**Original Research Article**

**Environmental Effects of Paddy Straw Burning: Farmer Satisfaction and Practices by Land Size in Punjab**

**Abstract**

In Punjab, India, a vital rice-wheat region generating 20 million tons of paddy straw each year, burning this residue creates substantial environmental issues, emitting pollutants such as PM2.5 and CO2 that impair air quality and soil vitality while exacerbating climate change. Here, farmers, categorized as marginal, small, semi-medium, medium, and large, encounter socioeconomic constraints that fuel this practice, highlighting the need to investigate their satisfaction and management approaches to develop sustainable solutions. This study surveyed 60 farmers across Fatehgarh Sahib and Rupnagar districts using face-to-face interviews to collect data on management practices–-incorporation, mixing straw into soil to enhance fertility; burning, setting straw ablaze to clear fields; baling, compressing straw into bundles for removal or use; cattle feed, using straw as livestock fodder; mulching, spreading straw over soil to retain moisture. This study surveyed 60 farmers across Fatehgarh Sahib and Rupnagar districts using face-to-face interviews to collect data on management practices. Results show 53.3% of farmers use incorporation, 28.3% burn straw, and 18.3% use baling. Marginal farmers favor burning, large farmers lean toward incorporation, and show higher awareness, while small and semi-medium/medium farmers vary. Machinery awareness is 80%, but adoption lags due to costs. The study reveals marginal farmers burn due to necessity and low awareness, while large farmers adopt sustainable methods, reflecting resource disparities, with small and semi-medium farmers showing mixed practices, highlighting the need for targeted interventions, subsidies for machinery access and comprehensive education, to reduce burning’s ecological toll and support Punjab’s shift toward sustainable straw management tailored to its diverse agrarian context.

**Keywords:** Paddy straw burning, farmer satisfaction, straw management, awareness

**1. Introduction**

Paddy straw burning in Punjab, India, a cornerstone of the Indo-Gangetic Plains’ rice-wheat system, producing 19–20 million tons of straw annually, poses severe environmental and agricultural challenges (Dutta et al., 2022). This practice releases pollutants like PM2.5, CO₂, and NOx, degrading air quality, contributing to climate change, and affecting soil health (Kumar et al., 2019a). During October-November, burning aligns with the tight rice-to-wheat transition, amplifying pollution that impacts Punjab and Delhi (Kaur et al., 2022). Socioeconomic pressures compel farmers across all landholding categories–marginal, small, semi-medium/medium, and large–to resort to straw burning, highlighting the need to understand their management practices (Kumar et al., 2015). Burning depletes ecosystem services, costing northwest India dearly in soil fertility and air quality, with studies estimating significant losses in soil microbial populations and enzyme activity post-burning (Kumar et al., 2019a; Ravali et al., 2022), while health risks rise with a noted increase in respiratory issues (Singh, 2018).

Punjab’s intensive agriculture generates vast volumes of straw, traditionally used for livestock feed (Lohan et al., 2017). Marginal and small farmers, constrained by time and resources, favor burning, while larger farmers explore alternatives (Lopes et al., 2023). Mechanized harvesting exacerbates stubble accumulation, making rapid disposal critical (Bhuvaneshwari et al., 2019). Sustainable options like incorporation and baling offer environmental gains, improving soil carbon and reducing emissions, but face adoption barriers (Bhattacharyya et al., 2021). In-situ management, such as Happy Seeder use, enhances resource efficiency, yet cost and awareness limit its reach among smaller landholders (Chaudhary et al., 2019). Biochar production from straw presents an ecological solution, cutting emissions and enriching soil, highlighting its feasibility from paddy straw, yielding 35–40% biochar under pyrolysis at 400–500°C, alongside bio-oil and pyro-gas as co-products. However, infrastructure lags hinder widespread use (Tokas et al., 2021; Aier et al., 2021; Shah & Valaki, 2023).

