# Agroecological Evaluation of Sustainable Stubble Management Strategies in Punjab
# Environmental, Socio-Economic, and Policy Dimensions

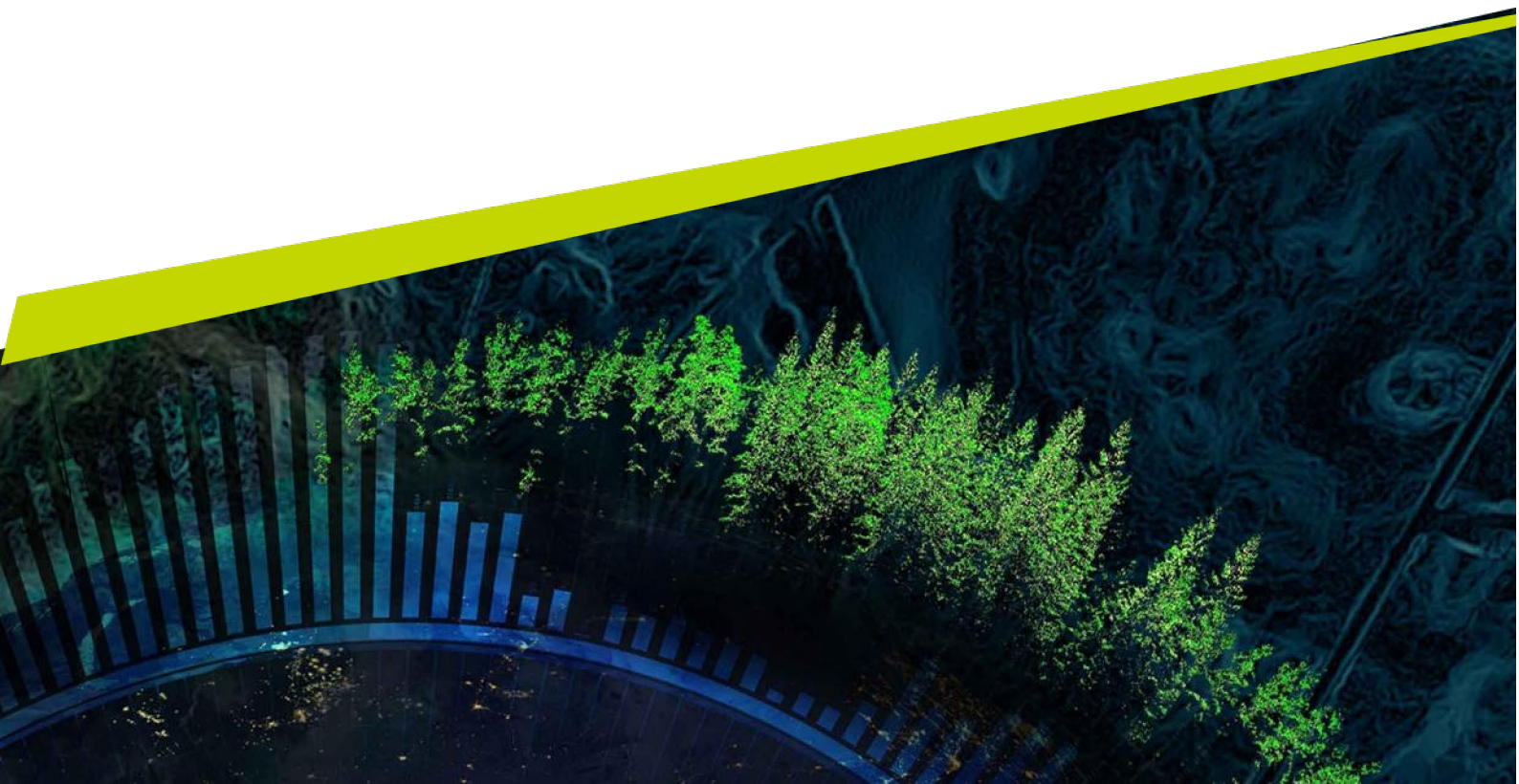
Shubkaran Singh

Degree project/Independent project • 30 credits

Swedish University of Agricultural Sciences, SLU
Faculty of Landscape Architecture, Horticulture, and Crop Production Sciences

Department of Biosystems and Technology
Agroecology-Master's Program

Course Title: Independent project in Agricultural Science, A2E -Agroecology-Master's Program



**Agroecological Evaluation of Sustainable Stubble Management Strategies in Punjab. Environmental, Socio-Economic, and Policy Dimensions**

**Shubkaran Singh**

| | |
|---|---|
| **Supervisor:** | **Raj Chongtham, Swedish University of Agricultural Sciences (SLU), Department of Biosystems and Technology** |
| **Examiner:** | Dr. Anna Manourova, Swedish University of Agricultural Sciences |


| | |
|---|---|
| **Credits:** | 30 credits |
| **Level:** | Second cycle, A2E |
| **Course title:** | Independent Project in Agricultural science, A2E - Agroecology - Master´s Programme |
| **Course code:** | EX0848 |
| **Programme/education:** | Agroecology - Master's Programme |
| **Course coordinating dept:** | Department of Biosystems and Technology |
| **Place of publication:** | Alnarp, Sweden |
| **Year of publication:** | 2026 |


**Copyright:** All featured images are used with permission from the copyright owner.

**Keywords:** agroecology, Punjab, stubble burning, crop residue management, Happy Seeder, soil health, policy, sustainable agriculture.

**Swedish University of Agricultural Sciences**
Faculty of Landscape Architecture, Horticulture, and Crop Production Sciences
Department of Biosystems and Technology

## Preface

This thesis is submitted in partial fulfilment of the Master's programme in Agroecology at the Swedish University of Agricultural Sciences (SLU), Alnarp, as an independent project of 30 credits (EX0848). The idea for the study grew out of my interest in the environmental and social dimensions of crop residue management in Punjab, India, and my wish to connect agroecological theory with the everyday realities faced by farmers and other stakeholders in the region.

Every October and November, smoke from burning paddy straw becomes a visible part of life in Punjab and across the wider Indo-Gangetic Plain. Public debate about it is often framed around farmer behaviour or technology alone. I wanted to understand how the constraints look from the perspective of those who actually have to manage the straw within a few weeks, and from the institutions that are meant to support them. The thesis therefore builds on first-hand interviews with 30 farmers, machinery providers, extension officers and policy stakeholders in Ludhiana, Sangrur and Mansa, carried out between 15 October and 12 November 2025, and combines them with a review of policy documents and the scientific literature. The interviews took place during the harvest and sowing season itself, when the decisions discussed in this thesis were being made.

The thesis is organised in five chapters. Chapter 1 introduces the problem and the objectives; Chapter 2 reviews the literature and sets out a conceptual framework; Chapter 3 describes the materials and methods; Chapter 4 presents and discusses the results; and Chapter 5 gives the conclusions, recommendations and limitations. The interview guide and the coding framework are provided as appendices.

I would like to thank my supervisor, Raj Chongtham, for guidance and constructive feedback throughout this work. I am also grateful to the farmers, machinery operators, extension officers and policy actors who generously shared their time and experiences during the interviews, without whom this study would not have been possible.

## Abstract

Stubble burning in Punjab has become a recurring environmental and agricultural challenge linked to the intensive rice-wheat cropping system. While this intensive cropping system has supported food security, it has also created large volumes of paddy residue and a short turnaround period before wheat sowing. If untreated, this residue is often burned in open fields, emitting particulate matter, greenhouse gases, reducing soil fertility and organic matter levels, and leading to high levels of seasonal air pollution in the broader Indo-Gangetic Plain. The thesis offers an agroecological assessment taking into account the environmental, social-economic and policy context of stubble burning, where as the previous studies have focused on the environmental drivers and the technological alternatives to stubble burning separately, the original contribution of this study is based on first-hand qualitative evidence collected from the field of Punjab. This thesis examines sustainable stubble management strategies in Punjab, North India, across three selected districts of Punjab (Ludhiana, Sangrur and Mansa), covering villages through an agroecological lens, focusing on environmental, socio-economic and policy dimensions. The study follows a qualitative research design based on semi-structured interviews, policy document review and literature analysis. The project plan and earlier thesis chapters frame the study around soil health, air pollution, farmer decision-making, machinery access, subsidies, and institutional support.

The results show that stubble burning is not just a lack of awareness or individual behaviour. During the interviews, 27 of 30 respondents (90%) indicated that smoke emissions were a direct impact of burning, and 27 respondents (90%) indicated that the short period between paddy harvest and sowing of wheat was a significant practical problem. The respondents were 30 consisting of 18 farmers, four (4) representatives of the Custom Hiring Centres/machinery providers, four (4) agricultural extension officers and four (4) policy/institutional stakeholders interviewed in the villages of Ludhiana, Sangrur and Mansa. Although stakeholder groups broadly agreed that residue burning was driven by practical constraints rather than a simple lack of awareness, their emphasis differed. Farmers primarily described time pressure, machinery and labour constraints; machinery providers emphasised peak-season shortages; extension officers highlighted the importance of demonstrations and technical support; and policy stakeholders focused on subsidy implementation, Custom Hiring Centre capacity and institutional coordination. These findings indicate that reducing burning requires a combination of timely access to residue-management machinery, stronger extension and demonstration support, more effective implementation of subsidy programmes, and longer-term crop diversification. Among the available technologies, the Happy Seeder directly sows wheat into paddy residue while retaining it as mulch, whereas the Super Seeder incorporates paddy residue into the soil while sowing wheat. Both technologies reduce stubble burning and support timely wheat sowing. This

is because respondents identified the narrow harvest-to-sowing period, machinery shortages, machinery costs, labour constraints and difficulties in accessing institutional support as important barriers to adopting alternatives. In particular, the findings suggest that improving machinery availability through Custom Hiring Centres, combining subsidies with practical training and demonstrations, and reducing market and procurement barriers to crop diversification could address several of the constraints identified by respondents.

Keywords: agroecology, Punjab, stubble burning, crop residue management, Happy Seeder, soil health, policy, sustainable agriculture.

## Table of contents


**Preface** ..... **3**

**1. Introduction** ..... **11**

**1.1 Objectives** ..... 14

**2. Review of literature** ..... **15**

**2.1 Rice-wheat system and the emergence of stubble burning in Punjab** ..... 15

**2.2 Causes of stubble burning** ..... 16

**2.3 Spatial and temporal trends in burning incidents** ..... 17

**2.4 Management strategies for stubble burning** ..... 18

**2.4.1 In-situ residue management** ..... 18

**2.4.2 Ex-situ residue management and circular economy approaches** ..... 22

**2.4.3 Overview and comparison of residue-management options** ..... 24

**2.5 Socio-economic factors influencing different crop residue management practices** ..... 26

**2.6 Externalities due to paddy crop residue burning** ..... 28

**2.7 Constraints in the adoption of environment-friendly management practices** 31

**2.8 Policy interventions and institutional challenges** ..... 34

**2.9 Crop diversification and structural alternatives** ..... 35

**2.10 Conceptual framework** ..... 37

**3. Materials and methods** ..... **39**

**3.1 Study area** ..... 39

**3.2 Research design** ..... 40

**3.3 Data collection methods** ..... 40

**3.3.1 Semi-structured interviews** ..... 40

**3.3.2 Semi-structured interview guide** ..... 41

**3.3.3 Policy document review** ..... 43

**3.3.4 Literature review** ..... 43

**3.4 Sampling strategy** ..... 44

**3.5 Sample size determination** ..... 44

**3.6 Data analysis** ..... 45

**3.7 Ethical considerations** ..... 46

**4. Results and discussion** ..... **47**

**4.1 Introduction to the findings** ..... 47

**4.2 Theme one: environmental awareness and soil concerns** ..... 47

**4.3 Theme two: time pressure and economic decision-making** ..... 53

**4.4 Theme three: machinery access and uneven technological transition** ..... 59

**4.5 Theme four: policy support, subsidies and institutional trust** ..... 62

**4.6 Theme five: agroecological transition and crop diversification** ..... 66

**4.7 Overall discussion** ..... 69

4.7.1 Reframing stubble burning as a socio-ecological problem ..... 69
4.7.2 Relationship with previous literature ..... 69
4.7.3 Balance between farmer responsibility and structural constraints ..... 70
4.7.4 Toward a multi-level agroecological strategy ..... 70
5. Conclusion and recommendations ..... 72
5.1 Conclusion ..... 72
5.2 Recommendations ..... 72
5.2.1 Increase the capacity and outreach of Custom Hiring Centres ..... 72
5.2.2 Link machinery incentives to extension services and training ..... 73
5.2.3 Streamline the process and make subsidy delivery transparent ..... 73
5.2.4 Promote combined in-situ and ex-situ residue-management approaches ..... 73
5.2.5 Minimize the risk to farmers in the harvest-to-sowing window ..... 73
5.2.6 Improve the value of diversifying crops ..... 74
5.2.7 Improve collaborative policy development and institutional cooperation ..... 74
5.2.8 Adopt an agroecological and systems approach for residue management ..... 74
5.3 Limitations and future research ..... 75
Declaration of AI use ..... 76
Popular science summary ..... 77
References ..... 78
Appendix A. Coding framework used for thematic analysis ..... 86
Appendix B. Summary of farmer interview transcripts ..... 89
Appendix C. Interview guide ..... 91
Publishing and archiving ..... 93

## List of figures

**Figure 1. Paddy stubble burning incidents in Punjab, 2020–2025. Sources: Kohli et al. (2024), Government of India (2025) and PIB (2025). ..... 17**

**Figure 2. Indicative comparison of residue management options. Scores are an indicative qualitative synthesis by the author, not measured values. Source: Author synthesis from Sidhu et al. (2007), Keil et al. (2021), Porichha et al. (2021) and Kemanth et al. (2024). ..... 25**

**Figure 3. Conceptual framework linking stubble burning, constraints and agroecological transition. Source: Author, based on Gliessman (2015), Downing et al. (2022) and Erbaugh et al. (2024). ..... 37**

**Figure 4. Schematic locator of the study interview districts (Ludhiana, Sangrur and Mansa). ..... 39**

**Figure 5. Environmental effects of stubble burning identified by respondents (n=30) ..... 48**

**Figure 6. Respondents raising soil-health concerns, by stakeholder group (23 of 30 respondents in total). ..... 49**

**Figure 7. Narrow paddy-harvest-to-wheat-sowing window as a constraint, by stakeholder group (number of respondents agreeing out of group size shown above each bar). ..... 54**

**Figure 8. Main residue-management practice of the 18 farmers, by district. ..... 56**

**Figure 9. Barriers to adoption cited by the eight non-adopting farmers (number citing each barrier out of eight). ..... 60**

**Figure 10. Respondents mentioning government policies, subsidy programmes or institutional support, by stakeholder group (26 of 30 respondents in total). . 63**

**Figure 11. Respondents who considered that long-term reduction of burning requires change in the rice-wheat production system, by stakeholder group (24 of 30 respondents in total). ..... 66**

## List of tables

**Table 2.1. Crop-residue management practices used or promoted in Punjab ..... 24**

**Table 3.1. Number of interview participants by stakeholder category and district . 40**

**Table 3.2. Gender and age group of interview participants by stakeholder category ..... 41**

**Table A1. The types and proportions of coded responses..... 86**

## List of abbreviations

| | |
|---|---|
| AI | Artificial intelligence |
| BC | Black carbon |
| CAQM | Commission for Air Quality Management |
| CCAC | Climate and Clean Air Coalition |
| CHC | Custom Hiring Centre |
| CRM | Crop Residue Management |
| DAP | Diammonium phosphate |
| FAO | Food and Agriculture Organization of the United Nations |
| GHG | Greenhouse gas |
| HYV | High-yielding variety |
| MSP | Minimum Support Price |
| NMHC | Non-methane hydrocarbon |
| NPK | Nitrogen, phosphorus and potassium |
| PAU | Punjab Agricultural University |
| PIB | Press Information Bureau |
| PM | Particulate matter |
| PRSC | Punjab Remote Sensing Centre |
| RMB | Reversible mould-board (plough) |
| RRM | Rice residue management |
| SLU | Swedish University of Agricultural Sciences |
| SMS | Straw Management System |
| SOC | Soil organic carbon |
| SOM | Soil organic matter |
| SST | Stale-seedbed technique |
| VOC | Volatile organic compound |

# 1. Introduction

Punjab's agricultural landscape has undergone a profound transformation since the Green Revolution, which marked a turning point in India's food production system. The introduction of high-yielding varieties (HYVs), chemical fertilizers, irrigation expansion, and mechanization led to the establishment of an intensive rice-wheat cropping system, particularly in north-western India. While this system has played a critical role in ensuring national food security, it has also resulted in significant ecological and management challenges (Dhanda et al., 2022). One of the most pressing among these is the generation and disposal of large quantities of crop residues, particularly paddy straw, which has led to the widespread practice of stubble burning (Erbaugh et al., 2024).

Agricultural production systems are both globally and, with particular intensity, in India increasingly challenged by climate change, which threatens food security and exacerbates environmental pressures(Negi et al., 2022; Pathak, 2023). To sustain vital ecosystem services, it is essential to ensure food security while simultaneously reducing the environmental footprint of agricultural practices (Rehman et al., 2022).There is a critical need for a paradigm shift from intensive, chemical-based production systems to more sustainable models based on the law of return (the agroecological principle that organic matter and nutrients removed from the soil through cultivation should be returned to it, for example through residue retention, composting or manuring, in order to sustain long-term soil fertility). Crop diversification is often proposed as part of such a shift, and it is reviewed briefly in Section 2.9 as background to the structural dimension of the problem (Beillouin et al., 2021; Tamburini et al., 2020); it is not, however, the central theme of this thesis.

These pressures are directly relevant to Punjab's rice–wheat system. The concentration of paddy harvesting within a short period before wheat sowing produces a large volume of residue that must be managed quickly. Where farmers lack timely access to affordable alternatives, rapid field clearance can encourage burning. The residue problem is therefore connected not only to environmental impacts but also to the crop calendar, machinery availability and the limited diversification of the prevailing production system (Downing et al. 2022).

India generates approximately 500-550 million tons of crop residues annually, with rice and wheat accounting for the majority share. Punjab alone contributes significantly to this total, producing nearly 19-20 million tonnes of paddy straw each year due to its extensive rice cultivation area (Kohli et al., 2024). Although a portion of this residue is used for fodder, industrial purposes, and energy production, a substantial amount remains unutilized and is often burned in situ. Recent policy reports indicate that while efforts are being made to manage this residue through both in-situ and ex-situ methods, the scale of the problem remains considerable,

necessitating more integrated and sustainable approaches (Bhuvaneshwari et al., 2019; Dutta et al., 2022).

The environmental implications of stubble burning are profound and multifaceted. The combustion of crop residues releases significant quantities of particulate matter ($PM_{2.5}$ and $PM_{10}$), greenhouse gases such as carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$), as well as other pollutants including carbon monoxide (CO) and nitrogen oxides ($NO_x$). These emissions contribute to severe air pollution episodes across the Indo-Gangetic Plains, particularly during the post-harvest season in October and November (Yang et al., 2025). Atmospheric conditions during winter, such as low wind speed and temperature inversion, exacerbate the accumulation of pollutants, leading to smog formation and deterioration of air quality in regions including Punjab, Haryana, and even distant urban centres like Delhi (Sidhu et al., 2007).

Recent data highlight that stubble burning continues to contribute significantly to regional air pollution, although there have been notable improvements in recent years. For instance, Punjab reported a substantial reduction in burning incidents due to increased adoption of residue management strategies and policy interventions. A government report indicated a 70% decline in burning cases between 2023 and 2024, attributed to improved management practices and increased awareness among farmers (Punjab Department of Agriculture and Farmers' Welfare, 2024). However, periodic spikes in farm fire incidents still occur, demonstrating that the problem has not been fully resolved and requires sustained efforts (Hindustan Times, 2025). Beyond air pollution, stubble burning has serious implications for soil health and agroecosystem sustainability. The burning process leads to the loss of essential nutrients, including nitrogen, phosphorus, potassium, and sulphur, which are otherwise valuable for maintaining soil fertility. It also results in a decline in soil organic carbon, adversely affecting soil structure, water retention capacity, and microbial activity. The destruction of beneficial soil organisms further disrupts nutrient cycling processes and reduces long-term agricultural productivity. Consequently, farmers may become increasingly dependent on chemical fertilizers to maintain yields, leading to higher input costs and environmental degradation (Arunrat et al., 2023; Pradhan et al., 2024).

Crop diversification is treated in this thesis as background and long-term context rather than as a central theme. In principle, reducing the area under rice would lessen the volume and concentration of paddy residue generated in the narrow post-harvest period and could ease pressure on groundwater (Downing et al., 2022). However, the literature shows that farmers' willingness to diversify depends on procurement, prices, markets and institutional support, and the interviews in this study point the same way: only five of the 18 farmers said they would consider growing a mix of crops under present market conditions (Section 4.6). Diversification is therefore considered a long-term structural complement to, rather

than a realistic short-term substitute for, immediate residue-management measures, and the analytical focus of the thesis is on residue management, machinery access and institutional support.

Despite the well-documented environmental impacts, farmers continue to engage in stubble burning due to a range of socio-economic factors. Studies have shown that farmers perceive burning as a low-cost, efficient, and reliable method for clearing fields, particularly in the absence of affordable and accessible alternatives (Erbaugh et al., 2024). The high cost of machinery such as the Happy Seeder, limited availability of custom hiring centres, fragmented landholdings, and labour shortages further constrain the adoption of alternative practices.

Recent research also highlights institutional and infrastructural barriers to sustainable residue management (Singh et al., 2020; Jain et al., 2025). Government support has increased the availability of crop-residue-management machinery and Custom Hiring Centres, but studies continue to report uneven access, peak-season shortages, maintenance costs and operational difficulties (Singh et al., 2020; Jain et al., 2025). These issues are directly related to residue management because a technically effective machine cannot reduce burning if farmers cannot obtain it during the short period in which fields must be prepared. The present study therefore examines technology access together with the institutional arrangements that enable or constrain its use.

