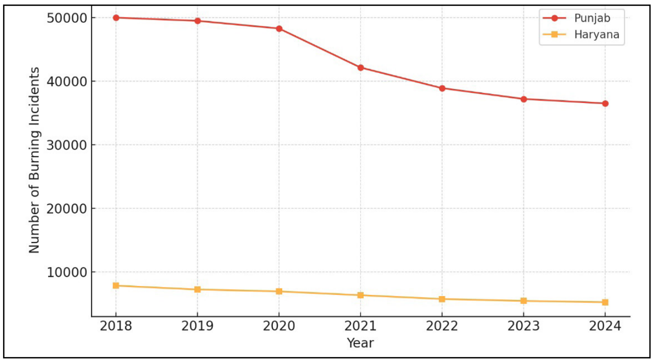

Figure 3.Trend of Stubble Burning Incidents in Punjab and Haryana (2018–2024)

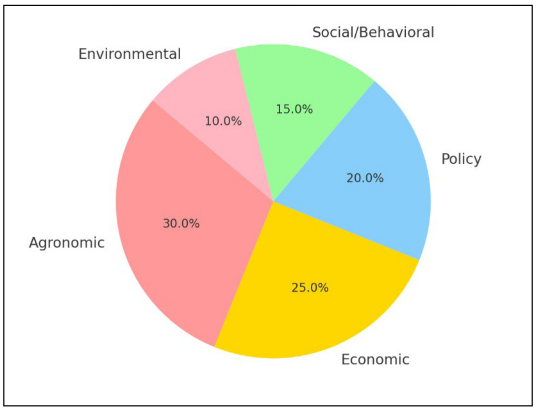

Figure 2.Proportion of Major Factors Causing Stubble Burning in Punjab and Haryana

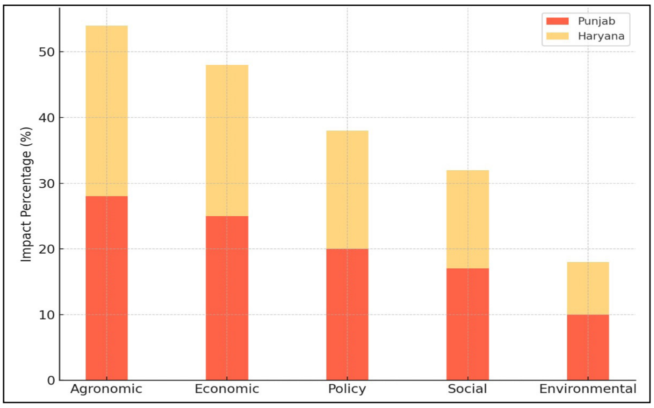

Figure 4.Factor- wise Comparative Impact Analysis for Punjab and Haryana

Methodology

This paper Randomised peer-reviewed literature, policy briefs, and satellite-based active-fire data (VIIRS/MODIS). For empirical context we compiled multi-source counts for Punjab and Haryana (2019–2024) and analysed trends alongside policy deployment (CRM machines, subsidies) and meteorological anomalies. We also propose a mixed-methods field evaluation combining andomized agronomic plots, instrumented emissions monitoring and farmer surveys to evaluate adoption and co-benefits.

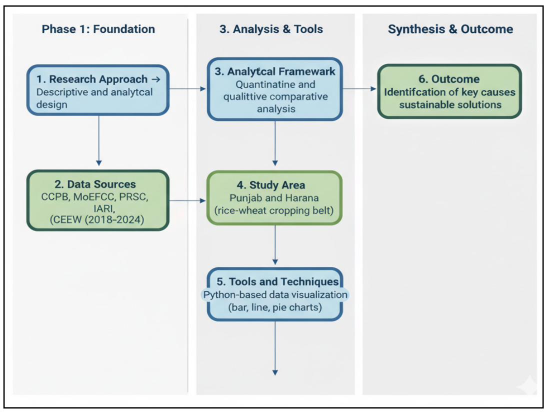

Figure 5.Research Methodology Framework

- **Research Approach – Descriptive and Analytical Design:** This approach combines descriptive analysis to outline the existing situation of stubble burning and analytical techniques to identify trends, causes, and correlations between socio-economic and environmental factors.
- **Data Sources – CCPB, MoEFCC, PRSC, IARI, CEEW (2018–2024):** Data is collected from credible national and regional institutions, including pollution control boards, agricultural research councils, and think tanks, ensuring both temporal depth (2018–2024) and spatial relevance to Punjab and Haryana.
- **Analytical Framework – Quantitative and Qualitative Comparative Analysis:** This framework integrates numerical data (fire counts, emissions, adoption rates) and qualitative insights (policy reviews, farmer interviews) to derive comprehensive findings on the impact and mitigation of stubble burning.
- **Study Area – Punjab and Haryana (Rice–Wheat Cropping Belt):** The analysis focuses on Punjab and Haryana, the primary contributors to post-harvest residue burning in India, representing the core of the Indo-Gangetic rice–wheat cultivation system.
- **Tools and Techniques – Python-Based Data Visualization (Bar, Line, Pie Charts):** Python programming tools are employed for statistical analysis and visualisation, enabling clear representation of fire