Burning’s environmental toll includes 140–150 million tons of CO2-equivalent emissions annually, with Punjab as a major contributor (Launio et al., 2016). Soil properties suffer long-term degradation, losing organic matter and microbial diversity, while air pollution drives regional haze (Singh et al., 2022; Pradhan et al., 2024). Health studies link it to breathing woes, disproportionately affecting rural communities (Chopra & Bansal, 2022). Policy measures such as subsidies and bans often fail to discourage stubble burning, as many farmers, particularly small and marginal holders, find it the most cost-effective option (Bhuvaneshwari et al., 2019). Larger farmers (>10 ha), with better access to machinery, adopt alternatives, reflecting a land-size divide (Erbaugh et al., 2024). Biochar, rich in carbon and energy potential, offers a viable alternative to stubble burning; however, its adoption is limited by the need for investment in pyrolysis equipment (Shah & Valaki, 2023).

**2. Methodology**

This study was conducted in Fatehgarh Sahib and Rupnagar districts of Punjab, India, selected due to their prominence in rice-wheat cropping systems and high incidence of paddy straw burning, ensuring relevance to regional environmental challenges. A survey of 60 farmers was undertaken, chosen to balance statistical reliability with logistical feasibility, capturing diverse landholding perspectives. Face-to-face interviews were employed as the primary data collection method to secure direct, accurate responses from farmers, minimizing misinterpretation common in self-reported surveys, and allowing for clarification of complex practices like incorporation—mixing straw into soil to enhance fertility—or baling—compressing straw into bundles for removal or use. Farmers were classified into marginal with less than 1 hectare, small with 1–2 hectares, semi-medium or medium with 2–10 hectares, and large with over 10 hectares, based on standard agricultural categorizations, to investigate how land size influences straw management choices and environmental awareness. Data were collected on various management practices—incorporation, burning, baling, use as cattle feed, and mulching, as well as farmers’ perceptions of ease, cost-effectiveness, and awareness of environmental and health impacts, all crucial for understanding the factors influencing adoption. Analysis focused on variations across landholding sizes, using descriptive statistics to identify patterns and inform targeted interventions, justified by the need to address Punjab’s diverse agrarian context and tailor sustainable solutions to specific farmer groups.

**Table 1. Distribution of Farmers by Landholding Classification Across Villages**

| **Village** | **Marginal (<1 ha)** | **Small (1–2 ha)** | **Semi-Medium/Medium (2–10 ha)** | **Large (>10 ha)** |
| --- | --- | --- | --- | --- |
| Khant | 2 (17%) | 3 (25%) | 4 (33%) | 3 (25%) |
| Kajoli | 3 (25%) | 3 (25%) | 3 (25%) | 3 (25%) |
| Manpur | 2 (17%) | 4 (33%) | 4 (33%) | 2 (17%) |
| Kotli | 3 (25%) | 3 (25%) | 2 (17%) | 4 (33%) |
| Rauni Kalan/Khurd | 2 (17%) | 5 (42%) | 2 (17%) | 3 (24%) |

**3. Results and Discussion**

**3.1 Farmer Profile**

The farmers surveyed represent a cross-section of Punjab’s agrarian community, ranging from 15 to 60 years, reflecting a blend of generational knowledge and newer entrants adapting to established practices. All farmers had access to mobile phones and internet connectivity, suggesting potential for digital outreach and information dissemination, though the adoption of advanced machinery varied widely across the sample. Livestock ownership was reported by 60%, influencing straw use for feed, while irrigation reliance, via canals and groundwater, underscored the intensive nature of their rice production, generating substantial straw residue annually.

**3.2 Environmental Effects of Paddy Straw Burning**

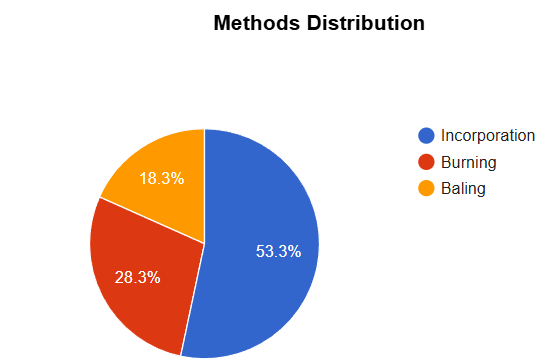
The survey centered around six key questions aimed at assessing the environmental impacts of paddy straw burning, and the responses were examined through in-depth comparative analysis.