The Happy Seeder is a tractor-mounted machine that sows wheat directly into standing paddy stubble while simultaneously mulching the residue, removing the need to burn or clear it first. The Super Straw Management System (SMS) is an attachment fitted to combine harvesters that chops and spreads paddy straw evenly across the field during harvesting, making it easier to manage in place. Zero tillage refers to sowing the next crop directly into the soil without ploughing, which leaves the straw as a protective surface mulch rather than removing it. Sustainable residue-management strategies include in-situ practices such as residue retention and mulching and ex-situ approaches such as baling and biomass utilisation. Technologies such as the Happy Seeder and Super SMS can reduce the need to remove or burn residue before wheat sowing, although their adoption depends on cost, availability, operator skills and timely access.

Studies have shown that policy interventions such as the Crop Residue Management (CRM) Scheme provide financial and institutional support for these practices (Jain et al., 2025). However, the literature suggests that policy support is most effective when machinery subsidies are accompanied by extension, training, accessible Custom Hiring Centres and reliable markets for alternative residue uses. An agroecological perspective is useful here because it connects residue management with soil health, water use, farmer livelihoods and the wider organisation of the farming system.

This study seeks to understand how environmental; socio-economic and policy factors interact to influence farmers' and other stakeholders decision to burn or sustainably manage paddy residue, and what an agroecological perspective brings to the understanding and solution to this issue in Punjab. An agroecological evaluation of sustainable stubble management strategies is therefore essential for developing context-specific solutions that promote environmental sustainability, economic viability, and social equity. Hence, the present study was undertaken with the following objectives.

## 1.1 Objectives

1. To examine the environmental impacts (examined qualitatively, through stakeholder perceptions, policy documents and secondary evidence, rather than through direct field measurement) of stubble burning and sustainable residue management practices in Punjab.
2. To analyse socio-economic factors influencing farmers' adoption or rejection of non-burning alternatives.
3. To review the effectiveness of policy measures, subsidies and institutional support related to crop residue management.
4. To develop agroecologically informed recommendations for sustainable stubble management in Punjab.

## 2. Review of literature

The stubble burning still remains an important environmental problem in Punjab, mostly owing to its contribution to the air pollution as well as degradation of the agroecosystem. Burning of the residues emits large volumes of greenhouse gases including $CO_2$, $CH_4$, $N_2O$, and particulates such as $PM_{2.5}$ and $PM_{10}$, leading to poor air quality and formation of regional smog. Not only are these emissions affecting the local environment, but also have impacts on the broader region of the Indo-Gangetic Plain. Therefore, the stubble burning becomes both a regional and global environmental problem (Das et al., 2024; Sidhu et al., 2007). A critical review of the previous research becomes essential for identifying the relevant problems and issues in a particular field. It helps a researcher collect the right data for the analysis using proper reasoning and interpretation. The following section contains a brief review of the relevant literature in the current study. Based on the goals of the study, the reviewed literature has been divided into the following sections.

### 2.1 Rice-wheat system and the emergence of stubble burning in Punjab

The rice-wheat cropping system in Punjab represents one of the most intensive agricultural production systems in the world. While it has ensured food security, it has also created structural conditions that Favor residue burning. Awasthi et al. (2011) reported that crop residue burning in Indian Punjab emits significant quantities of particulate matter, adversely impacting human health, climate systems, and agricultural sustainability. Their study emphasizes that despite the availability of economically viable alternatives, residue burning persists due to deeply embedded socio-ecological feedback mechanisms. The authors further highlight that the current agricultural system is “locked-in” to residue burning due to interactions among policy incentives, cropping patterns, and market structures. Government policies, particularly procurement systems for rice and wheat, have reinforced monocropping practices, thereby increasing residue generation. This indicates that stubble burning is not merely a behavioural issue but a systemic outcome of agricultural intensification.

Similarly, Singh et al. (2019) reported that the rice-wheat system contributes to high levels of air pollutants, with $PM_{2.5}$ concentrations ranging between 200-500 μg/m³ during burning periods. The study also links burning practices to a 30-40% reduction in soil organic carbon and a significant increase in respiratory health issues. These findings suggest that the environmental and health impacts of residue burning are both immediate and long-term.

Gulati et al., (2023) reported that stubble burning persists primarily because it is the fastest and most economical method for field clearance. Their study

highlights that despite growing awareness, constraints such as limited access to machinery, poor economic returns from residue, and tight cropping schedules continue to drive this practice. Importantly, the authors point out that technological interventions alone are insufficient unless supported by behavioural change and policy alignment. Collectively, these studies indicate that the emergence and persistence of stubble burning in Punjab are rooted in structural, economic, and institutional factors. Therefore, any sustainable solution must move beyond technological fixes and address the broader agricultural system.

## 2.2 Causes of stubble burning

One of the primary drivers of stubble burning in Punjab is the lack of accessible and affordable residue management infrastructure. Technologies such as Happy Seeder, mulchers, and balers have been developed to manage residues without burning; however, their adoption remains limited. Small and marginal farmers, in particular, face financial and logistical constraints in accessing such machinery(Erbaugh et al., 2024) . Although government subsidies are available, they often do not fully cover the cost of machinery, and access to custom hiring centres is uneven. This creates a gap between policy intent and field-level implementation. As a result, burning continues to be perceived as the most practical option for residue disposal. The narrow time window between paddy harvesting and wheat sowing is another critical factor influencing stubble burning. Farmers typically have only 15-20 days to prepare their fields, leaving limited scope for alternative residue management practices. Delayed sowing of wheat can significantly reduce yield potential, thereby increasing the economic risk for farmers.

Oraby et al. (2025) highlight that this time constraint creates intense pressure on farmers to adopt quick solutions, with burning being the most time-efficient method. This finding underscores the importance of developing time-efficient alternatives that align with existing cropping cycles.

Financial barriers compound this problem: Alawode (2025) shows that existing subsidy schemes are often inadequately implemented and fail to address the real financial challenges faced by farmers. Delays in subsidy disbursement, high initial investment costs, and lack of operational support reduce the attractiveness of alternative technologies. Moreover, there is a lack of strong economic incentives for adopting sustainable residue management practices. For instance, markets for crop residues, such as bioenergy or composting industries, are still underdeveloped. Without assured economic returns, farmers have little motivation to shift away from burning (Bustos-Terrones, 2026).

Awareness gaps add a further layer to the problem. Abdurrahman et al. (2020) point out that many farmers are either unaware of the long-term environmental impacts or are sceptical about the effectiveness of alternative practices.

Additionally, resistance to change, particularly among older farmers, and lack of exposure to sustainable techniques further hinder adoption. This suggests that behavioural change strategies, including farmer education and community-based approaches, are essential for promoting sustainable residue management.

### 2.3 Spatial and temporal trends in burning incidents

Data from the Punjab Remote Sensing Centre (PRSC) indicate significant spatial variation in stubble burning across districts such as Barnala, Bathinda, Sangrur, and Fazilka. PRSC (2024) documented that fire incidents peaked at 76,590 in 2020, followed by a decline to 49,922 in 2022.

While this decline indicates some success of policy interventions, the persistently high number of incidents highlights the limitations of current strategies. These findings emphasize the need for region-specific interventions that account for local agricultural and socio-economic conditions.Figure 1 shows the reported trend in paddy stubble-burning incidents in Punjab between 2020 and 2025.

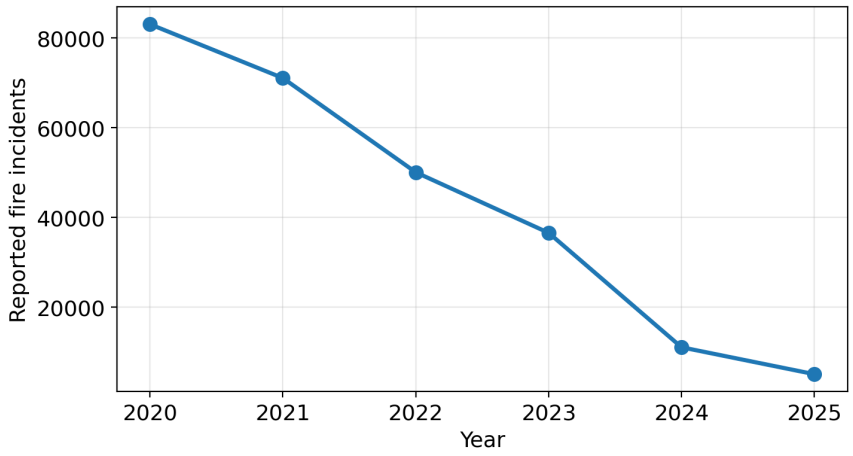



*Figure 1. Paddy stubble burning incidents in Punjab, 2020–2025. Sources: Kohli et al. (2024), Government of India (2025) and PIB (2025).*

Reported burning incidents fell by more than 90% between 2020 and 2025, coinciding with the expansion of the Crop Residue Management (CRM) Scheme, the growth of Custom Hiring Centres (CHCs) and wider promotion of in-situ machinery such as the Happy Seeder. Two cautions apply when reading this trend. First, the figures are satellite-detected fire counts, which depend on overpass timing and cloud cover and should therefore be read as indicative rather than exact. Second, a fall in counts does not by itself show that the constraints behind burning have disappeared: periodic spikes continue to be reported (Hindustan Times, 2025), and the literature reviewed in Sections 2.2 and 2.7 identifies the narrow sowing window and uneven machinery access as persistent drivers. The interview evidence in Chapter 4 is used to examine what lies behind the decline, as respondents linked reduced burning to greater machinery availability while noting

that the practice persists where the window between paddy harvest and wheat sowing is too short.

## 2.4 Management strategies for stubble burning

### 2.4.1 In-situ residue management

In situ management of crop residues involves their retention, incorporation, or mulching within the field. Several studies highlight its positive effects on soil health, crop productivity, and sustainability. Surekha et al. (2003) demonstrated that incorporation of rice straw residues, either alone or combined with green manure, significantly improved soil properties compared to fertilizer-only control plots. Residue incorporation enhanced soil organic carbon, available potassium, and total nitrogen content, while reducing bulk density. Yield attributes such as panicle and spikelet number improved notably after repeated incorporation cycles, leading to an increase in rice yield by 1.0-1.2 t/ha in the dry season and 0.4-0.8 t/ha in the wet season.

Similarly, Yadvinder-Singh et al. (2004) emphasized that incorporation and surface retention of residues in the rice-wheat system contribute to the buildup of soil organic matter (SOM) and nutrients (N, P, K), although temporary nitrogen immobilization can occur. Application of a starter nitrogen dose (15-20 kg/ha) helps mitigate this limitation and enhances crop yields. Surface retention also significantly increased nitrate availability (46%), nitrogen uptake (29%), and yield (37%) compared to burning. Rahman et al. (2005) further reported that straw mulching conserves soil moisture, reduces weed infestation, and improves root growth parameters such as root length density and root weight density in wheat under no-till systems.

Sidhu et al. (2007) demonstrated that this technology can eliminate the need for burning while maintaining crop yields. Technologies such as the Happy Seeder have gained significant attention for their ability to sow wheat directly into standing rice stubble. Long-term benefits of residue incorporation were also reported by Sidhu and (Sidhu & Beri, 1989), showing improvements in soil physical, chemical, and biological properties, although yield gains in wheat ranged from 0 to 0.5 t/ha. Sidhu & Beri (1989) found that surface mulching of rice residues enhanced soil moisture retention, leading to improved crop growth and water productivity, particularly under water-limited conditions. Rahman et al. (2005) observed that straw incorporation along with decomposers such as cellulolytic microorganisms and earthworms significantly improved rice productivity, with the highest yields recorded when straw was combined with both decomposers.

Verma & Pandey (2013) reported that integrating residue incorporation with additional NPK fertilization improved growth parameters, yield attributes, and nitrogen uptake in wheat. Sommer et al. (2014) demonstrated that zero tillage with

straw retention (ZTsr) combined with optimal nitrogen application (200 kg N/ha) resulted in higher wheat yield, soil organic matter, and total soil nitrogen compared to burning practices. Singh & Sidhu (2014) highlighted that conservation agriculture practices, including residue retention and minimal tillage, enhance yield, water use efficiency, and profitability while reducing weed pressure and environmental risks.

Singh & Sidhu (2014) documented the role of Happy Seeder technology in addressing the challenges of paddy straw management and stated that the straw management system should be made mandatory for all combine harvesters in Punjab. The results indicated that the adoption of Happy Seeder technology led to significant savings in fertilizers, with urea, DAP, and potash savings amounting to Rs 424.15 (4.5 USD or 1 USD is about 90 Rs), Rs 366.25, and Rs 1989, respectively, totalling Rs 2779.40 per acre (1124 Ha). In addition to these economic benefits, the technology also contributed to improvements in soil physical characteristics over time. During the year 2013-14, the highest additional benefit-cost (B:C) ratio of 4.36 was recorded in Happy Seeder plots. Apart from preventing the burning of paddy straw, the use of Happy Seeder for wheat sowing resulted in a saving of Rs 2311.25 per hectare in operations related to field preparation, sowing, and overall crop management when compared to conventional wheat sowing methods.

A study conducted by Kumar et al. (2016) examined rice-residue management in wheat under different tillage practices and nitrogen levels in Baghpat, Uttar Pradesh. The study evaluated wheat growth, yield and economic performance under alternative residue-management practices, providing evidence that residue can be managed without open-field burning. This evidence is relevant to the present study because it illustrates the agronomic feasibility of retaining or incorporating residue when appropriate management practices are available.

Chendrashekhar & Lokesh, (2018) analysed the cost and returns of paddy cultivation under different residue management practices in the Tungabhadra command area of Karnataka, India. The study identified four major methods of paddy residue management: (a) removal of straw followed by burning of stubbles, (b) burning of both straw and stubbles, (c) removal of straw with incorporation of stubbles, and (d) incorporation of both straw and stubbles. The findings revealed that the overall variable cost per acre was highest when straw was retained (Rs 30,029.25), followed by removal and burning of straw (Rs 29,345.33), removal with incorporation of stubbles (Rs 29,345.33), and lowest in the case of burning of straw and stubbles (Rs 26,616.61). In terms of total cost per acre, incorporation of straw and stubbles incurred the highest cost (Rs 41,845.65), whereas burning of straw and stubbles resulted in the lowest cost (Rs 38,411.33). However, yield performance showed a different trend, where incorporation of paddy straw recorded the highest yield (29.75 q/acre). In metric terms, these variable-cost figures are approximately Rs 74,220/ha (straw retained), Rs 72,510/ha (removal

and burning of straw), Rs 72,510/ha (removal with incorporation of stubbles) and Rs 65,790/ha (burning of straw and stubbles); total costs are approximately Rs 103,420/ha (incorporation of straw and stubbles) and Rs 94,930/ha (burning of straw and stubbles). Corresponding yields are approximately 7,350 kg/ha (incorporation), 7,200 kg/ha (removal), 7,060 kg/ha (removal with incorporation) and 6,950 kg/ha (burning), using 1 acre ≈ 0.405 ha and 1 quintal = 100 kg., followed by straw removal (29.15 q/acre), removal combined with incorporation (28.58 q/acre), and the lowest yield under straw burning (28.11 q/acre).

Lohan et al. (2018) reported that in the north-western states of India, particularly Punjab and Haryana, disposal of paddy residue continues to be a major challenge, with farmers predominantly preferring in-field burning. The study aimed to quantify residue generation, assess both in situ and ex situ utilization options, and evaluate the adverse impacts of residue management practices on human health, soil quality, and the environment. The results indicated that the operational cost of Happy Seeder technology was Rs 2,620 per hectare, which resulted in an energy saving of 84.64 per cent compared to Rs 9,551 per hectare required under conventional methods.

Sandhu et al. (2019) conducted an economic evaluation of paddy stubble management technologies in the Amritsar district of Punjab during 2018-19. The study found that although the adoption of stubble management technologies increased the cost of paddy cultivation per acre, it simultaneously reduced input costs and enhanced crop yield, thereby compensating for the additional expenses. Key determinants influencing adoption included farmer age, availability of machinery, reduced input use, and size of landholding. However, high initial cost and non-availability of machinery at cooperative societies were identified as major constraints among non-adopters. The study emphasized the need to increase the availability of machinery through cooperatives, raise awareness regarding the importance of crop residues in conservation agriculture, and provide incentives to farmers adopting residue management technologies.

Singh & Sidhu (2014) carried out a comparative economic analysis of wheat cultivation in Ludhiana and Sangrur districts of Punjab during 2017-18, considering different paddy straw management techniques such as wet mixing, dry mixing, and Happy Seeder, along with the conventional practice of burning residues. The study concluded that the Happy Seeder method was the most economically viable option for managing paddy straw before wheat sowing. The use of this technology resulted in savings of 732 $m^3$ of water, a 27.47 per cent reduction in tractor usage, and significant reductions in emissions, including 18 kg particulate matter, 360 kg CO, 8.76 tonnes $CO_2$, 1.2 tonnes ash, and 12 kg $SO_2$ per hectare. Despite these benefits, farmers faced challenges such as lack of high-horsepower tractors, limited availability of Happy Seeder, rodent attacks, and slow straw decomposition. Although farmers were aware of the health hazards associated with residue

burning, labour shortages and a narrow sowing window forced them to continue the practice. The study suggested compensating farmers for ecosystem services by incorporating residue management costs into the Minimum Support Price (MSP).

Gill and Singh (2020) compared wheat production under different paddy residue management practices in Firozpur and Jalandhar districts of Punjab by analysing growth parameters and yield attributes. Field experiments were conducted on 10 farmers' fields in each district over two rabi seasons (2016-17 and 2017-18), comparing wheat sown using Happy Seeder under residue retention with wheat sown using conventional drill after residue burning. Statistical analysis using an unpaired t-test revealed no significant differences in growth parameters and yield attributes between the two methods, with mean grain yields of 5.48 t/ha and 5.35 t/ha, respectively. However, economic analysis showed that the Happy Seeder method reduced cultivation costs by 15.17 per cent and increased gross and net returns by 2 per cent and 5.55 per cent, respectively, compared to the conventional method.

Rathod et al. (2021) evaluated the impact of tillage and crop residue management practices on wheat yield and economic returns under conservation agriculture. The study was conducted using a split-plot design with fifteen treatments at the agronomy farm of Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani. Results indicated that grain yield was significantly influenced by tillage practices, with reduced tillage recording the highest yield, followed by conventional tillage and zero tillage. The highest gross returns (Rs 44,350/ha), net returns (Rs 21,927/ha), and benefit-cost ratio (1.99) were also observed under reduced tillage systems.

Singh & Sidhu (2014) studied the impact of various rice residue management practices on wheat productivity and soil fertility in the western region of Punjab over three consecutive rabi seasons (2016-2019). Rice straw was managed using a straw management system (SMS) attached to combine harvesters, and wheat was sown using different methods including Happy Seeder, mulcher, reversible mould board plough (RMB), zero till drill, and conventional practices. The study revealed that wheat sown using the Happy Seeder recorded significantly higher productivity and maximum grain yield compared to other methods. The highest gross returns (Rs 1,11,136/ha) and net returns (Rs 89,716/ha) were also recorded under Happy Seeder due to higher grain yield (60.4 q/ha). In contrast, the highest cost of cultivation was observed under conventional methods (Rs 31,542/ha), while lower costs were recorded under RMB plough (Rs 25,575/ha), mulcher (Rs 24,075/ha), Happy Seeder (Rs 21,420/ha), and zero till drill (Rs 20,850/ha). The benefit-cost ratio was highest (4.18) under the Happy Seeder method.

Paudel et al. (2024) further analysed the economic feasibility of the Happy Seeder and concluded that its adoption depends on factors such as cost, machine

availability, and compatibility with local farming conditions. More recent studies indicate that adoption remains uneven due to operational challenges and limited access to machinery. Zero tillage and mulching are also important in-situ practices that enhance soil health and reduce residue burning. These practices align strongly with agroecological principles, as they promote nutrient recycling and reduce external input dependence (Porichha et al., 2021)

Singh et al. (2022) conducted an economic analysis of paddy straw management practices in Ludhiana and Mansa districts of Punjab during 2019-20, based on a sample of 80 rice farmers. The study examined various residue management strategies including complete burning, partial burning, and non-burning using different technologies. The results indicated that the Happy Seeder was the most cost-effective method for managing paddy straw prior to wheat sowing. Other methods such as straw baling, incorporation using mould board plough, and super seeder technology increased farmers' costs by Rs 2,000 to Rs 5,100 per hectare. Wheat yields under Happy Seeder were comparable to those obtained after burning, but higher variable costs under alternative practices resulted in relatively lower returns. Farmers also reported several constraints, including rodent infestation, increased pest and disease incidence, and high equipment costs, which limited the widespread adoption of these technologies.

### 2.4.2 Ex-situ residue management and circular economy approaches

Ex situ residue management involves removal, burning, or utilization of crop residues outside the field. Among these, open-field burning remains a widely practiced but environmentally detrimental method. Mohanty (2004) reported that burning causes significant nutrient losses, including up to 80% nitrogen, 25% phosphorus, 21% potassium, and 4-60% sulphur, along with substantial emissions of $CO_2$ (13 t/ha). This practice also reduces soil organic matter, posing a threat to long-term soil fertility and sustainability.

Gupta et al. (2004) highlighted that residue burning in rice-wheat systems lead to emissions of greenhouse gases such as $CO_2$, CO, $CH_4$, and $N_2O$, significantly contributing to atmospheric pollution. In India alone, emissions from residue burning were estimated at 110 Gg $CH_4$, 2306 Gg CO, 2 Gg $N_2O$, and 84 Gg NOx. Similarly, Naser et al. (2007) demonstrated that rice straw application influences methane emissions in flooded paddy fields, showing a strong correlation between straw carbon input and $CH_4$ emissions.

Bhattacharyya et al. (2021) discussed that although rice straw has traditional uses such as fodder and construction material, the surplus generated due to intensified agriculture often leads to its disposal through burning, which remains the most cost-effective but environmentally harmful option. Kanokkanjana & Garivait (2013) further quantified carbon emissions from open burning and suggested alternative strategies such as straw collection and off-field utilization.

Their study indicated that improved management practices could reduce straw burning from 10.41 ± 4.29 million tons to 4.89 ± 2.34 million tons and significantly lower carbon emissions.

Kaur (2017) in her study on crop residue management in Punjab agriculture, reported that a substantial quantity of crop residue is generated due to the dominance of the rice-wheat cropping system, with nearly 70 per cent of the net sown area under paddy during the kharif season and 84.6 per cent under wheat in the rabi season. The study highlighted that residue burning has emerged as a hazardous practice, adversely affecting human health, air quality, road safety, and soil health, thereby leading to significant physical and economic losses. However, about 67.47 per cent of the sampled farmers did not burn agricultural residues. The persistence of residue burning was mainly attributed to the lack of market demand for residues, insufficient government support, and the limited time gap between harvesting and sowing of successive crops. The study suggested several alternative solutions, including the use of residues as animal feed, provision of subsidies for machinery such as the Happy Seeder, utilization in cardboard industries, power generation, composting, development of low-residue crop varieties, and reducing the cost of manual harvesting.