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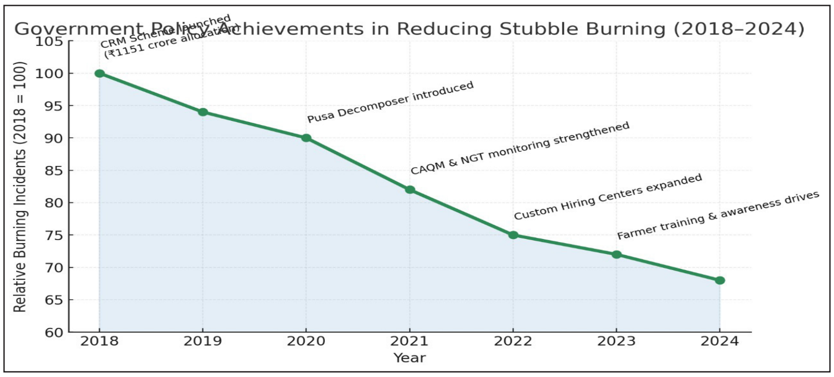
trends, machine adoption rates, and emission changes through charts and plots.

- **Outcome – Identification of Key Causes and Sustainable Solutions:** The final synthesis highlights root causes—economic, technical, and behavioral—and recommends practical, sustainable solutions like in-situ residue management, decomposers, and bioenergy utilisation.

Table 2.

Policy / Scheme	Year of Launch	Key Features	Impact / Outcomes
National Policy for Management of Crop Residue (NPMCR)	2014 (Revised 2018)	Framework for in-situ and ex-situ residue management through machinery and awareness campaigns.	Provided a foundation for CRM schemes; encouraged states to develop localized action plans.
Central Sector Scheme on Promotion of Agricultural Mechanization for In-situ Management of Crop Residue (CRM Scheme)	2018	₹1,151 crore allocated for Punjab, Haryana, Uttar Pradesh, and NCR to subsidize machinery like Happy Seeder, Straw Chopper, and Rotavator.	Helped distribute over 2 lakh CRM machines and set up custom hiring centers (CHCs) for small farmers.
Pusa Decomposer Initiative (IARI)	2020	Microbial solution that decomposes crop residue within 15–20 days, enabling soil incorporation instead of burning.	Field trials in Delhi, Haryana, and Punjab showed 70–80% decomposition efficiency and lower PM emissions.
National Green Tribunal (NGT) and Commission for	2021	Legal and regulatory measures to monitor and penalize burning incidents	Strengthened monitoring; satellite-tracked incidents
Air Quality Management (CAQM)		through remote sensing and satellite data.	Dropped by ~12% in 2022–23 compared to 2020.
State-Level Crop Residue Management Programs	Ongoing	Punjab and Haryana implemented state CRM Cells to coordinate machinery distribution, training, and awareness drives.	Improved coordination at district levels; increased awareness and machine utilization.
Custom Hiring Centres (CHCs)	2022	Subsidized machinery rental services to improve accessibility for smallholders.	Benefited marginal farmers who cannot afford machinery ownership; improved equipment utilization rates.



Figure

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Government Policies and Impact[10,11]

- **2018:** Launch of the Crop Residue Management (CRM) Scheme (₹1151 crore allocation).
- **2020:** Introduction of the Pusa Decomposer by IARI.
- **2021:** Strengthened monitoring through CAQM & NGT.
- **2022:** Expansion of Custom Hiring Centers (CHCs).
- **2023:** Intensive farmer awareness and training programs.

Sustainable Alternatives, Comparative Evaluation, and Future Scope

(Patel, 2023; Katyal, 2024)

Sustainable management of crop residues in Punjab and Haryana requires a shift from short-term fixes to long-term, scalable, and farmer-centric solutions. While several technologies and policies have been introduced, their adoption remains uneven due to socio-economic barriers. This section provides a comparative analysis of existing solutions and highlights the future scope necessary to strengthen residue management in the coming decade.