**3.2.1 Straw Management Methods:**

Incorporation (53.3%), prevalent among large (>10 ha) and semi-medium/medium (2–10 ha) farmers, aligns with sustainable practices that bolster soil organic matter and resource use efficiency, reducing emissions as emphasized by (Bhattacharyya et al., 2021; Chaudhary et al., 2019). Burning (28.3%), dominant among marginal farmers (<1 ha), persists due to its speed and low cost, intensifying air quality degradation with PM2.5 and CO emissions, a concern highlighted by (Lohan et al., 2017; Singh, 2018). Baling (18.3%), adopted by small (1–2 ha) and large farmers, offers an alternative for resource utilization, though infrastructural constraints limit its scalability (Yadav et al., 2022; Aier et al., 2021).

**Table 2. Straw Management Methods**

| **Method** | **Count (%)** | **Land Size Insight** |
| --- | --- | --- |
| Incorporation | 32 (53.3%) | Large (>10 ha) |
| Burning | 17 (28.3%) | Marginal (<1 ha) |
| Baling | 11 (18.3%) | Small (1–2 ha), Large (>10 ha) |



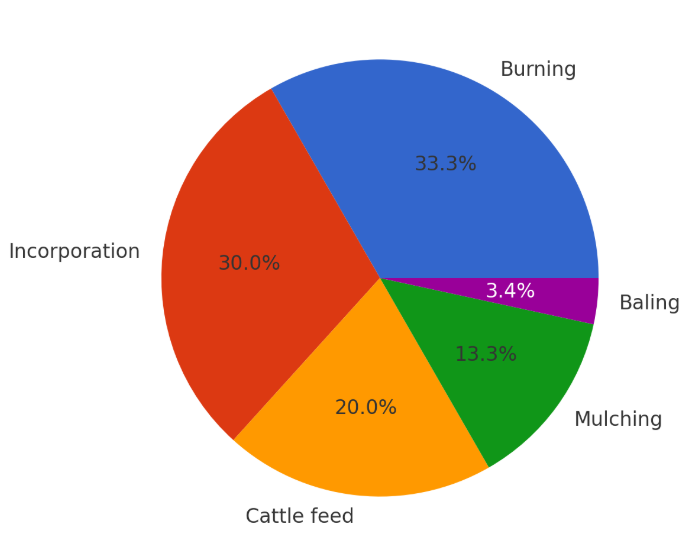
**Fig. 1. Proportion of Different Straw Management Methods**

**3.2.2 Perceived Easiest Straw Management Method:**

Perceived ease reveals 33.3% of marginal farmers favoring burning for its simplicity, exacerbating air pollution and health risks like respiratory ailments (Chopra & Bansal, 2022; Singh et al., 2022). Incorporation (30%), common among small farmers, balances practicality with soil health benefits (Jat et al., 2020), while cattle feed (20%), mulching (13.3%), and baling (3.4%) appeal to larger farmers, though equipment access remains a barrier (Kaur et al., 2021; Tokas et al., 2021). Cost-effectiveness perceptions show 30% of marginal farmers fully endorsing burning for its negligible upfront cost, 43% of small, semi-medium farmers partially agreeing due to mixed economic pressures, and 27% of large farmers disagreeing, favoring long-term gains from sustainable practices (Mishra et al., 2020; Gupta et al., 2023). Machinery awareness is high (80%), yet 20% of marginal farmers remain uninformed, reflecting adoption gaps tied to resource efficiency (Lohan et al., 2017; Lopes et al., 2023).