Ahmed et al. (2015) investigated the determinants influencing farmers' adoption of rice residue management practices in Pakistan's rice-wheat cropping system. Using primary data from 400 farmers and applying a multinomial logit model, the study found that farmers commonly adopt practices such as residue removal, burning, and incorporation. The probability of adopting burning, partial removal, partial burning, and incorporation increased with factors such as farm size, total cost of field preparation for wheat after rice, farming experience, and the turnaround time between rice harvesting and wheat sowing. Conversely, the likelihood of burning decreased when rice residues were utilized as fuel or animal feed. The study emphasized the need for government intervention to promote technologies for electricity generation from crop residues, residue enrichment for livestock feed, and in-situ incorporation into the soil. It also recommended that agricultural institutions focus on developing dwarf rice varieties, encouraging crop diversification, and implementing strict regulations to control residue burning.

Singh et al. (2022) in their study conducted during 2019-20 in the Mansa district of Punjab, analysed the extent and practices of rice residue management (RRM). The findings revealed that village Biro Ke Kalan in Budhlada block had the largest area under RRM (404.0 ± 12.6 ha), accounting for approximately 30 per cent of the total study area, whereas Kahlon village in Mansa block had the smallest area (28.4 ± 3.1 ha), representing only 4.6 per cent. Overall, farmers adopted RRM practices such as mulching, incorporation, and residue removal on about 43.15 per cent of the area. Residue removal was the most preferred method, covering around 37 per cent of the total paddy area. Among mechanized technologies, the Happy

Seeder was used for mulching on 31 per cent of the area, followed by rotavator (14%) and super seeder (7.7%). Manual removal of loose straw was minimal, accounting for only 2.3 per cent of the area. The study also reported several challenges faced by farmers, including leaf yellowing, pink stem borer infestation, water stagnation, and heavy straw load. Additionally, constraints such as the lack of high-horsepower tractors and insufficient technical knowledge regarding advanced machinery were identified as major barriers to the adoption of RRM practices.

Porichha et al. (2021) highlight the potential of biomass-based energy systems to reduce residue burning while generating additional income. They reported that removing crop residues from the field and using them for alternative purposes such as bioenergy production, composting, packaging materials, and industrial fuel. Recent reports by the Climate and Clean Air Coalition (CCAC & FAO, 2022) emphasize the role of circular economy approaches in transforming agricultural waste into valuable resources. However, the success of ex-situ systems depends on efficient supply chains, including residue collection, storage, transportation, and market linkages. From an agroecological perspective, ex-situ management must be carefully balanced. While it reduces burning and creates economic value, excessive removal of residues can reduce soil organic matter. Therefore, a combination of in-situ and ex-situ strategies is recommended for sustainable residue management. This indicates that sustainable residue management must be linked with broader agricultural system transformation rather than treated as an isolated issue.

### 2.4.3 Overview and comparison of residue-management options

Table 2.1 gives an overview of the crop-residue management practices used or promoted in Punjab, grouped into the in-situ and ex-situ approaches discussed above, with open-field burning as the baseline against which the alternatives are judged. Figure 2 then compares the main options indicatively.

**Table 2.1. Crop-residue management practices used or promoted in Punjab**

| Practice | Approach | Description | Main advantages reported | Main constraints reported |
|---|---|---|---|---|
| Open-field burning | Burning (baseline) | Straw and stubble are set alight in the field after combine harvesting | Fastest and cheapest way to clear the field (Gulati et al., 2023) | Emits particulates and greenhouse gases; losses of N, P, K, S and soil organic matter (Mohanty, 2004; Gupta et al., 2004) |
| Happy Seeder | In-situ | Tractor-mounted machine that sows wheat directly into loose residue, which stays on the surface as mulch | No burning; lower field-preparation costs; moisture conservation (Sidhu et al., 2007; Gill & Singh, 2020) | Machinery cost and availability; high-horsepower tractor needed; rodents and slow straw decomposition (Singh et al., 2022) |
| Super Seeder | In-situ | Machine that incorporates the residue into the soil while sowing wheat | Allows sowing without burning (Singh et al., 2022) | Higher cost to farmers than the Happy Seeder (Singh et al., 2022) |

| Practice | Approach | Description | Main advantages reported | Main constraints reported |
|---|---|---|---|---|
| Super Straw Management System (Super SMS) | In-situ (harvest stage) | Attachment fitted to combine harvesters that chops and spreads straw evenly during harvest | Makes straw easier to manage in place before sowing (Singh & Sidhu, 2014) | Adoption depends on cost, availability, operator skills and timely access |
| Incorporation (rotavator, mould-board plough) | In-situ | Chopped straw is mixed into the soil before sowing | Raises soil organic carbon, nitrogen and potassium (Surekha et al., 2003; Yadvinder-Singh et al., 2004) | Temporary nitrogen immobilisation; extra operations and cost (Yadvinder-Singh et al., 2004; Singh et al., 2022) |
| Surface retention and mulching (zero tillage) | In-situ | Straw is kept on the surface as mulch and the next crop is sown with zero tillage | Conserves soil moisture and suppresses weeds (Rahman et al., 2005; Chhokar et al., 2009) | Weed infestation and poor establishment unless weeds are managed (Rahman et al., 2005; Chhokar et al., 2009) |
| Baling and removal | Ex-situ | Straw is baled and removed for fodder, bioenergy or industrial use | Income from residue; no burning (Porichha et al., 2021) | Needs collection, storage, transport and markets; adds cost (Porichha et al., 2021; Singh et al., 2022) |
| Composting | Ex-situ / on farm | Straw is composted and the compost applied to the soil | Higher yields; nutrient recycling (Tirol-Padre et al., 2007) | Labour-intensive and technically complex (Poungchompu et al., 2013) |
| Biomass energy and industrial uses | Ex-situ | Residue is used for bioenergy, packaging materials or industrial fuel | Additional income from surplus straw (Porichha et al., 2021; Bhuvaneshwari et al., 2019) | Depends on supply chains and market links; excessive removal can reduce soil organic matter (Porichha et al., 2021) |

Figure 2 compares burning, the Happy Seeder, mulching, incorporation and baling on three criteria: pollution risk, soil benefit and ease or time efficiency.

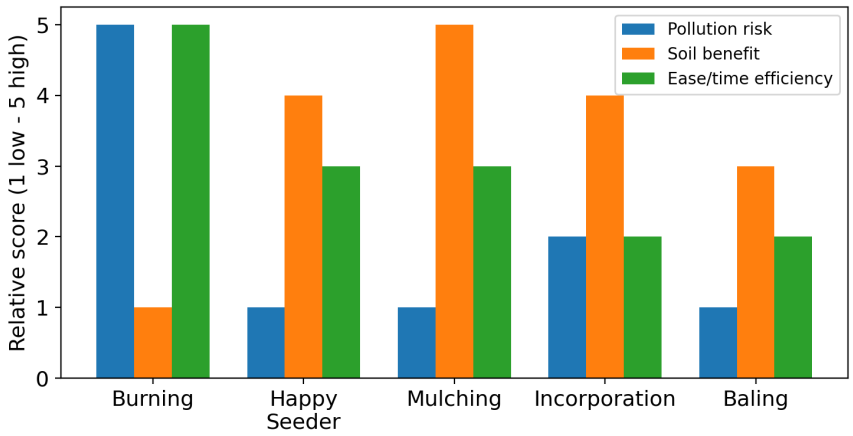



*Figure 2. Indicative comparison of residue management options. Scores are an indicative qualitative synthesis by the author, not measured values. Source: Author synthesis from Sidhu et al. (2007), Keil et al. (2021), Porichha et al. (2021) and Kemanth et al. (2024).*

The comparison indicates why burning remains attractive in practice: it scores highest on ease and time efficiency even though it performs worst on pollution risk and soil benefit. The Happy Seeder and mulching offer the strongest combination of soil benefit and moderate ease, which is consistent with their promotion under the Crop Residue Management Scheme, while incorporation and baling involve a greater trade-off between soil or market benefits and the time available before wheat sowing. This trade-off structure recurs throughout the interview findings in

Chapter 4. The scores in Figure 2 are a qualitative synthesis of the studies summarised in Table 2.1 and are intended to show relative trade-offs, not measured differences. Read together, Table 2.1 and Figure 2 show that no single option is best on every criterion, which is why the policy literature reviewed in Section 2.8 stresses combinations of machinery, extension support and markets. The interview findings in Chapter 4 return to these trade-offs, particularly the tension between soil benefit and time efficiency.

## 2.5 Socio-economic factors influencing different crop residue management practices

Socio-economic factors play a central role in shaping farmers' decisions regarding crop residue management practices. These factors determine not only the choice of residue disposal method but also the extent to which farmers are willing to adopt sustainable alternatives. Studies consistently show that farmers often prefer residue burning because it is a cost-effective, time-saving, and reliable method under existing constraints such as labour shortages, limited access to machinery, and narrow time windows between successive crops (Ahmed et al., 2015). The decision-making process is therefore not solely based on environmental awareness but is strongly influenced by economic feasibility and operational convenience.

Malasa & Roguel (2002) studied the social impacts of weed management techniques such as rice hull-burning (RHB) and stale-seedbed technique (SST) in two barangays of Nueva Ecija, namely Palestina in San Jose City and Kaingin in Bongabon. Their study revealed that farmers in San Jose had already adopted RHB as an essential component of weed control during the onion season, whereas farmers in Bongabon had not adopted this practice. The comparative analysis indicated that adoption was influenced by factors such as rice-hull availability and road accessibility, which affect the ease of transporting and utilizing residues. Additionally, heavy reliance on herbicides in both areas highlighted potential health risks, indicating that socio-economic and infrastructural constraints can indirectly lead to environmentally and health-compromising practices.

Valbuena et al. (2012) conducted a multi-country study across 12 sites in Sub-Saharan Africa and South Asia to examine crop residue management practices under varying population and livestock densities. Their findings revealed that in high-density areas, although pressure on resources is high, biomass production is also substantial, allowing farmers to allocate part of the residues for mulching. In contrast, in medium-density areas, biomass scarcity and competing demands for livestock feed increase the opportunity cost of using residues as mulch. In low-density areas, despite lower population pressure, farmers rely heavily on crop residues as a primary feed source during dry seasons, making it economically unviable to use residues for soil management. This study clearly demonstrates that

socio-economic context and competing resource demands significantly influence residue management decisions.

Mohammadi et al. (2017) analysed the economic benefits of residue burning and found that it is often a rational choice for farmers under existing conditions. Burning provides immediate benefits such as reduced labour requirements, lower operational costs, and effective control of weeds, pests, and diseases. The study reported that farmers practicing residue burning gained a net benefit of Tk. 3,240-3,353 per acre annually compared to those who did not burn residues. Furthermore, the willingness of farmers to accept compensation for discontinuing burning was found to be lower than the market value of residues, indicating that economic incentives play a crucial role in influencing behaviour.

Ojo et al. (2013) examined factors influencing enterprise choices among smallholder farmers and found that variables such as income, farm size, and output levels significantly affect decision-making. Although the study focused on enterprise selection, these factors indirectly influence residue management practices by determining resource availability and production priorities. Similarly, Poungchompu et al., (2013) investigated the adoption of rice straw composting and found that education level, participation in training programs, labour availability, and technical knowledge significantly affect adoption. The study highlighted that the labour-intensive and complex nature of composting discourages farmers, but repeated training and awareness programs can positively influence adoption.

Sidhu et al. (2015) reported that the Turbo Happy Seeder technology enables direct drilling of wheat into standing stubble, reducing operational costs by 50-60% compared to conventional tillage. The technology also resulted in higher yields, reduced weed growth, improved soil health, and better environmental outcomes. However, its adoption depends on factors such as proper straw management, availability of machinery, and labour conditions. Kumar et al. (2019) further noted that mechanized harvesting using combine harvesters leaves large quantities of loose straw in fields, which often leads to burning due to the lack of efficient residue management options.

Rosmiza et al. (2014) found that farmers generally have limited knowledge about the diverse uses of crop residues beyond traditional applications such as animal feed and compost. This lack of awareness is attributed to weak agricultural extension systems and limited access to information. Additional constraints identified include inadequate incentives, lack of infrastructure such as baling machines and storage facilities, and insufficient capital. Zuo et al. (2020) emphasized that market efficiency for biomass products also affects farmers' decisions, with wheat straw markets being more efficient compared to paddy straw markets.

Erbaugh et al. (2024) highlight that residue management decisions are influenced by a complex interaction of factors, including machinery access, labour

availability, policy support, and time constraints. The study emphasizes that farmer behaviour cannot be explained solely by awareness levels, as practical constraints often outweigh environmental considerations. Farmer perceptions, such as concerns about pest infestation, delayed sowing, and uncertain yield outcomes, also significantly influence decision-making. These perceptions are shaped by past experiences and must be addressed through participatory approaches and effective extension services.

### 2.6 Externalities due to paddy crop residue burning

Miura & Kanno (1997) estimated that the emissions of trace gases such as $CO_2$, CO, $CH_4$, and $N_2O$ resulting from rice straw burning were measured using the open chamber method. The carbon contained in rice straw was mainly released into the atmosphere as $CO_2$. The percentage of $CO_2$-C emitted in total carbon in rice straw ranged from 57-81 per cent, followed by CO-C (5-9%). Accordingly, the major part of the carbon contained in rice straw was emitted into the atmosphere in the form of $CO_2$. The emissions of $CH_4$ and $N_2O$ were low compared with those of $CO_2$ or CO. The amounts of carbon emitted as $CH_4$ and nitrogen emitted as $N_2O$ were 0.43-0.90 and 1.16-1.50 per cent of those in the original rice straw, respectively. The percentages of $CH_4$-C and $N_2O$-N in total carbon and nitrogen in rice straw were in the range of 0.43-0.90 and 1.16-1.50 per cent, respectively.

Chendrashekhar (2016) reported that air pollution is responsible for increased respiratory morbidity. After the fall harvest, Canadian prairie farmers sometimes burn agricultural residue, straw and stubble in the fields. Smoke from farms around Winnipeg, Manitoba, Canada, a city of about 650,000 people, invades the city and causes widespread complaints from residents. However, due to relatively short exposure, smoke from burning agricultural residue may be more of a nuisance than a serious health hazard. During the 1992 episode, the Lung Health Study (LHS) was conducted. The participants were a well-characterized group with mild to moderately severe chronic airflow obstruction whose lung function and respiratory symptoms were known at the time of the air pollution episode. Assuming that their risk was higher than average, they were surveyed to determine the frequency of pollution-related symptoms and identify characteristics associated with increased susceptibility. It was expected that individuals with respiratory symptoms, more severe airway obstruction, and elevated bronchial hyperresponsiveness (BHR) would be more likely to report breathing difficulties.

Andreae & Merlet (2001) found that average emission factors for many important species, such as CO and $CH_4$ are known with an uncertainty of about 20-30 per cent; however, large uncertainties persist for regional and global fire emissions due to difficulties in estimating the amount of biomass burned. Their estimates, derived from inverse modelling of CO and $CH_4$ budgets, indicated that pyrogenic $CH_4$ emissions (39 Tg/year) agree closely with model estimates (40 ±

12 Tg/year). For different scenarios, CO emissions were predicted to be 483-633 Tg/year (tropical forests), 140-245 Tg/year (savannas), and 0-87 Tg/year (higher latitudes). Total pyrogenic CO emissions were estimated between 663 and 807 Tg/year. These findings imply that total biomass burned annually has an uncertainty range of about ±50% around 8600 Tg dry matter.

Auffhammer et al. (2006) analysed that emissions from burning fossil fuels and biomass lead to the formation of Atmospheric Brown Clouds (ABC) consisting of black carbon and aerosols. These clouds reduce surface radiation and rainfall. Their findings showed that reducing brown clouds and greenhouse gases has complementary positive impacts on rice harvests. These clouds persist over South Asia, affecting regional climate, agricultural productivity, glacial melting, and human health. Biomass burning during wheat and rice harvesting periods adversely affects climate and crop output.

Badarinath et al. (2006) observed agricultural crop residue burning in Punjab using Indian Remote Sensing Satellite (IRS-P6) AWiFS data. The analysis estimated that about 5504 sq. km area was affected by wheat residue burning and 12,685 sq. km by rice residue burning. This resulted in significant greenhouse gas emissions. The study suggested that incorporating residues into the soil in rice-wheat systems is a better mitigation strategy than burning.

Gustafsson et al. (2009) found that emission inventory models suggest biofuel burning contributes 50-90 per cent of emissions, whereas aerosol composition indicates fossil fuel contributions. Using radiocarbon measurements, the study concluded that biomass combustion contributes two-thirds of carbonaceous aerosols and significant portions of black carbon. Both biomass and fossil fuel combustion need to be targeted for air quality improvement.

Kumar and Kumar (2010) estimated the value of health effects of air pollution in rural Punjab, where air pollution problems arise from crop residue burning. A consumer choice model was used to obtain monetary estimates of reducing air pollution levels to safer limits. The total annual welfare loss in terms of health damages due to air pollution caused by the burning of rice straw in rural Punjab amounts to 76 million. When additional factors such as expenses on averting activities, productivity loss due to illness, monetary value of discomfort and utility loss, and increased use of fertilizers, pesticides, and irrigation are considered, the overall losses become substantially higher.

Ramanathan & Carmichael (2008) revealed that black carbon (BC) contributes both directly and indirectly to changes in the earth’s radiative balance and consequently impacts global warming as the second largest contributor after carbon dioxide. One of the major sources of aerosol emissions from biomass burning is the open burning of agricultural residues. The study conducted experiments on open burning both in the field and in controlled chamber conditions to simulate burning and determine emission factors of BC emissions, including

PM2.5, CO, and $CO_2$ through continuous real-time measurement equipment. The emission factor results of BC from open burning experiments in the chamber were reported as 0.79±0.36 g BC/kg dry matter for rain-fed rice residues and 0.72±0.03 g BC/kg dry matter for irrigated rice residues.

Sahai et al. (2011) reported that burning of crop residues in fields is becoming a growing environmental concern in developing countries. Field burning of crop residues contributed about 44 per cent of non-biofuel biomass burning and 14 per cent of total biomass burning in India in the year 2000. The total dry residue generated was estimated at 217, 239, and 253 Tg, of which 45, 60, and 63 Tg of dry biomass were subjected to field burning in the years 1994, 2005, and 2010, respectively. Wheat and rice crops together accounted for about 76 per cent of this burning. The burning of such large amounts of biomass is estimated to emit 22.4, 24.4, and 26.1 Tg of carbon; 0.30, 0.33, and 0.35 Tg of nitrogen; and 4.18, 4.59, and 4.86 Tg of carbon dioxide equivalents of greenhouse gases.

Gupta (2012) conducted a study in the Indo-Gangetic plains region using a sample of farmers from seven districts of Punjab to identify the determinants of emissions from open-field burning of rice residue. The study found that the use of coarse rice varieties, as opposed to fine-grained varieties such as Basmati, increases the likelihood of farmers using combine harvesters, which in turn leads to residue burning. A second sample of users of the Happy Seeder machine was also studied to examine the potential for adoption of this new technology. The Happy Seeder enables planting into loose residues, thereby eliminating the need for burning. However, the results concluded that farmers are slow to adopt this technology, and therefore, it needs to play a more significant role through promotion to reduce residue burning and associated external costs.

Malik & Kumar (2019) describe burning of crop residues as a common approach used worldwide to eliminate agricultural waste after harvesting. The burning of these residues emits gases such as sulphur dioxide ($SO_2$), oxides of nitrogen (NOx), carbon dioxide ($CO_2$), carbon monoxide (CO), black carbon (BC), organic carbon (OC), methane ($CH_4$), volatile organic compounds (VOCs), non-methane hydrocarbons (NMHCs), ozone ($O_3$), and aerosols. These emissions significantly affect global atmospheric chemistry and climate. Crop residue or biomass burning not only influences air quality and climate but also adversely affects human health. The review further suggests alternative management practices that can reduce air pollution and climate risks associated with residue burning.

A study done by Farag et al. (2013) showed that emissions resulting from rice cultivation, including emissions from mechanical operations, field burning, and nitrogen fertilization, were significant. The results indicated that the largest number of emissions originated from Lower Egypt (Nile Delta), where high-emission regions form a rice belt in the northern part of the delta. Methane emissions from flooded rice fields were identified as the primary source of greenhouse gas

emissions, contributing about 53.25 per cent of the total emissions. Rice straw burning after harvesting was the second largest contributor, accounting for 35.82 per cent. Nitrogen fertilization contributed about 9.92 per cent, while mechanical activities contributed approximately 1 per cent. The overall carbon footprint for paddy rice was estimated at 1.90 kg $CO_2$ equivalent per kg of paddy rice.

Pandey & Sahu (2014) found that major species analysed in biomass burning emissions include $C_2H_4$, $C_2H_4O$, $C_2H_6$, $C_2H_6S$, $C_3H_6$, $C_3H_6S$, $C_3H_8$, $C_5H_8$, $CH_3OH$, higher alkenes, terpenes, and toluene compounds. The study highlighted that emissions of volatile organic compounds from biomass burning exhibit large inter-annual variation. Analysis of data on volatile organic compounds in the upper troposphere over India for the year 2008 showed that annual emissions of non-methane hydrocarbons (NMHCs) and $CH_3OH$ varied in the range of 100-470 Gg/year and 46-211 Gg/year, respectively. Biomass sources were categorized into deforestation, fuel wood, forest fires, and agricultural residues. Among these, agricultural residue burning was the dominant source contributing to emissions of $CH_3OH$ (59%), isoprene (80%), and toluene (72%). In contrast, the major sources of NMHC emissions were agricultural residues and deforestation across all years.