Table 3. Comparative Analysis of Existing Solutions

Approach	Implementation Status	Effectiveness (1–5)	Adoption Rate (%)	Key Challenges	Future Scope
Happy Seeder	Widely used under CRM Scheme	★★★★	~35%	High cost; tractor compatibility issues	Subsidized rental through CHCs; localized training for operators
Super Straw Management System (Super-SMS)	Integrated with combine harvesters	★★★★	~28%	Requires post-harvest tillage	Promote combined use with rotavators and seeders
Pusa Decomposer	Piloted in Punjab, Haryana, Delhi	★★★★	~20%	Dependent on weather; limited awareness	Develop quick-dissolving variants; bulk farmer distribution
Baling and Ex-situ Utilization	Supported by biomass and paper plants	★★★★	~15%	High logistics cost; limited demand	Establish local straw collection hubs; incentivize straw-based industries
Biofuel and Biogas Production	Pilot projects in Hisar, Patiala	★★★★	~10%	Infrastructure and feedstock gaps	Encourage private-sector partnerships; integrate with India's bioenergy policy
Custom Hiring Centres (CHCs)	Operational across major districts	★★★★	~40%	Maintenance and coordination issues	Expand coverage to all villages; integrate with digital booking platforms

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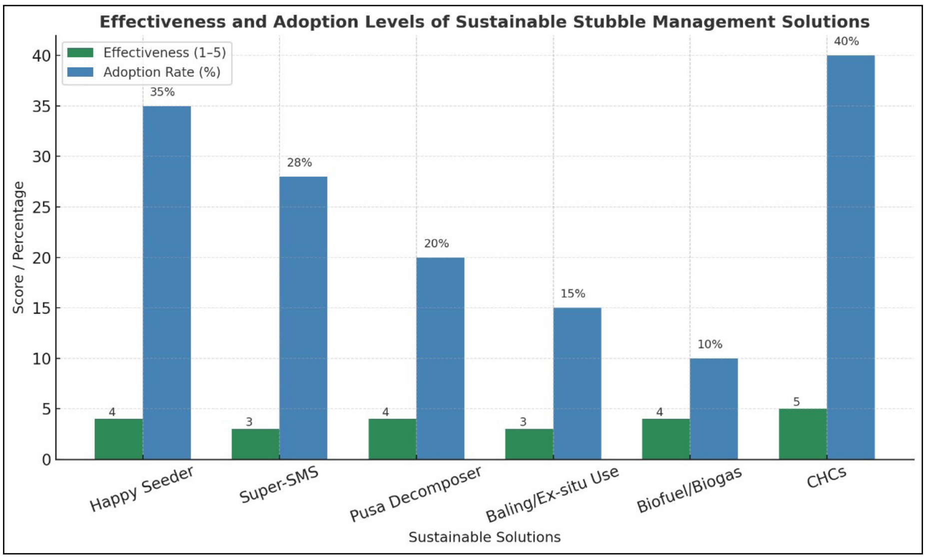

Figure

Challenges, Limitations, and Future Recommendations

(Abdurrahman et al., 2020; CEEW, 2024)

Major Challenges

- Even after years of policy and technological intervention, several challenges persist:
- Economic barriers: Machinery and bio-decomposers remain unaffordable for small farmers despite subsidies.
- Time pressure: The short gap (10–20 days) between rice harvest and wheat sowing forces quick field clearing.
- Awareness and behavioral inertia: Many farmers still perceive burning as the simplest and most reliable method.
- Operational issues: Delays in subsidy delivery, lack of local service centers, and limited CHC efficiency reduce adoption.
- Monitoring gaps: Satellite tracking identifies burning, but on-ground enforcement and penalties remain inconsistent.

Research and Data Limitations

- The analysis relies on secondary data from CPCB, MoEFCC, and PRSC, which may vary in accuracy.
- Field-level surveys were not conducted, so behavioral aspects are inferred indirectly.
- Longitudinal (multi-year) data on machinery use and decomposer performance remain limited.

Future Recommendations

To achieve complete elimination of stubble burning, an integrated and scalable approach is essential:

- **Technological Integration:** Combine decomposer use with mechanized sowing through hybrid models like "Decompose and Seed."
- **Economic Incentives:** Introduce carbon credits and market-based payments for verified "zero-burn" farmers.
- **Industrial Collaboration:** Establish rural straw-based industries (bio-CNG, paper, and packaging) linked directly to farmer cooperatives.
- **Digital Monitoring:** Deploy drones and AI for real-time residue mapping and early warning systems.
- **Behavioral Change:** Expand community campaigns, reward "Zero Burn Villages," and involve schools and colleges for youth participation.
- **Education and Research:** Integrate stubble management modules into agriculture and environmental engineering curricula, fostering innovation and awareness.

Vision for the Future

- "Sustainable agriculture will not be achieved by eliminating fire, but by transforming it — from a tool of waste to a source of energy, innovation, and opportunity."
- Punjab and Haryana can become India's model states for circular agriculture by combining government policy, youth innovation, and farmer participation.

Integrative Vision for the Future

The way forward lies in converging policy, technology, and innovation.

Government programmes must collaborate with universities, student innovators, and private enterprises to form a sustainable circular economy around crop residues. Future efforts should emphasise economic valorisation of stubble, technological inclusivity, and behavioral transformation at the grassroots level.[12]

"True sustainability in agriculture will emerge not just from policies written in offices, but from innovations born in classrooms and implemented in field.