**Table 3. Perceived Easiest Straw Management Method**

| **Method** | **Count (%)** | **Land Size Insight** |
| --- | --- | --- |
| Burning | 20 (33.3%) | Marginal (<1 ha) |
| Incorporation | 18 (30%) | Small (1–2 ha) |
| Cattle feed | 12 (20%) | Large (>10 ha) |
| Mulching | 8 (13.3%) | Semi-Medium/Medium (2–10 ha) |
| Baling | 2 (3.4%) | Large (>10 ha) |



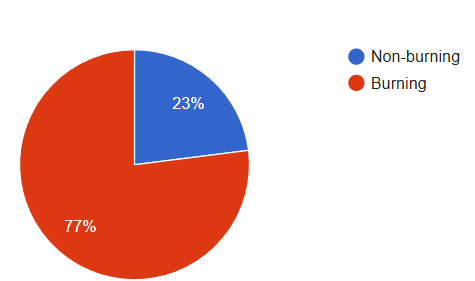
**Fig. 2. Percentage Breakdown of Easiest Straw Management Method**

**3.2.3 Awareness of Environmental and Health Impacts of Straw Burning:**

Awareness of the wide-ranging impacts of stubble burning remains critically low, with only 23% of farmers, mainly large landholders, acknowledging its harmful effects on air quality, soil health, climate, and human health, while the remaining 77%, primarily small and marginal farmers, remain unaware. This aligns with (Tripathi et al., 2019), who note that awareness campaigns in Punjab have limited reach among smaller landholders, often due to inadequate rural extension services and literacy barriers. Larger farmers, with better access to information via agricultural networks, acknowledge burning’s role in regional smog, contributing to Delhi’s haze (Dutta et al., 2022), and its health toll, with a 10–15% rise in respiratory hospital admissions during peak seasons (Kumar et al., 2015). The unaware majority underestimates climate impacts, such as 140–150 million tons of CO₂-equivalent emissions annually (Launio et al., 2016), and ecosystem losses, including biodiversity decline (Kumar et al., 2019b). Health risks, notably breathing problems, are well-documented by Chopra & Bansal (2022). Yet rural farmers rarely connect these to their practices, as Erbaugh et al. (2024) suggest, due to a focus on immediate economic survival over long-term environmental costs. This knowledge gap perpetuates burning, amplifying air pollution and climate change while undermining sustainable alternatives like biochar, which offers a 35-40% yield from straw with high carbon sequestration potential (Aier et al., 2021; Shah & Valaki, 2023).

**Table 4. Awareness of Environmental and Health Impacts of Straw Burning**

| **Response** | **Count (%)** | **Land Size Insight** | **Management Correlation** |
| --- | --- | --- | --- |
| Yes | 14 (23%) | Large (>10 ha) | Non-burning |
| No | 46 (77%) | Smaller (<5 ha) | Burning |



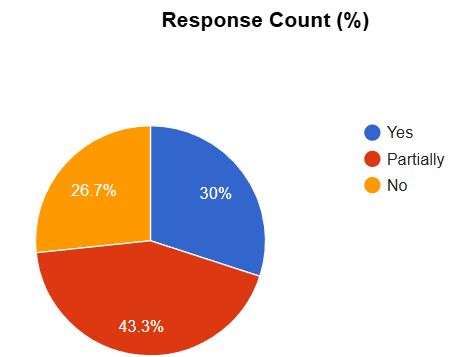
**Fig. 3. Distribution of Awareness of Environmental and Health Impacts of Straw Burning**

**3.2.4 Perception of Cost-Effectiveness of Straw Burning:**

Cost-effectiveness perceptions indicate 30% of marginal farmers endorsing burning, 43.3% of small, semi-medium farmers partially agreeing, and 26.7% of large farmers disagreeing, aligning with socioeconomic drivers and trade-offs (Mishra et al., 2020; Gupta et al., 2023). Soil fertility changes are noted by 17% of large farmers, with 83% unaware, underscoring burning’s subtle impact (Jain et al., 2022). Machinery awareness is 80%, yet 20% of marginal farmers remain uninformed, highlighting adoption barriers (Lohan et al., 2017; Lopes et al., 2023).