Jain et al. (2014) reported a state-wise inventory of crop residue burning in India. The total amount of residue generated in 2008-09 was estimated at 620 Mt, of which 15.9 per cent was burnt on-farm. Rice straw contributed 40 per cent of the total residue burnt, followed by wheat straw (22%) and sugarcane trash (20%). Burning of crop residues emitted 8.57 Mt of CO, 141.15 Mt of $CO_2$, 0.037 Mt of $SO_2$, 0.23 Mt of $NO_2$, 0.12 Mt of $NH_3$, 1.46 Mt of NMVOC, 0.65 Mt of NMHC, and 1.21 Mt of particulate matter during the year 2008-09. The study also observed a variability of 21.46 per cent in annual emissions of air pollutants from 1995 to 2009.

## 2.7 Constraints in the adoption of environment-friendly management practices

Gupta (2012) reported that crop residue burning causes significant nutrient and resource losses while adversely affecting soil properties, and emphasized the need for improvements in harvesting technologies and residue management systems. They attributed open field burning of crop residues to the use of combine harvesters, which leave a large amount of loose residue on the field. Burning of straw also emits large amounts of particulates composed of a wide variety of organic and inorganic species. It was observed that burning one tonne of straw releases 3 kg particulate matter, 60 kg CO, 1460 kg $CO_2$, 199 kg ash and 2 kg $SO_2$. A major constraint in the rice-wheat cropping system is the short time interval between rice harvesting (late October and early November) and sowing of wheat, due to which farmers find it difficult to utilize the residue and therefore opt for burning.

Rahman et al. (2005) conducted an experiment in a research farm and reported that wheat cultivation in no-till soil of a post-rice harvest field utilizes residual soil moisture and reduces the time period between rice harvest and wheat seeding in intensive rice-wheat cropping systems. However, major constraints in no-till wheat production include high weed infestation and poor crop establishment. Rice straw mulching had a significant effect on conserving initial soil moisture and reducing weed growth. Root length density and root weight density of wheat were positively influenced by both straw mulching and nitrogen levels. Application of nitrogen at 120 kg/ha along with straw mulch was found to be suitable for no-till wheat under experimental field conditions.

Döring et al. (2005) analysed that the application of straw mulch to organic seed potatoes (*Solanum tuberosum* L.) has been shown to reduce virus incidence. To determine the associated agronomic effects, straw mulch was applied at 2.5-5 t/ha and its effects on soil nitrate dynamics, weed development, tuber yield and soil erosion were studied. Under the edaphic and climatic conditions of the study (loamy silt soils and temperate climate) and with light to moderate quantities of straw, yield was not affected by straw mulching. This indicates that straw mulch can provide benefits such as virus vector control and soil erosion reduction without negatively affecting yield.

Tirol-Padre et al. (2007) revealed that decomposed organic matter was used in rice-wheat crop production under normal soil conditions (Organic C = 0.33%, Available P = 5.72 $\mu g/g^{-1}$, K = 5.7 cmolc $L^{-1}$, $pH_s$ = 8.19, $EC_e$ = 2.35 dS $m^{-1}$ and SAR = 7.20). Compost at 12 and 24 t/ha was applied with and without chemical fertilizers (Rice: 100-70-70 and Wheat: 140-110-70 NPK kg/ha) to study its effects on crop yield. The grain yield and yield components (plant height, number of fertile tillers and 1000 grain weight) of both rice and wheat increased significantly with the application of organic material in the form of compost at both levels. The combination of compost with chemical fertilizers further enhanced biomass and grain yield, proving to be more economical than other treatments. Based on these results, it was recommended that farmers compost crop residues and apply them to soil for sustainable crop production.

Chhokar et al. (2009) studied the effect of straw retention and burning on *Phalaris minor* control. A survey conducted in the rice-wheat system revealed that a majority of farmers (65%) were burning rice straw in the north-western Indian plains. For sustainability of the rice-wheat system, it was suggested that residues should be retained on the surface or incorporated into the soil rather than burned. Surface retention of rice residue at 5.0 and 7.5 t/ha reduced weed dry weight in wheat by 23.4-30.3% and 35.5-44.1%, respectively. However, yield and weed control were lower under residue retention without herbicide use compared to treatments with herbicides. Therefore, efficient weed management strategies are required under residue retention systems.

Gupta (2012) reported that regulation of emissions from open field burning of rice residue in Punjab requires understanding the determinants of residue burning. The study found that the use of combine harvesters was the most important factor influencing farmers' decision to burn rice residue, which in turn was determined by the type of rice variety cultivated. Residue burning occurs mainly due to the lack of machinery for sowing into loose residues. The development of the Happy Seeder, a tractor-mounted machine that allows sowing of wheat directly into rice residues, provides a low-cost alternative to open field burning compared to conventional tillage systems.

Haider (2013) found that straw length, low elevation land, and distance of the plot from the homestead positively and significantly influence the decision to burn rice residue, whereas residue price has a negative effect. Farmers who burn residue obtain a net annual benefit of USD 43-45 per acre compared to those who do not burn. This benefit arises due to approximately 9% higher productivity in burned fields and about 10% lower harvesting costs including residue burning.

Bhatia et al. (2012) assessed emissions inventory considering incremental greenhouse gas emissions from rice straw management practices and reported that rice residues contribute around 16 Mt $CO_2$-equivalent emissions considering only $CH_4$ and $N_2O$, accounting for approximately 8% of total projected emissions for 2008. Farmers indicated that incorporating both stubble and straw into the soil 30 days before crop establishment is the most cost-effective option, with a negative abatement cost (benefit) of Php 21 (US$ 0.50) per ton $CO_2$-equivalent reduction. However, incorporating residues less than a month before cultivation slightly increases emissions. Rapid composting and incorporation of composted straw significantly reduces emissions but involves higher costs, making it the second most cost-effective option.

Jain et al. (2014) analysed that open-field burning of agricultural residues emits smoke, black carbon and greenhouse gases while causing loss of plant nutrients. A payment-based experiment conducted with 317 farmers in rural Nepal showed that 167 farmers participated after quoting below a cutoff value, and more than 86% adhered to the agreement of not burning residues. The average willingness to accept compensation to avoid residue burning was Rs. 5592 per hectare. The study suggested technological and policy interventions to reduce burning practices.

Kumar et al. (2018) reported, based on a three-year study, that a rice-wheat cropping system producing 7 t/ha rice and 4 t/ha wheat removes more than 300 kg N, 30 kg P and 300 kg K per hectare from the soil. Farmers face challenges in managing 7 t/ha rice residues before wheat planting. Burning of residues leads to significant nutrient losses, including up to 75% nitrogen, 25% phosphorus and 21% potassium. In contrast, incorporation of residues from both crops improves soil nutrient availability and enhances soil fertility.

Ahmed et al. (2015) studied that burning of crop residues has multiple negative effects, including local air pollution, increased black carbon emissions, and contributions to regional and global climate change. In Punjab, complete burning of rice residue is the most common practice, followed by removal for use as animal feed. Complete residue removal costs approximately PKR 4586 (US$ 55) per acre, which is about 34% higher than burning. Therefore, farmers would require subsidies to adopt alternatives to residue burning.

Gupta (2014) studied the determinants of emissions from open-field burning of crop residues using primary field data and evaluated the effectiveness of a new seeding machine that enables sowing without burning residues. The study found that the new technology reduces field preparation costs without significantly affecting crop yield or profits. The use of plot-level data with farmer fixed effects ensured reliable estimation of impacts. Considering the adverse effects of burning on health and mortality, the results suggest that adoption of such technology can reduce emissions at zero private cost and negative social cost. However, due to lack of strong private incentives, policy support through subsidies and extension services is necessary.

Roy & Kaur (2015) studied paddy straw management practices in major paddy-growing districts of West Bengal and found that 100% of farmers used paddy straw as animal feed, followed by use for thatching. All farmers were aware of its use for feed, cooking and packing purposes, but very few were aware of its industrial applications such as in paper mills and power generation. The study emphasized the need for capacity building among scientists, farmers and stakeholders, along with strengthening extension services, institutional linkages and collaborations at national and international levels to improve straw management practices.

## 2.8 Policy interventions and institutional challenges

Government policies have been central to efforts aimed at reducing stubble burning. Initiatives such as the Crop Residue Management (CRM) scheme provide subsidies for machinery and promote sustainable practices. Kemanth et al. (2024) reports that Punjab has made significant investments in scaling up residue management technologies. However, several studies argue that subsidies alone are insufficient. Gandhi (2024) highlights that financial incentives must be complemented by technical training, extension support, and trust-building measures. Weak coordination among institutions further limits policy effectiveness. The literature suggests that stubble burning is a governance challenge requiring multi-level coordination among stakeholders, including farmers, government agencies, industries, and local institutions. Policies must address not only environmental goals but also farmer livelihoods and economic realities. According to (Bhuvaneshwari et al., 2019), there are new laws and creative ways to reduce stubble burning, like encouraging the manufacture of biofuel from crop leftovers in

other ways and putting conservation agriculture into practice. Singh & Kaur (2023) discussion of the adoption patterns of agricultural machinery-based solutions highlights the possibility for scalable interventions and provides useful insights into Punjab's in-situ management practices.

## 2.9 Crop diversification and Structural alternatives

This section is included as background and context. Crop diversification is discussed because several of the reviewed studies, and some interview respondents, treat it as a long-term structural response to residue burning. The thesis itself, however, finds that diversification is not a realistic short-term option for most farmers under current procurement and market conditions (Section 4.6), so the analytical focus remains on residue management, machinery access and institutional support.

Holling & Gunderson (2001) emphasized that although alternative crops to rice and/or wheat, if selected appropriately, can significantly reduce residue burning as well as water use, any highly specialized agricultural system may still face similar vulnerabilities such as crop failure, demand shocks, and price fluctuations. Therefore, such systems may not necessarily provide a resilient solution for the agricultural sector. Crop diversification is often regarded as a win-win strategy from both environmental and socio-economic perspectives Chhatre et al. (2016) however, pathways for diversification in Punjab are complex and require substantial state support in terms of infrastructure development and skill enhancement to ensure long-term sustainability and to prevent farmers from bearing the associated risks. Historical attempts at crop diversification in Punjab, recommended as early as 1986 and revisited in 2002, with intermittent implementation phases between 2002-2006 and again from 2014, have largely failed due to two major reasons: firstly, alternative crops generally provide lower economic returns compared to the rice-wheat system, despite the availability of minimum support prices; and secondly, the economic benefits of water savings are not realized by farmers, as electricity for irrigation remains subsidized or free. Consequently, while diversification may offer long-term societal benefits, it does not currently provide a viable short-term economic pathway for farmers without income loss(Department of Agriculture & Cooperation, 2014) .Achieving significant adoption of diversified cropping systems in Punjab will require restructuring existing incentives that reinforce the rice-wheat system. The 2020 farm acts failed to bring about such a transformation, highlighting both the entrenched nature of the system and the importance of decentralized decision-making in India's democratic framework, where top-down reforms often face resistance if local concerns are not adequately addressed.

Downing et al. (2022) proposed basmati cultivation as a potential alternative to non-basmati rice to mitigate residue burning. Basmati residues are typically not

burned in Punjab, as the crop is largely harvested manually, making the leftover stems easier to incorporate into the soil. Additionally, basmati straw contains lower silica content, making it more suitable as animal fodder, thereby promoting on-farm utilization and reducing residue disposal issues. However, a complete shift to basmati is unlikely to fully resolve the problem of residue burning. If production is scaled up to match that of non-basmati rice and similar time constraints between cropping cycles persist, basmati cultivation may also become prone to residue burning, as observed in neighbouring Pakistan(Ahmed et al., 2015). Nevertheless, basmati can serve as a useful model for understanding how policy, trade dynamics, and market-driven systems can influence residue management practices. As a premium commodity not regulated under the Essential Commodities Act, basmati offers an opportunity to explore sustainability interventions within corporate and financial frameworks.

This is directly relevant to the present study because the less reliance on rice-wheat rotation would result in lesser amount of paddy residue during the narrow post harvest period, thus putting less time pressure on farmers to burn. The article Downing et al. (2022) argued that reducing dependence on the rice-wheat system can significantly decrease residue generation and environmental stress. Diversification towards crops such as maize, pulses, and oilseeds has the potential to improve soil health, reduce water consumption, and enhance biodiversity. However, successful adoption of these alternatives depends heavily on factors such as market support, procurement systems, and farmer confidence.

Rosenberg et al. (2025) revealed that although crop diversification is widely promoted as a solution to global agricultural challenges, its economic viability compared to high-yield monoculture systems remains insufficiently understood. Using grower focus groups and Monte Carlo simulations, their study evaluated the transition from continuous rice (*Oryza sativa* L.) to diversified cropping systems involving tomato (Solanum lycopersicum L.), sunflower (*Helianthus annuus* L.), beans (*Phaseolus vulgaris* L.), and safflower (*Carthamus tinctorius* L.) in California. The findings indicated that crop diversification can enhance long-term profitability; however, its adoption is constrained by factors such as initial investment requirements, labour demands, risk, opportunity costs, and market access. The study highlighted the need for supportive policies and incentives to overcome these barriers.

Gawdiya et al. (2025) showed, in a global review, that crop diversification plays a crucial role in supporting natural agroecosystem processes and enhancing biodiversity in agricultural landscapes. Despite strong scientific evidence supporting its ecological and economic benefits, the adoption of diversification practices remains limited. This gap is influenced by factors such as farmer attitudes, governance structures, policy incentives, and market acceptance. The study emphasized that effective agronomic interventions require a shift in subsidy

frameworks toward promoting biodiversity, sustaining high yields, and encouraging soil-focused agricultural practices. Furthermore, achieving landscape-level diversification and restoring ecological balance necessitates strong institutional support, collaborative networks, and knowledge dissemination. Crop diversification thus contributes to improved yield stability, environmental resilience, and long-term profitability, making it a critical strategy for sustainable agriculture. The study concluded that scaling up diversification practices is essential for biodiversity conservation, climate change mitigation, and transforming global food systems, calling for urgent attention from policymakers and researchers to facilitate an ecological paradigm shift in agriculture.

In the rice-wheat system of Punjab and neighbouring Haryana specifically, several field-based studies point to concrete diversification options: replacing paddy with maize, pulses or short-duration legumes such as mung bean has been shown to cut irrigation water use, energy input and greenhouse gas emissions while improving farm profitability and soil organic carbon compared with the conventional rice-wheat rotation (Dhanda et al., 2022). More targeted agronomic work on maize-based rotations in the same region similarly reports gains in system productivity and soil health relative to rice-wheat (Mal & Chaudhary, 2024).

## 2.10 Conceptual framework

Building on the literature reviewed in this chapter, Figure 3 presents the conceptual framework that guides the analysis in this thesis.

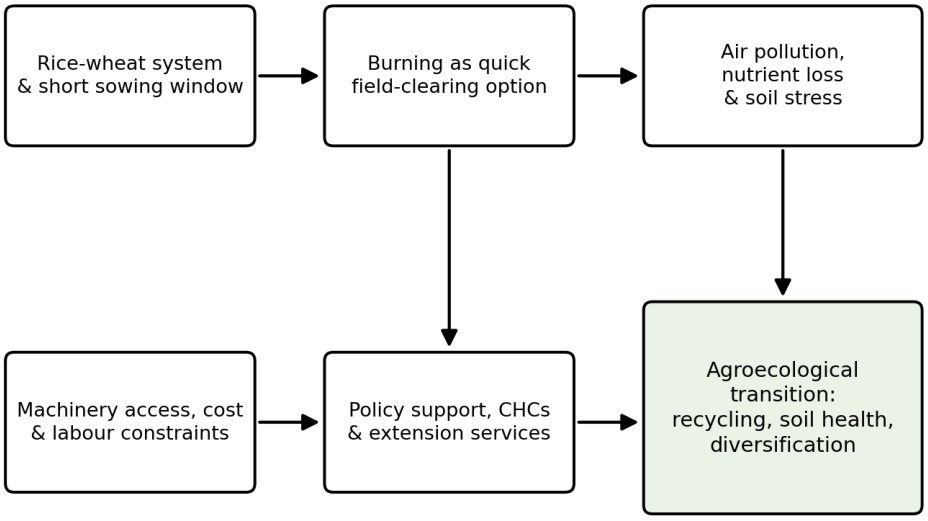



*Figure 3. Conceptual framework linking stubble burning, constraints and agroecological transition. Source: Author, based on Gliessman (2015), Downing et al. (2022) and Erbaugh et al. (2024).*

The framework summarises the argument developed in this thesis: the rice-wheat system and its short sowing window make burning an attractive quick-

clearing option, which in turn drives air pollution and soil stress. These environmental pressures, together with constraints in machinery access, cost and labour, create the conditions under which policy support, Custom Hiring Centres and extension services become decisive. Where this institutional support is adequate, it can enable an agroecological transition characterised by residue recycling, improved soil health and crop diversification; where it is weak, burning remains the default practice. The framework therefore treats stubble burning not as an isolated behaviour but as an outcome of the wider agroecological system, which is the perspective used to interpret the findings in Chapter 4.

The framework is used in Chapter 4 to organise the interpretation of the interview material. Theme one (environmental awareness and soil concerns) corresponds to the air-pollution, nutrient-loss and soil-stress box; Theme two (time pressure and economic decision-making) to the rice-wheat system and short sowing window; Theme three (machinery access) to the machinery, cost and labour constraints; Theme four (policy support, subsidies and institutional trust) to policy support, Custom Hiring Centres and extension services; and Theme five to the agroecological transition. Section 4.7 returns to the framework to assess how far the empirical findings support it.

## 3. Materials and methods

For this specific study, semi-structured interviews were conducted with farmers and other stakeholders in selected districts of Punjab, reviewing relevant policy documents, and situating the findings within the existing literature on stubble burning and residue management, in order to address the four objectives, set out at the end of Chapter 1. In this chapter, I explain the various methods and procedures that were followed to investigate the problem, under the following sub-head:

### 3.1 Study area

The study was conducted in three districts of Punjab: Ludhiana, Sangrur and Mansa (Figure 4). All three lie in Punjab's rice-wheat belt, where paddy cultivation and stubble burning are prominent. The districts were selected because they represent areas with intensive rice cultivation, frequent residue-burning incidents, availability of residue-management technologies, and feasible access to stakeholders for field data collection. Ludhiana is the location of Punjab Agricultural University (PAU) and a large number of agricultural institutions and machinery providers; Sangrur is one of the districts in which high numbers of fire incidents have been recorded (PRSC, 2024); and Mansa has been the setting of earlier residue-management studies (Singh et al., 2022). Interviews with policy and institutional stakeholders were additionally held at the Department of Agriculture and Farmers' Welfare in Chandigarh.

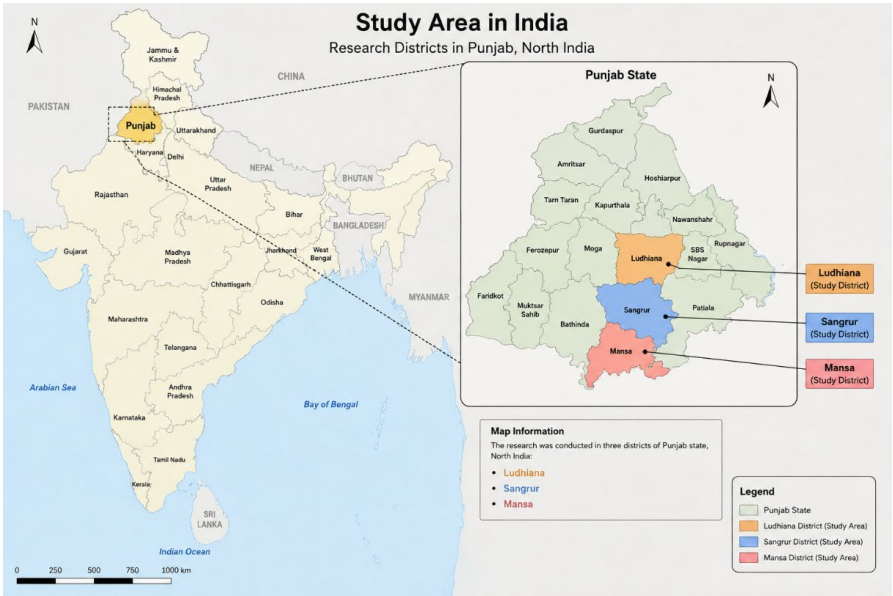



*Figure 4. Schematic locator of the study interview districts (Ludhiana, Sangrur and Mansa).*

## 3.2 Research design

The study used a qualitative research design. Qualitative research is suitable here as it enables rich and contextual information on farmers' and stakeholders' perceptions, decision-making processes and real experience of stubble management to be collected which could not be captured in numerical form(Creswell & Poth, 2016). This is directly relevant to the aims of the thesis as it seeks to gain an understanding of the environmental impacts of stubble burning (Objective 1) as well as the socio-economic reasoning behind the farmer's decision making (Objective 2), the experience of stakeholders of policy and institutional support (Objective 3) and the practical context specific basis required to make recommendations (Objective 4). A qualitative approach was well suited to this study because the research questions focused on understanding how farmers, machinery providers, and officials perceive stubble burning, explain their decisions, and evaluate alternative residue-management practices in relation to their own constraints and experiences. The interview-based design allowed me to collect detailed first-hand accounts of field realities, institutional challenges, and practical trade-offs that would not have been visible through survey numbers alone.

## 3.3 Data collection methods

### 3.3.1 Semi-structured interviews

Semi-structured interviews were conducted between 15 October and 12 November 2025. A total of 30 stakeholders were interviewed across three districts of Punjab (Ludhiana, Sangrur and Mansa) and in Chandigarh. The sample included 18 farmers, four machinery providers two staff of Custom Hiring Centres and 2 private machinery providers), four agricultural extension officers, and four policy/institutional stakeholders (two from the Department of Agriculture and Farmers' Welfare, one from Punjab Agricultural University and one from an agricultural research institute). Among all respondents, 25 were male and five were female. Respondents ranged in age from 28 to 67 years. Farmer participants represented small (<2 ha), medium (2–5 ha) and large (>5 ha) landholdings, enabling comparison across different farm contexts: 3 small, 9 medium and 6 large farms. The distribution of participants by stakeholder category and district is summarised in Table 3.1, and their gender and age group in Table 3.2.