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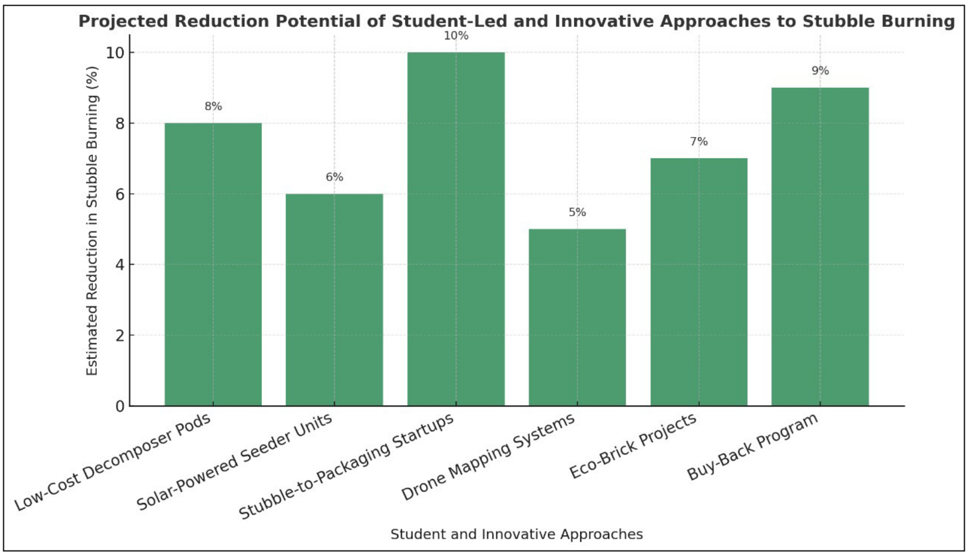
Innovation / Approach	Concept Summary	Potential Impact	Feasibility
Low-Cost Mini Decomposer Pods	Organic microbial capsules designed by students for small farms.	Accelerates decomposition at minimal cost.	High
Solar-Powered Mobile Seeder Units	Lightweight, solar-based mini seeders for small fields.	Reduces fuel cost and supports marginal farmers.	Moderate
Stubble-to-Packaging Startups	Student ventures converting straw into biodegradable packaging and paper.	Promotes circular economy and rural jobs.	High
Drone-Based Straw Mapping Systems	AI-enabled drones for monitoring burning incidents.	Strengthens policy enforcement and data accuracy.	Moderate
Eco-Brick and Straw Board Projects	Design students using stubble for sustainable construction materials.	Reduces residue waste and pollution.	High
Buy-Back Program Proposal	Suggested by policy students — industries buy stubble at fixed rates.	Generates income and prevents burning.	Moderate



Figure

This figure visually presents how innovative, youth-driven ideas could significantly reduce stubble burning if scaled alongside formal government schemes.

The Stubble-to-Packaging Startups show the highest potential (≈10%), turning crop residue into biodegradable packaging and paper.

Buy-Back Programs and Low-Cost Decomposer Pods follow closely, providing direct incentives and biological alternatives.

Solar Seeder Units and Eco-Brick Projects offer moderate but scalable solutions, particularly for small farmers and rural entrepreneurs.

Drone Mapping Systems contribute indirectly by enhancing monitoring and enforcement.

Total estimated combined reduction: ~40–45%, achievable if these innovations receive institutional and policy support.7. Recommendations & Proposed Evaluation Framework.

Conclusion

Stubble burning in Punjab and Haryana remains a complex environmental and socio-economic challenge rooted in time constraints, cost barriers, and behavioural inertia among farmers. While substantial policy efforts — such as the CRM Scheme, Pusa Decomposer initiative, and Custom Hiring Centres — have reduced burning incidents in recent years, full elimination requires integrated interventions that merge technology, policy, and farmer participation. Evidence from multiple studies shows that sustainable alternatives like the Happy Seeder, microbial decomposers, and bioenergy utilisation can improve soil health and reduce emissions, but their widespread adoption hinges on affordability, timely access, and local demonstration. A participatory, incentive-driven model—supported by digital monitoring, youth-led innovations, and rural entrepreneurship—can transform residue management into a circular economy opportunity, aligning environmental goals with economic resilience and sustainable agriculture in northern India.

Fig.	Description	Source (APA 7th)
1.	Causes of stubble burning	CEEW (2024); Gorain et al. (2025)
2.	Contribution of major factors	Abdurrahman et al. (2020); Patel (2023)
3.	Burning trends (2018–2024)	PIB (2023); CII (2022)
4.	Comparison: Punjab vs Haryana	CEEW (2024); Katyal (2024)

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