**Table 5. Perception of Cost-Effectiveness of Straw Burning**

| **Response** | **Count (%)** | **Land Size Insight** |
| --- | --- | --- |
| Yes | 18 (30%) | Marginal (<1 ha) |
| Partially | 26 (43.3%) | Smaller (<5 ha) |
| No | 16 (26.7%) | Large (>10 ha) |



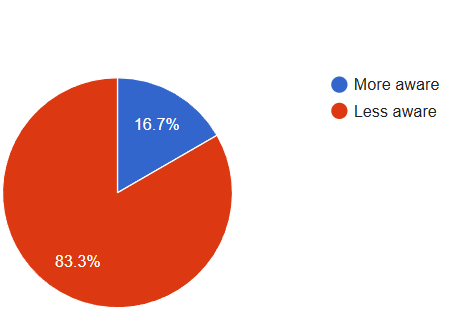
**Fig. 4. Percentage Breakdown of Perceived Cost-Effectiveness of Straw Burning**

**3.2.5 Observation of Soil Fertility Changes Due to Straw Burning:**

Only 17% of farmers, mainly large, observe soil fertility changes linked to burning, while 83% of marginal, small farmers report no noticeable impact, reflecting a critical awareness deficit. Burning depletes soil organic matter, nutrients like nitrogen and phosphorus, and microbial diversity, as detailed by (Kumar et al., 2019a; Pradhan et al., 2024), yet these gradual declines are subtle and often masked by short-term crop yields, leading smaller farmers to overlook them (Jain et al., 2022). Large farmers, transitioning to incorporation or mulching, notice improved soil structure and fertility over time (Bhattacharyya et al., 2021), corroborating (Chaudhary et al., 2019) findings on in-situ management. Marginal farmers’ lack of observation ties to their reliance on burning and limited exposure to soil science education (Lopes et al., 2023), missing ecosystem service losses like reduced water retention (Kumar et al., 2019b). This perceptual lag exacerbates soil degradation, undermining long-term productivity and resource efficiency, a concern linked to Punjab’s intensive farming system, where immediate field clearance trumps sustainability (Gupta et al., 2023). If Biochar is adopted, it could restore soil carbon (Shah & Valaki, 2023).

**Table 6. Observation of Soil Fertility Changes Due to Straw Burning**

| **Response** | **Count (%)** | **Land Size Insight** | **Awareness Correlation** |
| --- | --- | --- | --- |
| Yes | 10 (16.7%) | Large (>10 ha) | More aware |
| No | 50 (83.3%) | Marginal (< 1ha) | Less aware |



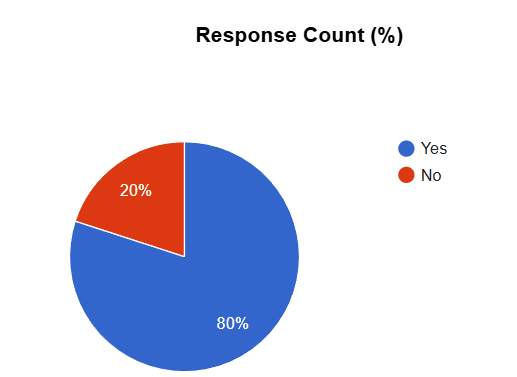
**Fig. 5. Farmer Observations of Soil Changes from Straw Burning**

**3.2.6 Awareness of Straw Management Machinery:**

Machinery awareness, at 80%, is notably high among large and semi-medium/medium farmers, reflecting effective dissemination of information about tools like the Happy Seeder through agricultural extension services, as documented by Yadav et al. (2022). However, the 20% who remain unaware, primarily marginal, align with their higher burning rates, as economic and logistical barriers, such as equipment cost and availability, prevent them from translating awareness into action, a gap also identified by Lohan et al. (2018). This discrepancy is evident in the low adoption of baling, despite widespread knowledge of machinery options, indicating that awareness alone is insufficient without financial and infrastructural support, a point reinforced by Tripathi et al. (2019) in their analysis of policy interventions.