**Table 3.1. Number of interview participants by stakeholder category and district**

| Stakeholder category | Ludhiana | Sangrur | Mansa | Chandigarh | Total |
|---|---|---|---|---|---|
| Farmers | 6 | 6 | 6 | – | 18 |
| Machinery providers / Custom Hiring Centre (CHC) representatives | 2 | 1 | 1 | – | 4 |
| Agricultural extension officers | 2 | 1 | 1 | – | 4 |

| Stakeholder category | Ludhiana | Sangrur | Mansa | Chandigarh | Total |
|---|---|---|---|---|---|
| Policy and institutional stakeholders | 1 | – | – | 3 | 4 |
| **Total** | **11** | **8** | **8** | **3** | **30** |

Note: Machinery providers/CHC representatives comprise 2 CHC staff and 2 private machinery providers. Policy and institutional stakeholders in Ludhiana represent Punjab Agricultural University (PAU), which is located in Ludhiana; those in Chandigarh represent the Department of Agriculture and Farmers' Welfare (two) and an agricultural research institute (one).

**Table 3.2. Gender and age group of interview participants by stakeholder category**

| Stakeholder category | Female | Male | 28–39 yrs | 40–49 yrs | 50–59 yrs | 60–67 yrs |
|---|---|---|---|---|---|---|
| Farmers (n = 18) | 3 | 15 | 5 | 6 | 4 | 3 |
| Machinery providers / CHC (n = 4) | 0 | 4 | 1 | 2 | 1 | 0 |
| Extension officers (n = 4) | 1 | 3 | 1 | 2 | 1 | 0 |
| Policy / institutional (n = 4) | 1 | 3 | 1 | 1 | 2 | 0 |
| **Total (n = 30)** | **5** | **25** | **8** | **11** | **8** | **3** |

Note: Farm size of the 18 farmers: 3 small (<2 ha), 9 medium (2–5 ha) and 6 large (>5 ha). At least nine farmers are described as medium-scale and five as large-scale in the quotations in Chapter 4.

The interviews were designed to obtain in-depth qualitative information regarding experiences with stubble burning and the adoption of alternative crop residue management practices. The discussions focused on multiple dimensions, including economic costs associated with residue management practices, perceived agronomic and environmental risks, accessibility and availability of machinery such as the Happy Seeder and Super Straw Management System (Super SMS), and the extent of training and extension support received by farmers.

### 3.3.2 Semi-structured interview guide

The semi structured interviews were conducted using an interview schedule, which included broad themes and open-ended questions, as opposed to a pre-determined questionnaire. The content of questions was tailored to meet the needs of the respondents with each question tailored according to the respondents' role (e.g., for farmers, the questions were tailored to obtain information relevant to their farming activities; for machinery providers, to obtain information relevant to their role and activities; and for extension officers and policy stakeholders). The following themes were covered in interviews: The full interview guide is provided in Appendix C.

- Experience of Participants on paddy residue management.
- Reasons for stubble burning or not.

- Awareness and perceptions regarding impacts of residue burning on environment and soil health.
- Experience with sustainable residue management practices, such as residue incorporation, mulching, biomass utilization, baling, and Happy Seeder/Super SMS.
- Economics factors such as costs of machinery, labour, profitability of other practices.
- Government Subsidies, Custom Hiring Centres & Extension Services Accessibility and effectiveness.
- Institutional and policy considerations that can affect residue management decisions.
- Challenges for the uptake of sustainable residue management technologies.
- Recommendations for the sustainable crop residue management in Punjab.

Interview Guide varied slightly between stakeholder groups. The main themes discussed in farmer interviews were farm-level decision-making, residue management, production constraints, and economics. Questions regarding machinery demand, availability, challenges, and farmer adoption were asked of the machinery providers. The farmer awareness, farmer extension and challenges in implementation were discussed with extension officers. Policy and institutional issues regarding government policies, subsidy programmes, institutional coordination, enforcement mechanisms and future policy directions were explored with policy and institutional stakeholders.

All of the interviews were in Punjabi, using the Hindi and English languages where necessary to enable communication with institutional respondents. The interviews were conducted for about 35-60 minutes, depending on the availability of the interviewees and the extent of discussion.

The majority of interviews (24 out of 30) were audio-taped, with informed consent of the participant, with a digital recording device or even with a cell phone. Handwritten field notes were done in detail for participants who did not want to be recorded and then expanded immediately after the interview. Audio recordings were transcribed and/or translated into English verbatim for analysis as needed. Interviews were transcribed and the audio files and field notes were given anonymous identification codes (e.g., Farmer A, Extension Officer B) and recorded in password-protected electronic folders that were kept by the researcher only. Transcripts were de-identified to protect participants' privacy.

Further, information was gathered on the role and effectiveness of government subsidies in influencing farmers' decisions regarding residue management practices. Respondents were also encouraged to share their perceptions of

existing policy frameworks, institutional support mechanisms, and the practical constraints faced in adopting sustainable alternatives to stubble burning. The semi-structured nature of the interviews allowed flexibility in probing emerging issues while maintaining consistency in the core thematic areas across all respondents.

### 3.3.3 Policy document review

The policy document review took place both prior to and during the interview phase. Relevant national and state policy documents were identified primarily through official government and institutional websites and published reports, including the Department of Agriculture and Farmers' Welfare, Government of Punjab, Punjab Agricultural University (PAU), the Government of India and the Commission for Air Quality Management (CAQM). Documents available through official online repositories were downloaded and reviewed for policy objectives, subsidy arrangements, machinery-support provisions, enforcement measures and crop-diversification initiatives. Documents identified during the interview period were added where they helped clarify issues raised by participants.

The review involved following documents: Crop Residue Management (CRM) Scheme guidelines, Department of Agriculture and Farmers' Welfare (Government of Punjab) reports, publications from the Punjab Agricultural University (PAU), reports of the Commission for Air Quality Management (CAQM) and other pertinent policy reports and technical documents on stubble burning, sustainable residue management, machinery subsidy and crop diversification. The data acquired from the policy document review was merged with the data acquired from the interviews in the analysis process by a data triangulation technique. The information collected from policy documents was analysed and compared to the experiences and perceptions of stakeholders to understand where there was common ground, difference and gaps in implementation. For instance, policy aims and subsidy arrangements as presented in official documents were reviewed, and farmers' experiences with obtaining machinery, extension and financial assistance were sought, and the views of extension officers and policy stakeholders were used to provide insights into policy implementation challenges. This integration allowed for a holistic view of the environmental, socio-economic and institutional aspects of sustainable stubble management and supported the credibility and validity of results of the study.

### 3.3.4 Literature review

An extensive and structured review of literature was carried out to develop a strong theoretical and empirical foundation for the study. Peer-reviewed journal articles, books, institutional reports, conference proceedings, and technical bulletins related to crop residue management, sustainable agriculture, air pollution, and environmental impacts of stubble burning were examined.

The literature review helped in identifying global and national trends, synthesizing existing scientific evidence, and highlighting research gaps in the area of residue management practices. It also provided a comparative framework for evaluating field-level findings against previously documented studies.

Furthermore, the literature review supported the interpretation of results by situating the study within the broader scientific and policy discourse on sustainable agricultural practices and environmental conservation.

### 3.4 Sampling strategy

A purposive sampling technique was adopted because the study required participants with direct knowledge or practical experience of crop-residue management. The sample included both farmers who practised stubble burning and farmers who used alternative residue-management practices. After the initial purposive interviews, participants were asked to suggest other individuals with relevant experience, and snowball sampling identified a further eight respondents: five farmers, one machinery provider, one extension officer and one Custom Hiring Centre (CHC) representative. In total, 22 respondents were therefore recruited purposively and eight through referral. Each referred participant was contacted separately and invited to participate voluntarily. Recruitment continued until the interviews provided sufficient diversity of perspectives and no substantially new themes were emerging. Additional stakeholders were drawn from CHCs and district agriculture offices in Ludhiana, Sangrur and Mansa, as well as from Punjab Agricultural University (Ludhiana) and the Department of Agriculture and Farmers' Welfare in Chandigarh.

CHC representatives and private machinery providers were distinguished during recruitment because their incentives differ: CHC staff run centres established with public support (Section 2.8), whereas private providers offer machinery services as a commercial activity. The final sample contained four respondents in this combined category, 2 CHC staff and 2 private machinery providers (Table 3.1). Because the group is small, their accounts are reported together under the heading 'machinery providers' in Chapter 4, and this is acknowledged as a limitation in Section 5.3.

### 3.5 Sample size determination

The sample size was determined by the qualitative objectives, the heterogeneity of stakeholders involved in crop-residue management, and information adequacy rather than by a statistical sample-size formula (Patton, 2002). Data collection continued until the researcher judged that additional interviews were no longer producing substantially new themes. The final sample comprised 18 farmers (eight

primarily practising burning and ten using one or more alternative residue-management practices), four machinery providers (CHC staff and private providers; see Section 3.4), four agricultural extension personnel and four local administrative or policy stakeholders. This distribution allowed comparison between technology adopters and non-adopters and between farm-level, service-provider, extension and policy perspectives.

### 3.6 Data analysis

The qualitative data were analysed using thematic analysis, carried out manually with Microsoft Word and Microsoft Excel. These two tools were chosen deliberately: they were readily available to me and familiar from everyday use, they carry no licence cost (unlike commercial qualitative-analysis packages such as NVivo or ATLAS.ti), and with a data set of 30 interviews they were sufficient for transcription, coding and comparison. Interview transcripts and field notes were first read repeatedly for familiarisation, followed by initial coding of recurring ideas and concepts. Word was used for transcript preparation and Excel for organising codes, comparing respondents and grouping related codes into broader themes. The preliminary coding included cost of residue management, time constraints, machinery access, soil-health impacts, policy trust and awareness, training and extension support, subsidy experiences, labour availability, risk perception and perceived ecological benefits. Codes were then grouped into environmental, socio-economic and policy/institutional themes. The coding hierarchy and the number of respondents associated with each code are presented in Appendix A.

No other analysis software or statistical method was used. The frequencies reported in Chapter 4 (for example, 27 of 30 respondents) are simple counts of the respondents who raised a given issue, tallied in Excel; no inferential statistics were applied, because the purposive sample is not statistically representative and the aim was to understand and explain rather than to generalise. This was a methodological choice, and it has limitations. Manual coding provides a less formal audit trail and fewer retrieval and query functions than dedicated software; coding was carried out by a single researcher, so inter-coder reliability could not be assessed; and the counts should be read as an indication of how widespread an issue was among respondents, not as population estimates. These limitations were partly offset by triangulating the interview findings with the policy documents and the literature (Sections 3.3.3 and 3.3.4).

This thematic structuring helped in systematically interpreting the relationships between farmer behaviour, institutional support systems, and environmental outcomes. Finally, the identified themes were critically analysed and interpreted in relation to the research objectives and existing literature. This facilitated comparison between field-level evidence and previously reported studies, thereby strengthening the validity and depth of the findings.

## 3.7 Ethical considerations

Ethical guidelines were strictly followed throughout the study to ensure the protection of respondents and the integrity of the research process. Before data collection, all participants were clearly informed about the purpose, scope, and objectives of the study. They were also briefed about how the collected information would be used for academic and research purposes. Participation in the study was entirely voluntary, and no respondent was coerced or pressured to take part. The participants were assured that they had the full right to refuse participation or withdraw from the interview at any stage without any consequences. To maintain confidentiality and protect privacy, the identities of all respondents were kept anonymous. Personal identifiers were not recorded in the thesis, and codes were used instead of names during data analysis and reporting. Furthermore, all collected data were used strictly for academic purposes only. The data were stored securely and handled with care to prevent unauthorized access, ensuring responsible data management throughout the study.

# 4. Results and discussion

## 4.1 Introduction to the findings

This chapter presents the findings from the qualitative material and interprets them in relation to the project plan, literature review and agroecological framework. The analysis is organized around themes that appeared repeatedly across stakeholder accounts and the reviewed policy material. The aim is not to defend one group against another, but to understand how environmental harm, farmer decision-making, technology access and policy systems interact in the real conditions of Punjab agriculture.

A central finding is that residue burning is widely recognized as environmentally harmful, yet it remains embedded in the crop calendar and economic organization of the rice-wheat system. This means that a purely moral or enforcement-based explanation is too narrow. The evidence points instead to a system in which many farmers are aware of the risks but still face strong practical pressures during the short period between paddy harvest and wheat sowing. The themes below are organised in a sequence based on the objective of the study; Theme 1 has a strong focus on Objective 1 (environmental impacts), Theme 2–4 on Objectives 2 and 3 (socio-economic factors and policy/institutional support) and Theme 5 on Objective 4 (agroecologically informed recommendations).

The interpretation of the themes is guided by the conceptual framework in Figure 3 (Section 2.10), and the national decline in burning incidents shown in Figure 1 (Section 2.3) provides the backdrop against which respondents' accounts of changing practice should be read.

## 4.2 Theme one: environmental awareness and soil concerns

Environmental awareness was evident across the respondent groups. Twenty-seven of the 30 respondents (90%) mentioned smoke emissions as an immediate effect of stubble burning: 16 farmers, all four extension officers, all four policy/institutional stakeholders and three machinery providers (Figure 6). Twenty-one respondents (70%) reported poor road visibility during the post-harvest season, including 13 farmers, four extension officers, three policy stakeholders and one machinery provider. Twenty-four respondents (80%) described breathing discomfort or related symptoms such as coughing and eye irritation; these included 15 farmers, all four extension officers, all four policy stakeholders and one machinery provider. Twenty-five respondents (83%) referred to seasonal deterioration in air quality, including 15 farmers, all four extension officers, all four policy stakeholders and two machinery providers. The consistency across stakeholder categories indicates that the environmental consequences of burning

were widely recognised, although respondents differed in how they weighed these consequences against production risks.

These environmental effects, and the share of respondents who identified each one, are summarised in Figure 5.

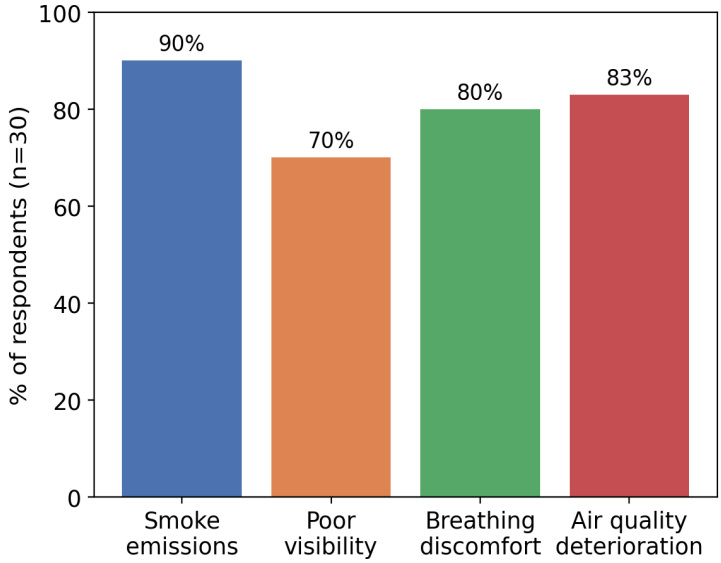



*Figure 5. Environmental effects of stubble burning identified by respondents (n=30)*

While the majority of the respondents recognized the environmental effects of burning residue, three respondents were more qualified in their opinion. Two large-scale farmers from Ludhiana and Sangrur said that burning was unavoidable due to the short duration between paddy harvest and wheat sowing, and that the environmental impacts did not outweigh the benefits of getting the fields ready in time so as not to lose out on wheat sowing. One machinery provider felt that while burning was a factor of air pollution, emissions from transport, brick kilns and industrial activities were also significant causes of seasonal air quality degradation. Such respondents thus saw stubble burning as being only one part of a larger environmental issue than its main cause. These observations are consistent with studies showing that burning contributes to particulate emissions and regional air pollution in the Indo-Gangetic Plain (Badarinath, Chand and Prasad, 2006; Downing et al., 2022; Sidhu et al., 2024).

The size of the soil was also significant. In all, 77% (23/30) of the respondents talked about the impact of stubble burning on soil health. This comprised 14 out of 18 farmers (78%), all four agricultural extension officers (100%), all four policy and institutional stakeholders (100%) and one machinery provider (25%). Most often, respondents reported that burning led to a loss of soil organic matter, loss of beneficial microorganisms and increased reliance on chemical fertilizers with time. Farmers practicing alternative residue management were more likely to report better soil structure and soil moisture retention than those who burned residues.

Figure 6. shows how these soil-health concerns were distributed across the stakeholder groups.

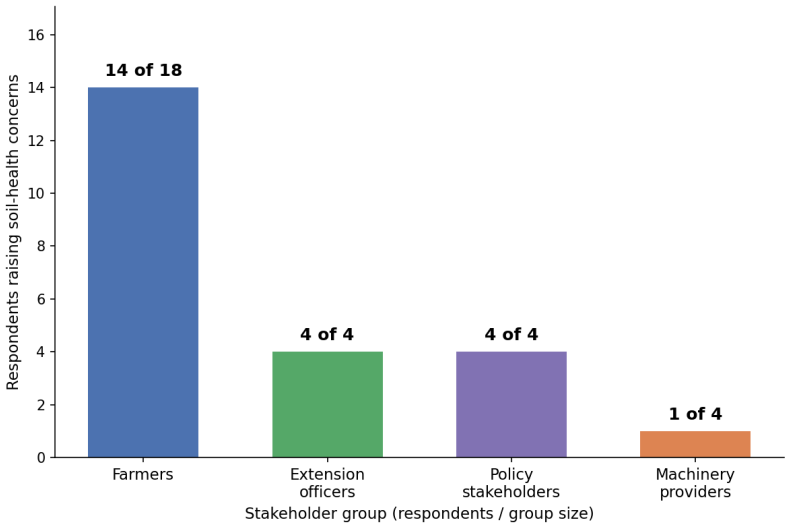



*Figure 6. Respondents raising soil-health concerns, by stakeholder group (23 of 30 respondents in total).*

Soil concerns were raised by all extension officers and policy stakeholders and by most farmers (14 of 18), but by only one of the four machinery providers, which is unsurprising given that their work centres on machine supply rather than field outcomes. The pattern is consistent with the agronomic literature summarised in Section 2.4.1 and Table 2.1, in which residue retention and incorporation raise soil organic carbon and nutrient availability (Surekha et al., 2003; Yadvinder-Singh et al., 2004), and with the nutrient losses from burning reported by Mohanty (2004) and Kumar et al. (2018). It also matches the framework in Figure 3, in which air pollution and soil stress are the environmental pressures that make the case for a transition.

A farmer from Ludhiana who has taken the happy seeder initiative for adoption explained:

*"I feel that since I am no longer burning and keeping straw in the field the soil remains moist for longer and the wheat crop establishment is good. I also feel that I need to apply slightly less fertilizer than previously." (Farmer, Ludhiana; Happy Seeder user)"*

Likewise, an agricultural extension officer from Sangrur commented:

*"It erodes away precious organic matter and soil micro-organisms, and farmers only realize the short-term benefit, and the long-term impact on soil fertility is significant." (Extension Officer, Sangrur)*

A representative of the Department of Agriculture also highlighted the need for soil conservation:

*“It is important to know that residue is not a waste but can be used as a resource as it contributes to nutrient cycling and enhances soil health if managed appropriately.” (Policy Stakeholder, Chandigarh)*

Some respondents, however, did not see soil degradation as a top priority issue. Four farmers who still carried on residue burning stated that the benefits of the residue burning were not significant when compared to the urgency of getting the field ready for wheat sowing.

Twenty-three of the 30 respondents (77%) raised soil-health concerns, while 20 respondents (67%) specifically mentioned nutrient loss or reduced nutrient recycling when residues were burned. Farmers who had used residue retention or incorporation tended to describe these benefits in practical terms.

A farmer from Mansa who continued burning acknowledged the soil concern but prioritised crop timing:

*"If wheat is planted late, I lose more money than I save by not burning the stubbles."*

These contrasting accounts show that recognition of soil benefits did not automatically translate into adoption; the perceived immediate risk to wheat establishment could outweigh a longer-term soil benefit.

The opposing views reflect the fact that, while everyone was aware of the degradation of soils, the farmers' decisions were often influenced by short-term economic and operational issues overarching their long-term environmental concerns.

Biomass that would otherwise be added to the field as organic matter and nutrients is removed when it is burned. Twenty respondents (67%) mentioned this, including 12 farmers (most of which are implementing residue retention and/or Happy Seeder technology), all 4 agricultural extension officers, and all 4 policy and institutional stakeholders. Crop residues are often reported to be a valuable resource that can enhance the soil fertility if not burned but left in the field or added to the soil.

A farmer from Sangrur who followed the practice of incorporating residues explained:

*“The straw is not waste. If it remains on the field, it will get incorporated in the soil at the end of the season benefiting the next crop.” (Farmer, Sangrur; residue incorporation user)*

A policy stakeholder from Chandigarh said:

*“The promotion of residue retention is not just a way to cut down on pollution; it's also a way to keep soil organic carbon and cut down on farmers' need to turn to outside inputs over time.” (Policy Stakeholder, Chandigarh)*

Three farmers involved in stubble burning, however, expressed doubts about the long-term benefits of the soil compared to the added expense and hassle of

alternative residue management practices. One of the respondents from Ludhiana said:

*"Straw is nutritive but having the machinery is costly and I don't want to postpone planting of wheat." (Farmer, Ludhiana; stubble-burning practitioner)*

There were contrasting responses suggesting that respondents were broadly aware of the ecological benefit of crop residues, however it was evident that there was a degree of variation in the perceptions of whether these longer-term benefits were greater than the economic and practical pressures of the short window between harvest and planting.

From an agroecological viewpoint, this is a major concern because crop residues are not waste; they are part of the nutrient cycle of the farm. Residue retention, incorporation and mulching therefore represent more than technical alternatives. They are practices that support nutrient cycling, moisture conservation and biological activity in the soil (Gliessman, 2015; Singh and Sidhu, 2014).

However, the findings also show that ecological awareness does not automatically lead to adoption of alternatives. While some farmers recognised the long-term soil and environmental benefits of keeping residues, they were not prepared to implement other residue management strategies because they saw significant short-term operational risks. Of the 18 farmers interviewed, 10 (56%) farmers agreed that keeping crop residues would increase soil organic matter, reduce soil moisture loss and increase soil fertility long-term. Nevertheless, 6 out of these farmers used the non-burning practices regularly and four farmers burned the residues, even though they were aware of these ecological advantages. The other eight farmers (44%) had limited confidence in the practical advantage of residue retention, mostly due to the delayed wheat sowing, limited decomposition of residues, increased pest and rodent problem, increased cost of machinery, and uncertainty over wheat establishment and yields.

There were clear differences among farmers based on the technology they used before and, to a lesser degree, their age and farm size. Young and middle aged farmers (30-49 years) generally felt more confident about sustainable residue management, with a higher number of farmers who had previously used the Happy Seeder or residue incorporation. On the other hand, some older farmers (50-67 years) particularly those operating larger farms were more concerned about efficiency and early sowing of wheat with burning being the least desirable management option.

A 36-year-old medium-scale farmer from Ludhiana who has used the Happy Seeder for three seasons explained that it helps him achieve good results:

*"Initially, I was worried that the straw would hinder wheat establishment, but after using the Happy Seeder, I found that wheat establishment is very good and soil remains moist for a longer time, and also reduce expenditure on field preparation."* (Farmer, 36 years, medium size farm, Ludhiana; Happy Seeder user)

But the implications of ecological awareness did not always lead to changes in behaviour. One of the 55-year-old large-scale farmers at Mansa, who still burned residues, admitted that residue retention is good for the environment but also said that the small window of sowing time is paramount.

*“Burning the stubbles is not good for the soil, but I can't afford to delay the wheat sowing; even a few days delay would mean a loss in the production and sometimes machinery is not available when needed.”* (Farmer, 55, large farm, Mansa; stubble-burning practitioner)

Similarly, a 61-year-old farmer, Sangrur, said that uncertainty about residue decomposition was responsible for non-adoption:

*“Burning provides me with assurance, although it's not a perfect solution, Sometimes the stubble does not burn properly before planting and I am afraid of the pests and inability to establish the crop on time"* (Farmer, 61 years, large farm, Sangrur; stubble-burning practitioner).

Several respondents expressed some of these concerns. Six of the 18 farmers (33%) said they were concerned about the delayed sowing of wheat, six said they were concerned about the residue being left in the field causing increased pest or rodent populations, five said they were concerned about the possibility of yield loss with residue retention systems and six said they were concerned about residue not decomposing. The perceived risks were more common among farmers who had not tried any residue management technology and learnt about it from other farmers or previous experience with conventional farming.

Extension officers generally agreed with the opinions of farmers who were successful with the new technologies and identified that some opinions were based on uncertainty, rather than consistent field evidence. “With respect, one extension officer from Ludhiana commented:

*“Farmers tend to overestimate the risks because they haven't experienced it on their own farms, and once they witness successful demonstrations, they are much more likely to implement residue management.”* (Extension Officer, Ludhiana)

Likewise, another policy maker indicated that the farmer's decision was influenced more by practical and economic factors than by environmental awareness.

*“Most farmers know that burning is bad, but the question is how to lower their financial and operational risks in changing their current practice.”* (Policy Stakeholder, Department of Agriculture and Farmers' Welfare, Chandigarh)

This study suggests that knowledge of environmental effects is not the only factor affecting farmers' decisions on residue management; rather, the interplay of ecological concerns, production risks and access to reliable machinery and institutional support are all relevant.

A comparison of the farmer accounts suggests some tentative differences by age, farm size and prior experience. The older large-scale farmers who continued burning more often emphasised the short sowing window and the financial consequences of delayed wheat establishment, whereas several younger or middle-aged farmers with prior experience of the Happy Seeder or other alternatives described greater confidence in residue retention. For example, a 36-year-old medium-scale farmer from Ludhiana who had used the Happy Seeder for three seasons reported that the machine allowed satisfactory wheat establishment, while older large-scale farmers in Ludhiana and Sangrur more often described burning as unavoidable under time pressure. The pattern should not be interpreted as a simple age effect: access to machinery and previous experience appeared to interact with age and farm size.

### 4.3 Theme two: time pressure and economic decision-making

This theme directly relates to Objective 2, which examines the socio-economic considerations affecting acceptance or rejection of non-burning alternatives. Twenty-seven of the 30 respondents (90%) identified the short interval between paddy harvesting and wheat sowing as a major constraint: 17 of 18 farmers (94%), all four extension officers, all four policy/institutional stakeholders and two of four machinery providers, as shown by stakeholder group in Figure 7. Among the 18 farmers, eight were classified as primarily practising burning and ten as using one or more alternatives. Seven of the eight burning-practising farmers described burning as the fastest or most reliable way to clear fields, particularly when machinery or labour was unavailable. In contrast, farmers using alternatives generally accepted the time constraint but described machinery access, previous successful experience and planning through CHCs as ways of managing it. Extension officers and policy stakeholders agreed that the sowing window was structurally important but emphasised that timely machinery and institutional support could reduce its influence. Thus, the constraint was shared across groups, but farmers focused on immediate field operations while institutional respondents focused more on how support systems could reduce the operational risk.

The proportion of each stakeholder group agreeing that this narrow window is a key constraint is shown in Figure 7.

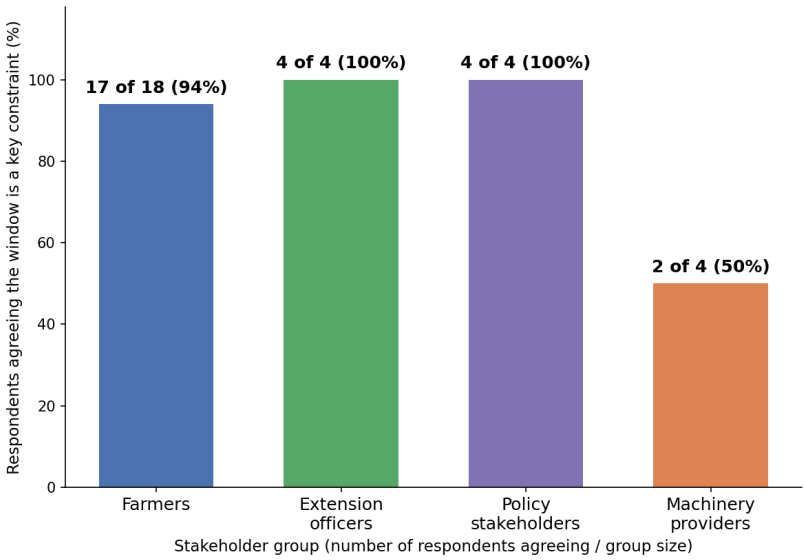



*Figure 7. Narrow paddy-harvest-to-wheat-sowing window as a constraint, by stakeholder group (number of respondents agreeing out of group size shown above each bar).*

*" The issue is that farmers don't want to burn, we are just very short of time between rice harvesting and sowing of wheat and burning is the only way to clear the field in one day." (Farmer, 58 years, large farm, Mansa; stubble-burning practitioner)*

However, alternative residue management technologies had been mostly adopted by the farmers, who generally recognised that the same time constraint exists, but felt it is manageable if machinery is available at the appropriate time. Six farmers who were experienced with using the Happy Seeder or residue incorporation reported that they were able to avoid burning while still getting the wheat in the ground on time thanks to timely access to machinery. A farmer aged 37 years from Ludhiana said:

*" The time pressure is there but as soon as the farmer could harvest he could get the Happy Seeder so no need to burn. Difficulty is that it is difficult to get the machine when everyone needs it." (Farmer, 37 years, medium farm, Ludhiana; Happy Seeder user)*

Machinery suppliers generally felt that the preparedness of the field was not determined by the adoption of sustainable practices of farmers but was determined by the availability of machines. Three of four machinery providers indicated that when harvest was at its peak, there was very little equipment available to manage residues, and waiting periods were long. One machinery operator from Ludhiana commented:

*“In October everyone wants the machine at the same time, we can't have everybody ready at the same time so many what to burn rather than waiting.” (Machinery Provider, Ludhiana)*

Agricultural extension officers expressed a similar view but added that it was a symptom of institutional and logistical problems. All four extension officers reported that the number of Custom Hiring Centres, availability of more machinery and effective management of schedule will significantly help in the reduction of residue burning. One extension officer from Sangrur commented: Extension Officer, Sangrur:

*“Farmers are aware of the environmental issues, but when in the need of the sowing time, there is no practical solution when machines are not available.”*

Policy stakeholders also noted that the short sowing window was not just a personal or farmer's preference but a structural characteristic of the rice–wheat production system. None of the four policy respondents suggested that a solution would be possible without coordinated investments in access to machinery, in the delivery of subsidies, in extension services, and in crop diversification. One policy stakeholder explained:

*" It is not just the farmer behaviour, but the production system itself, which has very little flexibility in residue management practices, because of the date of harvesting and sowing" (Policy Stakeholder, Department of Agriculture and Farmers' Welfare, Chandigarh)*

While there was general consensus that the short sowing window was a significant contributor to residue burning, there were some variations in opinion regarding what could be done about this. While farmers were most concerned about preventing production losses, and ensuring their fields were prepared on time, machinery providers identified a shortage of machinery, extension officers stressed the need for more robust advisory support, and policy stakeholders saw a need for institutional-level systemic reforms. The results show that residue burning is not only due to a lack of environmental awareness, but also involves agronomic, logistical, and institutional factors. This information was found to be consistent with the studies, which have revealed that one of the primary structural reasons for residue burning in Punjab is the shortened time horizon between crops (around 15–20 days between a paddy crop and a wheat sowing), where timely field preparation and yield protection are prioritized by farmers (Choudhary et al., 2022; Krishnapriya et al., 2024). It also corroborates studies showing that the availability of machines, their timely use, and institutional support for their use are critical to the adoption of residue management technologies, including the possibility of continued burning even for farmers who agree that burning residues is environmentally harmful J. Singh et al. (2019).

All 18 farmers interviewed cultivated wheat following the paddy harvest as part of the dominant rice–wheat cropping system in Punjab. They varied significantly

as far as the management of paddy residues was concerned before wheat sowing. Eight farmers (44%) said they routinely burned their crop residues and 10 farmers (56%) said they used one or more alternative practices for residue management such as the Happy Seeder, rotavator, incorporation or mulching, or straw baling. Those farmers who regularly used burning of the residues consistently reported that the narrow window of time between paddy harvest and wheat sowing was the main constraint for adoption. Seven of the eight farmers involved in burning reported that burning the fields was the quickest and easiest way to remove fields, and six reported that they had insufficient machinery for residue management during peak harvest. Five farmers indicated that wheat sowing was delayed and this would affect the yield of wheat, which was the most feasible solution despite the knowledge of the adverse effects of burning. For instance, the farmer from Mansa said:

Figure 8 shows the residue-management practice reported by the 18 farmers in each district (see also Appendix B).

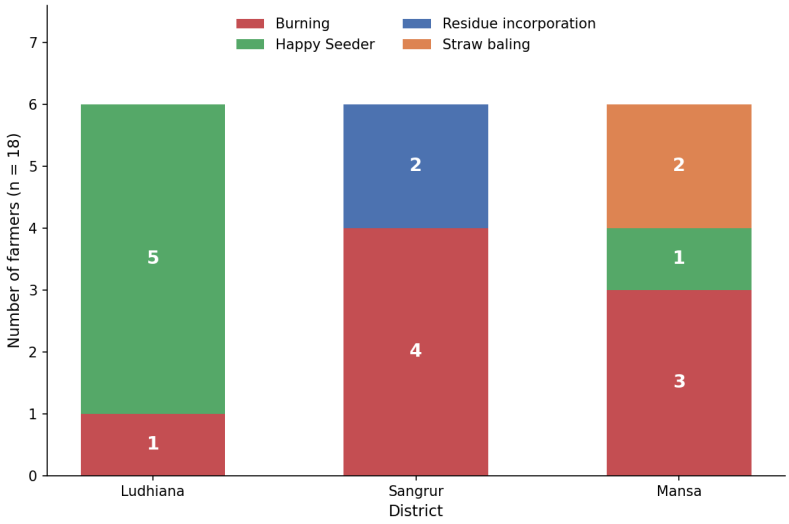



*Figure 8. Main residue-management practice of the 18 farmers, by district.*

Farmers who burned residues were concentrated in Sangrur (four of six) and Mansa (three of six), whereas only one of the six Ludhiana farmers burned. Conversely, five of the six Ludhiana farmers used the Happy Seeder, compared with one in Mansa and none in Sangrur; incorporation was reported only in Sangrur and straw baling only in Mansa. This uneven pattern is consistent with the policy respondents' observation that machinery was distributed inequitably among districts (Theme three), and with the fact that Ludhiana hosts Punjab Agricultural University and many machinery providers (Section 3.1). It also supports the structural reading of the problem developed in Section 2.1 and by Downing et al. (2022): where machinery and extension support are close at hand, farmers adopt alternatives, and where they are not, burning persists. The prominence of baling and removal among the Mansa farmers is consistent with the earlier finding that residue removal was the most common practice in that district (Singh et al., 2022).

*" Wheat sowing is already underway, we have still a few days to go and burning will clear the field immediately, otherwise I would have to wait for the machines which would be a problem because everybody has to use them at the same time." (Farmer, 55 years, large farm, Mansa; stubble-burning practitioner)*

Similarly, another farmer from Sangrur remarked:

*" I know burning is polluting, but if I wait to plant the wheat, I would save the environment at the expense of earning lesser income." (Farmer, 49 years, medium farm, Sangrur; stubble-burning practitioner)*

The ten farmers who did not burn residues, on the other hand, identified some of the motivations for implementing alternative management practices. Six farmers mentioned that they had positive experiences with the Happy Seeder, two farmers mentioned residue incorporation and two farmers mentioned selling or baling straw for livestock feed or biomass use. The general sentiment of these respondents was that the practice of leaving crop residues in the field benefits soil moisture, the soil's organic matter, and decreases the need for repeated tillage in the long term. Some also said that the demonstrations which they had seen conducted by the agricultural extension officers or neighbouring farmers had boosted their confidence to use these technologies.

One farmer aged 38 years from Ludhiana who has used Happy Seeder for three seasons said:

*" Once I observed that the wheat does not get affected by the application of residue in the field while sowing, I stopped burning. The moisture holding capacity of the soil is more and field preparation is easier." (Farmer, 38 years, medium farm, Ludhiana; Happy Seeder user)*

Although there were limitations, both sets of farmers realized the importance of getting wheat in the ground on schedule. The main difference between the two groups wasn't whether they knew of environmental impacts but whether they had the confidence to address operational risks related to residue retention. Farmers with prior experience with alternative technologies, or farmers who had good access to machinery through a Custom Hiring Centre were more likely than others to refrain from burning.

These findings are in line with the literature reporting the role of awareness alone as a driver of paddy residue burning in Punjab, while operational pressures like delayed planting time, limited access to machinery, and a tight window between rice harvest and wheat sowing were found to play a larger role (Krishnapriya et al., 2024). It is also consistent with field studies which found that farmers who have first-hand experience of the technologies like Happy Seeder or residue incorporation or straw-use options are more likely to adopt these technologies as they develop confidence in performing them in the field, managing soil moisture and timely sowing; while others who are not adopting these

technologies are more likely to be concerned about the risk, availability of technologies and yield losses (Lohan et al., 2018; Sandhu et al., 2019).

There was also a pressure from the economy for decision making. Whether a farmer could adopt a non-burning practice was affected by factors such as machinery hire, diesel, labour, repair expenses, and costs and availability of subsidies. The findings thus indicate that the decision to burn should not be made on the basis of ignorance or carelessness. Its conclusions, however, suggest that economic factors that render burning as a viable option should be the focus of environmental policy. This view was expressed in all stakeholder groups, but varied in terms of what respondents viewed as most important. All four agricultural extension officers interviewed confirmed that farmers were aware of environmental risks of burning but had lots of financial and operational constraints in implementing alternative options. The three extension officers identified high cost of machinery hire, low availability of machinery during peak harvest, and the inability of many small and medium scale farmers to afford special equipment for residue management as the major constraints. All four indicated that small and medium scale farmers were not able to buy special machinery for managing the residues. One of the extension officers of Ludhiana says he explained:

*" Most of the farmers have an awareness that burning is harmful to the environment, but when there is no machine available or cost is too high, farmers opt for the quickest solution to prepare the field." (Extension Officer, Ludhiana)*

While the four policy and institutional stakeholders had similar perceptions, they were more likely to have a stronger focus on structural and institutional barriers. Three policy respondents reported that subsidy schemes have led to more use of the machines, but they cited a lack of machinery availability, of machinery distribution and of Custom Hiring Centre capacity as a cause of slower subsidy uptake. All four emphasized the importance of policy measures to help change the fundamental economic rationale for burning residues, not just enforcement. A policy stakeholder from the Department of Agriculture and Farmers' Welfare stated:

*" It is not merely a matter of imposing penalties on the farmers, the objective should be to make them available with practical and economically feasible options to overcome the burning. Otherwise, they will not be able to comply with the burning ban." (Policy Stakeholder, Department of Agriculture and Farmers' Welfare, Chandigarh)*

The views of farmers were generally similar but with a slightly different focus. The immediate cost consequences of residue management were primarily highlighted by farmers, such as the cost of hiring machines, the cost of diesel, a shortage of labour and the danger of lower yields of wheat if the sowing was postponed. Extension officers, on the other hand, emphasized advisory service,

access to machinery and training of farmers while policy stakeholders emphasized institutional coordination, subsidy delivery, and long-term investments in residue-management infrastructure. Machinery suppliers affirmed these comments by stating that demand for Happy Seeders and Super SMS-equipped combines was always greater than the supply during the limited harvesting season, as well as straw balers. The three out of four machinery suppliers reported that farmers were happy to practice non-burning methods but that they could not access the equipment when needed.

Although there were variations in what each group considered to be the most important factors, there was general consensus that economic and logistical factors are the major factors in the practice of residue burning and that environmental awareness was not the main reason for burning residues. The farmers focused on protecting their household income and timely establishment of their crops while the extension officers, machinery providers and policy stakeholders focused on improving access to machinery, streamlining subsidy delivery, improving extension, and increasing Custom Hiring Centres to be able to reduce residue burning. The results indicate that successful policies on the management of residues should not only aim at environmental goals, but also at lowering the financial and operational risks associated with the implementation of sustainable residue management options.

This is a key interpretation to keep things in balance when it comes to academic stance. Some farmer realities are considered slightly, yet farmers are the actors who are directly involved in the management of residues in the field and are not completely 'clean'. Rather, it reveals a distribution of responsibility in the farming system, from markets, technologies, institutions, and the design of policy.

### 4.4 Theme three: machinery access and uneven technological transition

The technologies discussed by almost all stakeholder groups and which also proved to be a major theme during the interviews were technologies like Happy Seeder, Super Seeder, mulchers and balers. Overall, 28 of the 30 respondents (93%) referred to at least one residue-management technology. These comprised all 18 farmers, all four machinery providers, all four agricultural extension officers and two of four policy stakeholders. Respondents were broadly in agreement that these technologies provided an effective alternative to residue burning, but there were key issues about how easily available they were, the cost, and how well they worked under field conditions. Of the 18 farmers interviewed, ten (56%) farmers had direct experience with using one or more residue-management technologies while 8 (44%) had not used any technologies. There were six technology adopters who experienced using Happy Seeder, two who used residue incorporation with mulchers/rotavators and two who used straw balers for biomass/livestock feed. The positive experiences of these farmers, as described, are related mainly to wheat establishment in time, moisture availability in the field, and time saved on

field preparation over time. A 39-year-old farmer from Ludhiana who had used the Happy Seeder for several seasons explained:

*" At first I was not sure whether it is possible for wheat to germinate in the residue or not, but after trying out Happy Seeder I came to know that the crop established well and I would not say it is necessary to burn the residue." (Farmer, 39 years, medium farm, Ludhiana; Happy Seeder user)*

Likewise, a farmer from Mansa who was selling straw for making baling declared:

*I sell a portion of the straw as fodder and biomass which helps to prevent waste and provides extra income for me. (Farmer, 45 years, medium farm, Mansa; straw baling user)*

However, farmers who didn't use these technologies had another view. Seven of the eight non-adopters reported that it was difficult to find machinery during the short harvest season, and six reported that the cost of renting machinery and its reliance on diesel power reduced adoption of residue-management equipment each season. Four also wondered about the performance of the technologies under heavy residue. A 57-year-old farmer from Sangrur remarked:

*" Because all farmer are waiting for the same equipment during the harvest, so it becomes easier to burn the stubble." (Farmer, 57 years, large farm, Sangrur; stubble-burning practitioner)*. Figure 9 summarises the barriers cited by the eight farmers who had not used any residue-management technology.

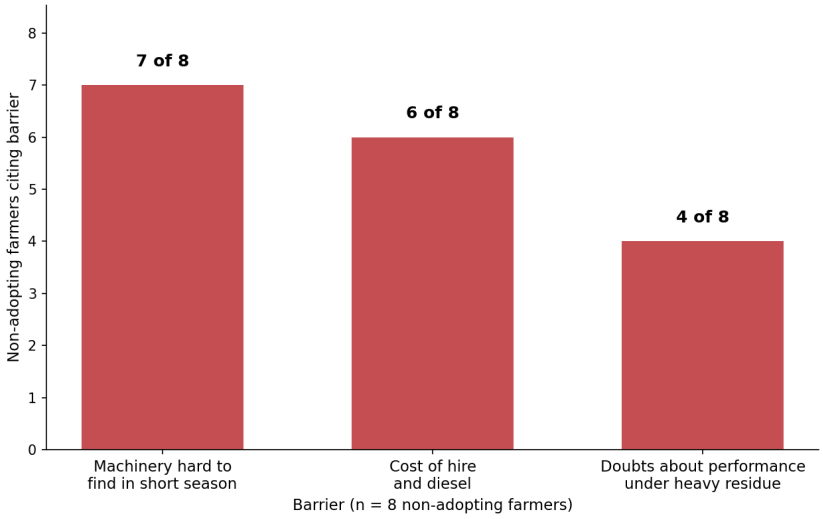



*Figure 9. Barriers to adoption cited by the eight non-adopting farmers (number citing each barrier out of eight).*

These barriers are about access and cost rather than agronomic performance, and they mirror those reported for Custom Hiring Centres in Punjab, where uneven access and peak-season shortages are widely documented (Jain et al., 2025; Singh et al., 2020). They also show why subsidy design matters. The Crop Residue Management (CRM) Scheme meets 50% of the cost of machines bought by

individual farmers and 80% of the cost of Custom Hiring Centres run by cooperatives, farmer producer organisations and panchayats (Ministry of Agriculture and Farmers Welfare, 2018). Subsidising the supply of machines, however, does not guarantee that a machine is available during the particular days when a given farmer must sow, which is exactly the difficulty respondents described.