**Table 7. Awareness of Straw Management Machinery**

| **Response** | **Count (%)** | **Land Size Insight** |
| --- | --- | --- |
| Yes | 48 (80%) | Large (>10 ha) |
| No | 12 (20%) | Smaller (<5 ha) |



**Fig. 6. Distribution of Farmers' Awareness About Straw Management Equipment**

Burning’s broader environmental toll includes air quality degradation with seasonal smog (Dutta et al., 2022), climate change via greenhouse gas emissions (Launio et al., 2016), and health risks from respiratory issues (Singh et al., 2022). Ecosystem services erode as soil and biodiversity suffer (Kumar et al., 2019b), and resource efficiency lags with straw’s potential wasted (Bhuvaneshwari et al., 2019; Tokas et al., 2021). Marginal farmers burn out of necessity, amplifying these impacts, while large farmers adopt sustainable methods, mitigating them (Shyamsundar et al., 2019). Small and semi-medium farmers show mixed practices, balancing cost and environmental awareness (Singh, 2018). Targeted interventions, subsidies for machinery to address air, climate, and efficiency issues, and education to highlight soil, health, and ecosystem impacts, are essential, as advocates to shift Punjab toward sustainability (Dutta et al., 2022; Kumar et al., 2015).

**4. Conclusion**

This study highlights apparent differences in how Punjab farmers manage paddy straw based on their land size, showing the environmental and practical challenges tied to burning. Marginal farmers with less than 1 hectare burn straw, 28.3 percent of the time, do so out of need and because they often don’t know the harm it causes—77 percent are unaware of its effects on air, soil, and health. Meanwhile, large farmers with over 10 hectares lean toward sustainable options like incorporation at 53.3 percent and baling at 18.3 percent, thanks to better access to tools and information, with 23 percent recognizing burning’s downsides. Small farmers with 1–2 hectares and semi-medium or medium farmers with 2–10 hectares mix these methods, balancing cost and what they can manage, pointing to a gap in resources and understanding across Punjab’s farming community.

Several evidence-based recommendations emerge from the study’s results to address these findings. Firstly, providing subsidies for mechanized equipment, such as Happy Seeders or balers, to marginal and small farmers, who account for the burning, is critical, given that 80 percent are aware of such technologies but lack access; this could substantially reduce the prevalence of burning. Secondly, implementing accessible educational initiatives, including localized demonstrations and community discussions, is essential to engage the 77 percent of farmers unaware of burning’s impacts, elucidating its detrimental effects on soil fertility and public health. Thirdly, establishing centralized straw collection facilities for baling or biochar production, especially targeting small and semi-medium farmers, would enhance the current percentage of baling adoption, facilitating carbon sequestration and emission reductions. Additionally, promoting biochar’s soil-enhancing benefits could encourage adoption, while strengthening extension services to deliver tailored technical support would bridge knowledge gaps. These strategies collectively aim to mitigate resource disparities, elevate environmental consciousness, and transform straw from an ecological liability into a sustainable asset, guiding Punjab’s diverse agricultural community toward a more resilient and environmentally sound future.

**5. Competing Interests**

Authors have declared that no competing interests exist.

**COMPETING INTERESTS DISCLAIMER:**

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology

Details of the AI usage are given below:

1. Name of AI Technology: ChatGPT

Version/Model: GPT-4-turbo (specifically via OpenAI's ChatGPT)

Source: OpenAI (https://chat.openai.com)

Tool Used for Image Generation: Integrated image generation tool within ChatGPT (DALL·E 3-based system)

Input Prompt Provided to AI:

Create a pie chart showing the distribution of paddy straw management practices among farmers with the following categories and percentages: Burning – 33.3%, Incorporation – 30.0%, Cattle feed – 20.0%, Mulching – 13.3%, and Baling – 3.4%. Use distinct colors for each segment and label them clearly with percentages and category names.

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