This sense of concern was largely echoed by machinery providers. In October and November, three of four machinery suppliers said they had a consistent excess of demand over supply for machinery with Happy Seeders and Super Seeder capabilities. One machinery provider from Ludhiana explained:

*" Although the technology is not an issue, "we are unable to meet the demand as hundreds of farmers are demanding the machines within a short span of time and we don't have enough machinery." (Machinery Provider, Ludhiana)*

Farmers' confidence in these technologies rose when they saw demonstrations that were successful, and agricultural extension officers confirmed this. Farmers who attended the field demonstrations or saw neighbouring farms practise residue retention were much more likely to be willing to do the same, with all four extension officers reporting significant increases in readiness to do so. One extension officer from Sangrur commented:

*" farmers who experience the machine working are much more confident than those who are made aware of it through awareness building activity alone; demonstration plots are often more effective." (Extension Officer, Sangrur)*

Policy stakeholders agreed on the benefits of these technologies, but also noted that residue burning would not be possible through technology. Three of the policy respondents noted that subsidy programmes had contributed significantly to the acquisition of machinery but also highlighted the lack of facilities at Custom Hiring Centres, slow subsidy processing and inequitable distribution of machinery among districts, as reasons for the uneven uptake of the technology.

The interviews thus suggest that overall the interviewees did not see residue-management technologies as less than technically successful. Economic and institutional rather than technological were the main constraints. Farmers considered the technologies based on their operational reliability, cost, and ready availability during the limited sowing window, while the machine providers pointed to supply related issues including difficulties in accessing the technology, demonstration activities and farmer confidence. Policy stakeholders raised issues related to the scaling-up of technology access, including the need to improve implementation mechanisms. The results indicate that extensive dissemination of new technologies in the field is not enough to drive the higher adoption rates; it is also necessary to improve the delivery system of farmers regarding the machinery, technical support, financial support, and machine maintenance. It is consistent with the research findings from Punjab that the timely availability of machines, their

cost, the farmer's confidence in their performance in the field, and low availability of machines during the limited harvesting window are key challenges in adoption; moreover, extension demonstrations and visible success on nearby farmer fields boosted adoption rates (Dhanger et al., 2022; Singh et al., 2021, Choudhary et al., 2022). The interviews show that non-adoption is not a resistance to innovation, but rather many farmers viewed the technologies positively, but were limited by the general economic and logistic environment in which decisions regarding residue management are taken by farmers.

The advantages that adopters described for the Happy Seeder (timely wheat establishment, soil moisture and savings in field preparation) correspond to the profile of the technology in Table 2.1 and Figure 2. What the interviews add to that literature-based comparison is that the main obstacle to its wider use is access at the right time rather than performance, so that the 'ease and time efficiency' that makes burning attractive in Figure 2 is partly a product of how machinery is organised and not only of the technologies themselves.

### 4.5 Theme four: policy support, subsidies and institutional trust

One of the most talked about themes by all stakeholder groups was policy support. When asked about the factors influencing their decisions on residues, 26 of the 30 respondents (87%) mentioned government policies, subsidy programmes or institutional support. Of the 18 farmers, 15 (83%), all four agricultural extension officers (100%), all four policy and institutional stakeholders (100%) and three out of four machinery providers (75%) were covered. The respondents were generally positive with regard to awareness and access to technologies to manage residues, but there were significant variations in the effectiveness, availability and uptake of these programmes. Farmers' attitudes were split over subsidy programmes. However, 9 out of 18 farmers (50%) felt that machinery subsidies and Custom Hiring Centres made it easier for farmers to access residue-management equipment, and also made them think about using alternatives to burning. Some respondents indicated that the provision of subsidised machinery eliminated financial barriers which otherwise would prevent machinery adoption. The 41 year-old farmer from Ludhiana, who was using the Happy Seeder regularly, said:

*" Without subsidy and Custom Hiring Centre, I could never afford to use this machinery. It made it possible for me to stop burning." (Farmer, 41 years, medium farm, Ludhiana; Happy Seeder user)*.Figure 10 shows how many respondents in each group mentioned government policies, subsidy programmes or institutional support.

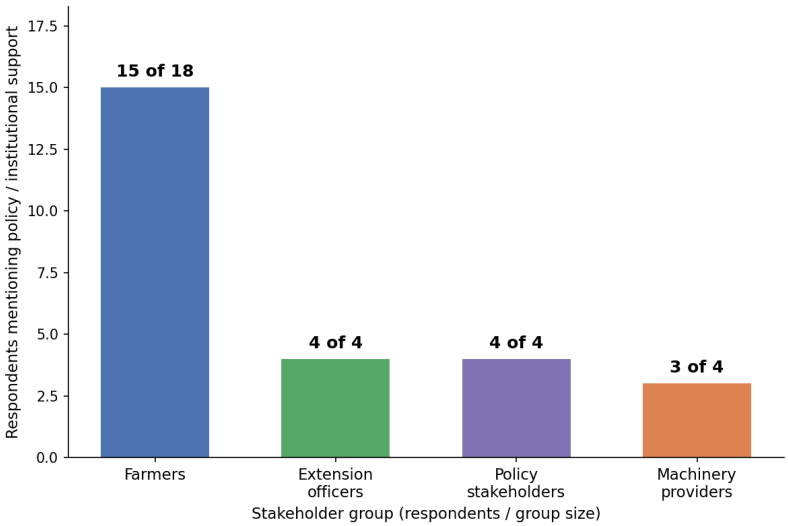



*Figure 10. Respondents mentioning government policies, subsidy programmes or institutional support, by stakeholder group (26 of 30 respondents in total).*

Six farmers (33%) reported, however, that while it was possible to have subsidies, the delay in processing applications and insufficient availability of machinery, combined with complex paperwork, significantly reduced the benefit they could derive from them. One farmer of Sangrur said:

*" The subsidy sounds good, but when all the things were approved, it was harvesting time, but there is still something to be done in the field." (Farmer, Sangrur; stubble-burning practitioner)*

Three farmers felt that the government programmes were not very successful as they felt the machinery was not available evenly or was more easily available to the larger farmers. A farmer from Mansa commented:

*" When wheat sowing cannot wait then burning becomes the only choice, because the machines are not available." (Farmer, Mansa; small-scale farmer)*

Government policies were generally seen as having enhanced farmers' knowledge of sustainable residue management practices. Field demonstrations, village meetings and advisory campaigns reported by all four extension officers led to improved awareness of environmental effects of residue burning among farmers. However, all four also contended that awareness alone was not enough if farmers were unable to have access to machines and institutional support in time.

An extension officer from Mansa observed:

*" Extension work can only be effective if farmers have the capacity to use the machines on a timely basis or even better, they can use it at the same time." (Extension Officer, Mansa)*

Policy and institutional stakeholders were generally more positive about the direction of recent government measures, but their accounts also revealed implementation gaps. All four policy respondents considered subsidies, machinery

distribution, awareness campaigns and monitoring to have contributed to progress, while three of the four pointed to continuing difficulties in ensuring timely access to machinery and sustained farmer participation. This partly agreed with the farmers' accounts: farmers valued subsidies when they reduced the cost of access, but several described delays or unequal access. The difference was therefore less about whether policy support was useful and more about how success was judged. Policy stakeholders tended to assess programme reach and overall reduction in burning, whereas farmers judged support by whether a machine or subsidy was available at the moment they needed to prepare the field. A policy stakeholder from the Department of Agriculture and Farmers' Welfare emphasised this implementation issue: "Along with provisioning of machines, there is a need for timely availability of machines, providing maintenance facility, training farmers to operate them and ensuring institutional support is in place if one wants to replace fire on a large scale." (Policy Stakeholder, Department of Agriculture and Farmers' Welfare, Chandigarh)

*"Though measurable gains have been achieved over the past few years, success in policy implementation relies on the consistent efforts of the district level. Availability of machinery, extension support and timely funding remain crucial to execution of the policy." (Policy Stakeholder, Department of Agriculture and Farmers' Welfare, Chandigarh)*

A representative from Punjab Agricultural University framed the issue somewhat differently:

*"The challenge is no longer the creation of awareness, it is now to improve the implementation." (Policy Stakeholder, Punjab Agricultural University*)

Machinery providers raised closely related concerns. Three of the four respondents agreed that government support had stimulated demand for residue-management equipment, but reported that supply growth had not kept pace with farmers' needs during the busy harvest window.

Overall, all stakeholder groups were generally supportive of the positive role played by government policies towards the reduction of residue burning, particularly through awareness creation and promoting residue management technologies. But there are variations in the assessment of implementation from one respondent to another. The main concerns farmers had about policies were whether they cut their short-term production expenses and risks. Extension officers were keen on enhancing advisory services and accessing machinery, while policy stakeholders highlighted institutional coordination, programme implementation and

investment. The results indicate that farmers' trust is not necessarily linked to the presence of policy measures, but rather to their day-to-day experiences of accessing machinery, getting subsidies on time and getting practical support during the critical harvesting time. Respondents not only evaluated policies in terms of their goals, but also their actual ‘delivery'. The literature is consistent with previous studies that indicate that agriculture policy works if the policy support measures are delivered in a manner that is accessible to farmers throughout the production process and not just formally or symbolically. The analysis of policy impacts on agriculture in India has illustrated that the willingness of farmers to change their practices is strongly influenced by their trust in the government and the timeliness of the support as well as the perceived fairness of its implementation, while the crop-residue management study in Punjab highlights that custom hiring centers, machinery subsidies, and extension campaigns are most effective when they are implemented during the narrow window between harvest and sowing (Choudhary et al., 2022). In this regard, the current results agree with the larger body of work which indicates that trust in institutions is not formed solely by the presence of policy programs, but rather by the reliability of service delivery on the ground, access to machinery based on equality and responsiveness of local administration (Brar, 2024; Gupta et al., 2026). The interview results, therefore, suggest that capacity strengthening of institutions and confidence-building of farmers in the implementation of the policies is more important than scaling up the policies themselves.

Triangulation with the policy documents reviewed (Section 3.3.3) sharpens this picture. The CRM Scheme guidelines subsidise machinery at 50% of cost for individual farmers and 80% for cooperatives, farmer producer organisations and panchayats establishing Custom Hiring Centres, and they list awareness creation and demonstration among the scheme's components (Ministry of Agriculture and Farmers Welfare, 2018). Official statements on the 2025 season credit the decline in fire counts to state action plans, large-scale deployment of residue-management machinery and strict enforcement under the Commission for Air Quality Management (PIB, 2025). The interviews do not contradict this account, but they add what such documents cannot show: that the benefit of a subsidised machine depends on whether it can be reached at the moment of need, that subsidy processing can be completed only after the sowing window has begun, and that farmers weigh the risk of penalties against the risk of late sowing. The documents emphasise the supply of machines and enforcement, whereas respondents emphasised timing and delivery. This agrees with Gandhi (2024), who argues that financial incentives must be complemented by technical training, extension support and trust-building, and with Kemanth et al. (2024) on the need to raise the adoption of residue-management methods beyond the initial provision of machines.

## 4.6 Theme five: agroecological transition and crop diversification

The interviews revealed that the respondents mostly characterized stubble burning as a manifestation of the overall framework of the rice–wheat production system of Punjab and not as a farm management issue. Overall, 24/30 of the respondents (80%) felt that any long-term lessening of residue burning would involve a change in the current production system. All four agricultural extension officers (100%), all four policy and institutional stakeholders (100%), three of the four machinery providers (75%) and 13/18 farmers (72%). Respondents were generally supportive of crop diversification as a potential long-term solution, but had mixed opinions on its feasibility and the necessary supports for its implementation. 13 farmers identified continuous rice–wheat farming as a reason for high crop residues and high pressure for burning. But under current conditions only five farmers said they would be interested in growing a mix of crops. The other eight respondents indicated that they would rather continue growing paddy due to guaranteed government procurement, market connections and relatively stable economic returns. The medium scale farmer of Ludhiana, who spoke at the event, said that the project was a great opportunity to contribute to the development of the village.

Figure 11 shows how this view was distributed across the stakeholder groups.

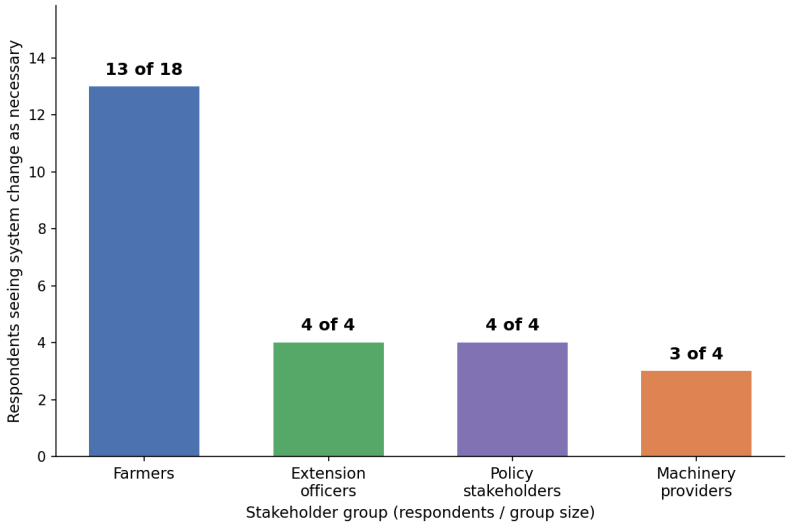



*Figure 11. Respondents who considered that long-term reduction of burning requires change in the rice-wheat production system, by stakeholder group (24 of 30 respondents in total).*

The view that burning is a feature of the production system was shared by every extension officer and policy stakeholder and by three of four machinery providers, but by a smaller share of farmers (13 of 18), and only five of the 18 farmers said they would consider diversifying under present market conditions. This gap between institutional and farm-level views is consistent with the literature: earlier diversification attempts in Punjab failed largely because alternative crops give

lower returns than rice-wheat and because farmers do not capture the economic benefit of water savings while irrigation electricity remains subsidised (Department of Agriculture & Cooperation, 2014), and even a shift towards basmati would not remove time pressure if production were scaled up (Downing et al., 2022). The interview evidence therefore supports treating diversification as a long-term structural complement to, not a substitute for, the residue-management measures discussed in Themes two to four.

*"Talking about changing the crop, but in the absence of assured market, it is hard to take that risk with other crops." (Farmer, 46 years, medium farm, Ludhiana)*

Similarly, a large-scale farmer from Sangrur commented:

*"We know that year after year, the grow of rice is a problem, but we have loans and the expenses of the household as well, and if we don't know how to grow it, how can we experiment?" (Farmer, 54 years, large farm, Sangrur)*

In contrast, five younger and middle-aged farmers (30–45 years), most of whom had already adopted residue-management technologies, expressed greater willingness to consider diversification if economic incentives were available. One farmer from Mansa stated:

*"If the government would guarantee the procurement of maize or pulses as they do for rice, many farmers would be willing to change as it will help them to overcome the challenges of residues and water shortages. (Farmer, 34 years, medium farm, Mansa; Happy Seeder user)*

Crop diversification was seen as one of the more sustainable long-term options by all agricultural extension officers, but they also noted that it was important to do so with the simultaneous modernization of markets and institutional mechanisms to enable farmers to transition. An extension officer from Ludhiana observed:

*"Technologies like Happy Seeder helps in reducing burning while not eradicating the dependence on rice–wheat system, diversification of cultivation will only happen when there is confidence that alternative crops will fetch a stable return." (Extension Officer, Ludhiana)*

Another extension officer from Mansa added:

*"While alternative options are of interest to the farmers, the economic realities create a sense of uncertainty in the markets and prevent them from considering the alternatives." (Extension Officer, Mansa)*

There were similar ideas but with greater emphasis on structural reforms among policy stakeholders. All the four policy respondents emphasized that coordinated efforts be undertaken for reducing the burning of residues, including procurement policy, market development, processing industries, conservation of groundwater resources, and agricultural diversification. A policy stakeholder from the Department of Agriculture and Farmers' Welfare explained:

*“Residue burning is related to the whole farming system and as long as farmers are under pressure during every harvesting season, the problem of residues will not be solved.” (Policy Stakeholder, Department of Agriculture and Farmers' Welfare, Chandigarh)*

Another respondent, from Punjab Agricultural University, added:

*“This transition should not be put solely on the shoulders of the farmers, as farmers need to invest in procurement systems, processing units, extension services, and value chains for the diversification to be widely adopted.” (Policy Stakeholder, Punjab Agricultural University)*

Machinery providers were broadly supportive of the idea of diversification to help alleviate pressure on the residue-management services, as this would bring a greater length and lower concentration of harvest periods. Three of the four machinery suppliers noted that the present rice-wheat farming system resulted in a very high seasonal market demand for machinery within a very short period of time. One machinery supplier said:

If cropping pattern diversified the demand will be spread over the period, which will become easy in residue management. *(Machinery Provider, Sangrur)*

Another significant discovery was the importance of the local knowledge of the farmers. Eleven of the 18 farmers (61%) explained that they used their own experience over many years when making decisions about managing their residues, not just on the formal advice from extension. Often farmers who had been successful with the Happy Seeder technology have stressed learning by trial and error and by witnessing neighbouring farms. On the other hand, farmers who persisted with crop burning tended to use their past experiences of late sowing or mechanisation constraints to be more leery of altering traditional practices. This indicates that farmers were not opposed to innovation but judged new practices based on their own experience on the field and their perceived risks of production.

These results collectively suggest that the respondents considered residue burning as an overall problem that is part of the rice-wheat production system of Punjab and not just a problem of the individual farmers. There was a general consensus that diversification would help to ease ecological stress, alleviate groundwater depletion, and help manage residue, but respondents repeatedly pointed out that it would only be a viable possibility if it was backed by reliable procurement systems, market incentives, processing infrastructure and appropriate institutional support. The interviews therefore indicate that agroecological transition will not be realized by merely promoting alternative technologies for residue management, but by rethinking the system of agriculture as a whole. Moreover, the results show that the farmers' knowledge and experience are of great value for the policy making process. Extension officers and policy stakeholders continually stressed the need for better interventions to be effective in the future if local knowledge of the conditions in the field, the performance of the machinery, residue decomposition and cropping constraints are taken into account when designing programmes.

This discussion is in line with the earlier studies on the burning of residues in Punjab, which indicated that the practice of burning the residue is not just a behavioural problem among farmers, but is part of the larger rice–wheat production system. Research on rice–wheat system in Punjab has revealed that assured procurement, subsidized inputs, and short seasonal time frame lead to a preference for monocropping and a lack of interest in diversification, as well as putting ecological pressure by fueling residue accumulation and drainage of groundwater (Downing et al., 2022). It is also important to note that while residue management technologies are essential, coordinated policy changes in procurement policy, market development and technology support are also needed to transition sustainably, and local knowledge and field experience of farmers is an important input in policy design (Bhatt et al., 2021; Dehal et al., 2025).

## 4.7 Overall discussion

### 4.7.1 Reframing stubble burning as a socio-ecological problem

The findings confirm that stubble burning in Punjab is best understood as a socio-ecological problem. It is ecological because it affects air, soil, nutrient cycling, biodiversity and climate. It is social because it is shaped by farmer livelihoods, labor arrangements, local norms, technology markets and policy systems. Treating it only as an environmental violation misses the practical pressures that keep the practice in place.

This interpretation fits the agroecological approach adopted in the project plan. Agroecology does not separate ecological processes from social and institutional realities. Instead, it asks how farming systems can be redesigned to support ecological regeneration while also remaining viable for farmers and rural communities (FAO, 2018).

### 4.7.2 Relationship with previous literature

The results are consistent with earlier studies that identify the rice-wheat system and narrow sowing window as major drivers of burning. Downing et al. (2022) describe crop residue burning in Punjab as part of a locked-in socio-ecological system, while Erbaugh et al. (2024) show how machinery, policies and unequal access shape residue management decisions. The findings of this thesis support these arguments by showing that awareness alone is insufficient when the farming system continues to reward speed and risk reduction.

The study also supports the literature on the ecological value of residue retention. Practices such as mulching, zero tillage and incorporation are important because they return biomass to the field and support soil organic matter. This

connects directly with agroecological principles of recycling, soil regeneration and reduced dependence on external inputs (Nicolétis et al., 2019) .

### 4.7.3 Balance between farmer responsibility and structural constraints

A careful balance is needed in interpreting the role of farmers. The thesis does not argue that burning is harmless or that farmers have no responsibility. Burning produces serious environmental externalities, including air pollution and loss of nutrients and organic matter. At the same time, the interviews show that farmers make decisions within a system that can limit practical alternatives. This interpretation is consistent with Erbaugh et al. (2024), who emphasise the importance of institutional and infrastructural conditions in residue-management decisions, and with Downing et al. (2022), who frame residue burning within the wider rice–wheat production system. A fair analysis therefore avoids both blaming farmers alone and excusing the practice completely.

This balanced position is important for academic credibility. It also strengthens the policy relevance of the thesis. If the issue is framed only as farmer behaviour, then the response becomes mainly punishment and awareness. If the issue is framed as a system problem, then solutions must also address machinery access, crop calendars, markets, extension services, subsidy design and crop diversification.

### 4.7.4 Toward a multi-level agroecological strategy

The study suggests that sustainable stubble management should be connected with wider agroecological transition. At the field level, this means encouraging residue retention, reduced tillage, organic matter recycling and soil biological health. At the farm-system level, it means supporting crop diversification and water-sensitive cropping patterns that reduce dependence on the intensive rice–wheat rotation. At the policy level, it means designing support systems that are timely, locally accessible and trusted by farmers. These findings are consistent with agroecological principles of recycling and resource conservation (Gliessman, 2015; FAO, 2018) and with residue-management research emphasising machinery access, institutional support and diversification (Downing et al., 2022; Erbaugh et al., 2024; Sidhu et al., 2024).

This multi-level approach is more realistic than promoting one technology as a universal solution. The Happy Seeder and similar tools are valuable, but they cannot solve the whole problem without supportive institutions. Ex-situ uses such as biomass energy and compressed biogas can also help, but they must be balanced with the need to maintain soil organic matter. Agroecology therefore supports a mixed strategy rather than a single solution

Seen against the conceptual framework in Figure 3, the findings support most of the proposed chain. The interviews confirm the links from the short sowing

window to burning (Theme two), from burning to air and soil stress (Theme one), and from machinery access, policy support and extension to the possibility of change (Themes three and four). The final link, from institutional support to an agroecological transition that includes diversification, is only partly supported: respondents saw diversification as desirable in principle but conditional on procurement, markets and processing capacity (Theme five). The framework therefore holds as a description of how the system works, while the interviews suggest that its last step lies further in the future than the residue-management measures that precede it.

# 5. Conclusion and recommendations

## 5.1 Conclusion

This directly addresses the gap in the Introduction that few studies have integrated environmental, socio-economic, and institutional evidence in a single agroecological approach using primary qualitative research in the context of Punjab. The results indicate that fire negatively affects air quality, soil fertility, nutrient cycling and agroecosystem sustainability. A sustainable approach is possible with use of sustainable alternatives such as Happy Seeder technology, mulching, incorporation of the residue, baling, and utilization of biomass. But, several practical considerations influence farmers choices of whether to use these practices or not: cost, availability of machines, workforce, confidence in institutions and availability of these practices in the existing crop calendar.

Overall, the thesis suggests that sustainable residue management in Punjab requires a package of policies rather than a single intervention. The findings support strengthening the Crop Residue Management (CRM) Scheme, improving the availability and seasonal scheduling of machinery through Custom Hiring Centres (CHCs), and linking machinery subsidies with practical farmer training and extension support. Respondents also highlighted the importance of timely subsidy disbursement, maintenance services, coordination between the Department of Agriculture and Farmers' Welfare, Punjab Agricultural University and district extension offices, and demonstration programmes that allow farmers to observe successful residue management under local conditions. For longer-term agroecological transition, the findings support stronger procurement and market development for alternative crops, investment in biomass and residue value chains, and measures that reduce the economic risk of diversification. These priorities address the environmental, economic and institutional drivers identified in the interviews rather than relying only on enforcement or awareness campaigns.

## 5.2 Recommendations

### 5.2.1 Increase the capacity and outreach of Custom Hiring Centres

Lack of availability of machines during the short harvesting period is cited by 17 of the 30 respondents including farmers, machinery suppliers, extension staff and policy makers as a key driver of burning. Some farmers reported that they were interested in using the Happy Seeder, but were unable to access it during their desired periods. The CHC's therefore need to be expanded in number, better

systems for booking equipment and expanded geographically to ensure equipment is available during the critical period between harvest and sowing.

### 5.2.2 Link machinery incentives to extension services and training

Theme 4 (Policy Support, Subsidies and Institutional Trust) indicated that 19 respondents believed that subsidy had helped to access sustainable technology, but many farmers continued to be uncertain about operating the technology or getting technical assistance after the operation. Regularly farmers' confidence increased following field demonstrations and follow-up visits by extension officers, extension workers and field staff, extension officers said. In this regard, the subsidy program of the CRM Scheme should be accompanied by demonstration plots, operator training and continued extension support not by distribution of machines.

### 5.2.3 Streamline the process and make subsidy delivery transparent

14 respondents had mentioned delays and/or administrative hassles in the subsidy process, while some farmers were displeased with the manner in which machinery were distributed. This indicates that trust within institutions is not confined to a binary choice of whether financial assistance is available, but also on how it is provided. By streamlining applications, timely provision of subsidies, and better farmer-DO-DHC communication could foster greater trust in the government and increase farmers' participation.

### 5.2.4 Promote combined in-situ and ex-situ residue-management approaches

Results from Theme 2 (Environmental and Soil Health) indicate that a large proportion of respondents appreciated the benefit of returning waste material on the field to boost the SOC and moisture content in the soil. Meanwhile, farmers and machine manufacturers noted that the surplus residue could be utilized economically – as animal feed, through baling, biomass energy, compost or compressed biogas. Policy should enable both choices: leaving residue in-situ if agronomically appropriate and developing robust markets and value chains for ex-situ use to allow farmers to make their choice of what is appropriate in their local context.

### 5.2.5 Minimize the risk to farmers in the harvest-to-sowing window

Theme 2 and Theme 3 identified 27 respondents, who identified the narrow gap between paddy harvest and wheat sowing as the primary reason for burning.

Farmers reported that concerns over sowing wheat later than usual, labour problems and the absence of machinery were more immediate than concerns over the environment. To alleviate this pressure, there is a need to develop future interventions, such as timely access to machinery, better harvest logistics, improved CHC scheduling and better extension support during peak season.

### 5.2.6 Improve the value of diversifying crops

In Theme 5 (Agroecological Transition and Crop Diversification), 24 respondents held the view that diversifying the crops could reduce the pressure towards burning, whereas only five of the 18 farmers stated that they would be willing to do so in current market situation. The biggest challenge most mentioned was the guaranteed supply of rice as against the uncertain markets for other crops. The diversification policy should therefore include guaranteed procurement, market development, processing infrastructure and enhanced financial support for crops other than rice and wheat, such as maize, pulses or oilseeds, in order to decrease the dependence on the rice-wheat cycle.

### 5.2.7 Improve collaborative policy development and institutional cooperation

In Theme 4, farmers, extension officers and policy stakeholders had broadly similar objectives but different views on the means of implementation, with farmers emphasising practicalities, extension officers the advisory role, and policy makers institutional coordination. Policy in the future should include better involvement of the farmers in planning and evaluation and also improve the cooperation between the Department of Agriculture and Farmers' Welfare, PAU, district extension offices and CHCs. Such a participatory process would foster confidence and increase policies' local farming reality.

### 5.2.8 Adopt an agroecological and systems approach for residue management

Theme 5 revealed that the respondents perceived residue burning as a sign of structural problems in the rice-wheat system rather than a standalone practice. Burning was linked to monocrop farming, depletion of ground water, agricultural methods and market incentives by all stakeholders involved in farming practices, extension and policy decision making. Policy development should thus be agroecological, that is, addressing soil health, water practices, biodiversity, climate resilience, livelihoods of farmers, and markets development, hand in hand.

Combating these complex problems will likely yield more sustainable decreases in burning than will either machinery adoption or enforcement.

## 5.3 Limitations and future research

The study has several limitations that should be considered when interpreting the findings. It was based on qualitative interviews with 30 respondents: 18 farmers, four machinery providers/CHC representatives, four extension officers and four policy/institutional stakeholders. Interviews were conducted in Ludhiana, Sangrur and Mansa between 15 October and 12 November 2025. Respondents were selected through purposive sampling, supplemented by snowball sampling, which identified eight additional respondents. The main fieldwork challenges were arranging interviews during the busy harvest and sowing period and obtaining candid accounts of burning where participants were concerned about monitoring or penalties. Because only four respondents represented machinery supply, differences between CHC staff and private machinery providers could not be analysed separately. Analysis was carried out manually in Microsoft Word and Excel by a single researcher, so no inter-coder reliability check was possible (Section 3.6). The study also relied on self-reported perceptions and did not directly measure emissions, soil properties, yields or farm-level economic outcomes. The findings should therefore be interpreted as an in-depth, context-specific account rather than a statistically representative picture of Punjab. Future research could combine qualitative interviews with field measurements, economic analysis and larger comparative samples across Punjab, Haryana and other rice-growing regions.

**Declaration of AI use**

Artificial Intelligence (AI) tools, specifically ChatGPT (OpenAI), were used in a limited capacity during the preparation of this thesis. AI assistance was used only for language editing, paraphrasing, improving sentence structure, grammar, clarity, and the overall readability of the text. It was also used to improve the academic writing style of some sections after the original content had been prepared by the author.

AI tools were not used to generate research data, conduct data analysis, interpret findings, develop the research methodology, or formulate the conclusions of this study. All research design, literature review, data collection, analysis, interpretation of results, and final academic decisions were undertaken solely by the author.

The author reviewed, verified, and edited all AI-assisted text to ensure its accuracy, originality, and consistency with the research findings and accepts full responsibility for the content of this thesis.

## Popular science summary

Farmers in Punjab already know that burning rice straw harms the environment. Most understand that the smoke pollutes the air, damages the soil and affects the health of people living nearby. Yet this awareness alone did not change what happens in the fields.

The biggest obstacle is time. Only a few weeks separate the rice harvest from the sowing of wheat, and farmers explained that they must prepare their fields in a hurry, because late sowing lowers the wheat yield. When machines are unavailable or too expensive, burning is the quickest and most dependable way to clear the field.

Money and logistics matter as well. Machinery costs, labour shortages, diesel prices and uncertainty about government subsidies all shape farmers' decisions. Many participants wanted to use sustainable practices but could not get the right machine at the right time, and machinery providers confirmed that equipment runs short during the harvest peak. Extension officers and policy stakeholders agreed that awareness campaigns have worked. They asked for practical support: timely access to machinery, effective extension services and smoother delivery of subsidies.

Many farmers saw crop diversification as a promising long-term strategy, but few were ready to give up rice, which offers relatively stable markets and government procurement. They said that alternative crops would become realistic only with market and price security and institutional support.

Overall, the study shows that burning is not simply a result of a lack of environmental awareness. It results from a combination of economic constraints, limited machinery availability, institutional obstacles and the way rice–wheat production is organised in Punjab. Tackling only one of these problems will not end burning. The study recommends strengthening Custom Hiring Centres, improving access to residue-management machinery, combining machinery subsidies with practical farmer training, making subsidy delivery more efficient, supporting markets for alternative crops, and involving farmers more in policy-making.

Managing crop residues sustainably requires cooperation among farmers, scientists, extension services, government institutions and the private sector. By documenting farmers' experiences and practical constraints, this research supports policies that are environmentally sustainable, economically feasible and socially acceptable, and that can improve air quality, soil health and the long-term sustainability of farming in Punjab.

## References


Abdurrahman, M. I., Chaki, S., & Saini, G. (2020). Stubble burning: Effects on health & environment, regulations and management practices. *Environmental Advances*, *2*, 100011.

Ahmed, T., Ahmad, B., & Ahmad, W. (2015). Why do farmers burn rice residue? Examining farmers' choices in Punjab, Pakistan. *Land Use Policy*, *47*, 448–458.

Alawode, A. (2025). Evaluating agricultural subsidy reforms and their effects on smallholder farmer income and efficiency. *International Journal of Advance Research Publication and Reviews*, *2*(5), 180–201.

Andreae, M. O., & Merlet, P. (2001). Emission of trace gases and aerosols from biomass burning. *Global Biogeochemical Cycles*, *15*(4), 955–966.

Arunrat, N., Sereenonchai, S., Sansupa, C., Kongsurakan, P., & Hatano, R. (2023). Effect of rice straw and stubble burning on soil physicochemical properties and bacterial communities in central Thailand. *Biology*, *12*(4), 501.

Auffhammer, M., Ramanathan, V., & Vincent, J. R. (2006). Integrated model shows that atmospheric brown clouds and greenhouse gases have reduced rice harvests in India. *Proceedings of the National Academy of Sciences*, *103*(52), 19668–19672.

Awasthi, A., Agarwal, R., Mittal, S. K., Singh, N., Singh, K., & Gupta, P. K. (2011). Study of size and mass distribution of particulate matter due to crop residue burning with seasonal variation in rural area of Punjab, India. *Journal of Environmental Monitoring*, *13*(4), 1073–1081.

Badarinath, K., Chand, T. K., & Prasad, V. K. (2006). Agriculture crop residue burning in the Indo-Gangetic Plains–a study using IRS-P6 AWiFS satellite data. *Current science*, 1085–1089.

Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V., & Makowski, D. (2021). Positive but variable effects of crop diversification on biodiversity and ecosystem services. *Global Change Biology*, *27*(19), 4697–4710.

Bhatia, A., Jain, N., & Pathak, H. (2012). Greenhouse gas emissions from Indian agriculture. *Low Carbon Technologies for Agriculture: a Study on Rice and Wheat Systems in the Indo-Gangetic Plains*, *1*(6), 12–23.

Bhatt, R., Singh, P., Hossain, A., & Timsina, J. (2021). Rice–wheat system in the northwest Indo-Gangetic plains of South Asia: issues and technological interventions for increasing productivity and sustainability. *Paddy and Water Environment*, *19*(3), 345–365.

Bhattacharyya, P., Bisen, J., Bhaduri, D., Priyadarsini, S., Munda, S., Chakraborti, M., Adak, T., Panneerselvam, P., Mukherjee, A., & Swain, S. L. (2021). Turn the wheel from waste to wealth: economic and environmental gain of sustainable rice straw management practices over field burning in reference to India. *Science of the Total Environment*, *775*, 145896.

Bhuvaneshwari, S., Hettiarachchi, H., & Meegoda, J. N. (2019). Crop residue burning in India: Policy challenges and potential solutions. *International Journal of Environmental Research and Public Health*, *16*(5), 832. https://doi.org/10.3390/ijerph16050832

Brar, P. (2024). *Economic and environmental effects of practicing crop residue on-field composting as a substitute for burning – A case study of Punjab (India)* [Thesis, University of Northern British Columbia].

Bustos-Terrones, V. (2026). Valorization routes for crop residues in sustainable bioeconomy: a scoping review of technologies and impacts. *Journal of Environmental Science and Health, Part B*, *61*(7), 393–415.

CCAC & FAO. (2022). *Establishing residue supply chains to reduce open burning: The case of rice straw and renewable energy in Punjab, India*. Climate and Clean Air Coalition and Food and Agriculture Organization of the United Nations.

Chendrashekhar, S., & Lokesh, G. (2018). Cost and Returns of Paddy Crop under Different Residue Management Practices in Tunga Bhadra Command Area of Karnataka (India). *International Journal of Current Microbiology and Applied Sciences*, *7*(12), 867–873.

Chendrashekhar, S. (2016). *An economic analysis of paddy residue management practices in TBP command area*.

Chhatre, A., Devalkar, S., & Seshadri, S. (2016). Crop diversification and risk management in Indian agriculture. *Decision*, *43*(2), 167–179.

Chhokar, R., Singh, S., Sharma, R., & Singh, M. (2009). Influence of straw management on *Phalaris minor* Retz. control. *Indian J. Weed Sci*, *41*(3&4), 150–156.

Choudhary, A., Kadian, K., Meena, M., & Kambale, P. (2022). Readiness of Farmers to Adopt Crop Residue Management Alternatives: A study from Haryana State. *Journal of AgriSearch*, *9*(1), 103–108.

Creswell, J. W., & Poth, C. N. (2016). *Qualitative inquiry and research design: Choosing among five approaches*. Sage publications.

Das, P., Behera, M., & Abhilash, P. (2024). A rapid assessment of stubble burning and air pollutants from satellite observations. *Tropical Ecology*, *65*(1), 152–157.

Dehal, L., Punia, A., & Chauhan, N. S. (2025). Circular Practices in Agriculture Sector: Current Challenges and Opportunities. *Circular Economy and Sustainable Innovation: Pathways and Applications for a Greener Future, Volume 2*, 127–150.

Department of Agriculture & Cooperation. (2014). *Annual report 2014–15*. Ministry of Agriculture, Government of India.

Dhanda, S., Yadav, A., Yadav, D. B., & Chauhan, B. S. (2022). Emerging issues and potential opportunities in the rice-wheat cropping system of north-western India. *Frontiers in Plant Science*, *13*, 832683. https://doi.org/10.3389/fpls.2022.832683

Dhanger, P., Jain, M., Rani, V., Kumar, M., & Ghanghas, S. (2022). Paddy straw management practices in Northern India for improved efficiency and techno-economic feasibility. *Indian J. Agric. Sci*, *92*(4), 526–530.

Döring, T. F., Brandt, M., Heß, J., Finckh, M. R., & Saucke, H. (2005). Effects of straw mulch on soil nitrate dynamics, weeds, yield and soil erosion in organically grown potatoes. *Field Crops Research*, *94*(2-3), 238–249.

Downing, A. S., Kumar, M., Andersson, A., Causevic, A., Gustafsson, Ö., Joshi, N. U., Krishnamurthy, C. K. B., Scholtens, B., & Crona, B. (2022). Unlocking the unsustainable rice-wheat system of Indian Punjab: Assessing alternatives to crop-residue burning from a systems perspective. *Ecological Economics*, *195*, 107364.

Dutta, A., Patra, A., Hazra, K. K., Nath, C. P., Kumar, N., & Rakshit, A. (2022). A state of the art review in crop residue burning in India: Previous knowledge, present circumstances and future strategies. *Environmental Challenges*, 8, 100581. https://doi.org/10.1016/j.envc.2022.100581

Erbaugh, J., Singh, G., Luo, Z., Koppa, G., Evans, J., & Shyamsundar, P. (2024). Farmer perspectives on crop residue burning and sociotechnical transition in Punjab, India. *Journal of Rural Studies*, *111*, 103387. https://doi.org/10.1016/j.jrurstud.2024.103387

FAO. (2018). *Agroecology: Principles for the conversion and redesign of farming systems*. Food and Agriculture Organization of the United Nations.

Farag, A., Radwan, H., Abdrabbo, M., Heggi, M., & McCarl, B. (2013). Carbon footprint for paddy rice production in Egypt. *Nat. Sci*, *11*(12), 40–45.

Gandhi, P. (2024). *Extinguishing the blaze: Impact of crop residue management on stubble burning in India* [Pre-analysis plan, AEARCTR-0014559]. AEA RCT Registry. https://doi.org/10.1257/rct.14559-1.0

Gawdiya, S., Sharma, R. K., Singh, H., & Kumar, D. (2025). Crop diversification as a cornerstone for sustainable agroecosystems: tackling biodiversity loss and global food system challenges. *Discover Applied Sciences*, *7*(5), 373.

Gill, Jagjot Singh, & Singh, Maninder. (2020). Comparison of wheat production under different paddy residue management methods. Current Journal of Applied Science and Technology, 38(6), 1-9.

Gliessman, S. R. (2015). *Agroecology: The ecology of sustainable food systems* (3rd ed.). CRC Press.

Government of India, Ministry of Environment, Forest and Climate Change. (2025, August 4). *Stubble burning incidents in Punjab and Haryana, 2021–2024* [Written reply in the Lok Sabha].

Gulati, B., Sharma, R., Kanga, S., Singh, S. K., Sajan, B., Meraj, G., Kumar, P., & Ramanathan, A. (2023). Unraveling the relationship between stubble burning and air quality degradation in Punjab: A temporal and spatial analysis (2019-2022). *Journal of Climate Change*, *9*(2), 43–53.

Gupta, E., Dutta, S., Sharma, H., Thakur, D., Agarwal, S., Singh, R., Erbaugh, J., Singh, G., Koppa, G., & Shyamsundar, P. (2026). From fields to policy: analyzing the interplay between technology adoption and residue burning in Punjab, India. *Environmental Research: Food Systems*, *3*(3), 035008.

Gupta, P. K., Sahai, S., Singh, N., Dixit, C., Singh, D., Sharma, C., Tiwari, M., Gupta, R. K., & Garg, S. (2004). Residue burning in rice–wheat cropping system: Causes and implications. *Current science*, 1713–1717.

Gupta, R. (2012). *Causes of emissions from agricultural residue burning in north-west India: evaluation of a technology policy response*. The Institute of Development Studies and Partner Organisations.

Gupta, R. (2014). Low-hanging fruit in black carbon mitigation: crop residue burning in South Asia. *Climate Change Economics*, *5*(04), 1450012.

Gustafsson, O., Krusa, M., Zencak, Z., Sheesley, R. J., Granat, L., Engstrom, E., Praveen, P., Rao, P., Leck, C., & Rodhe, H. (2009). Brown clouds over South Asia: biomass or fossil fuel combustion? *Science*, *323*(5913), 495–498.

Haider, M. Z. (2013). Determinants of rice residue burning in the field. *Journal of Environmental Management*, *128*, 15–21.

Hindustan Times. (2025, October 22). *Punjab sees highest single-day spike of 69 farm fires, tally nears 500*.

Holling, C. S., & Gunderson, L. H. (2001). *Panarchy: understanding transformations in human and natural systems*. Island press.

Jain, N., Bhatia, A., & Pathak, H. (2014). Emission of air pollutants from crop residue burning in India. *Aerosol and Air Quality Research*, *14*(1), 422–430.

Jain, S., Kemanth, K., & Sarao, N. S. (2025). Custom Hiring Centres for Better Crop Residue Management: Insights from Punjab. New Delhi: Council on Energy, Environment and Water.

Kanokkanjana, K., & Garivait, S. (2013). Alternative rice straw management practices to reduce field open burning in Thailand. *International Journal of Environmental Science and Development*, *4*(2), 119.

Kaur, A. (2017). Crop residue in Punjab agriculture-status and constraints. *J. Krishi Vigyan*, *5*(2), 22–26.

Keil, A., Krishnapriya, P. P., Mitra, A., Jat, M. L., Sidhu, H. S., Krishna, V. V., & Shyamsundar, P. (2021). Changing agricultural stubble burning practices in the Indo-Gangetic Plains: Is the Happy Seeder a profitable alternative? *International Journal of Agricultural Sustainability*, *19*(2), 128–151. https://doi.org/10.1080/14735903.2020.1834277

Kemanth, K., Singh, R., & Ignatious, M. (2024). *How can Punjab increase the adoption of crop residue management methods?* Council on Energy, Environment and Water (CEEW).

Kohli, R., Mittal, A., & Mittal, A. (2024). Research Insights into Punjab's Stubble Burning Menace. *Nature Environment & Pollution Technology*, *23*(3).

Krishnapriya, P., Pattanayak, S. K., Somanathan, E., Keil, A., Jat, M., Sidhu, H., & Shyamsundar, P. (2024). Mitigating agricultural residue burning: challenges and solutions across land classes in Punjab, India. *Environmental Research: Food Systems*, *1*(1), 015001.

Kumar, A., Jat, M., Kumar, A., Tomar, J., Kumar, S., & Kushwaha, S. (2016). Rice residue management in wheat under different tillage practices and nitrogen doses. *Annals of Agricultural Research*, *37*(1), 49–55.

Kumar, P., & Kumar, S. (2010). *Valuing the health effects of air pollution from agricultural residue burning*. Institute for Social and Economic Change and TERI University.

Kumar, S., Sharma, D., Singh, D., Biswas, H., Praveen, K., & Sharma, V. (2019). Estimating loss of ecosystem services due to paddy straw burning in North-west India. *International Journal of Agricultural Sustainability*, *17*(2), 146–157.

Kumar, V., Naresh, R., Kumar, S., Kumar, S., Kumar, A., Gupta, R., Rathore, R., Singh, S., Dwivedi, A., & Tyagi, S. (2018). Efficient nutrient management practices for sustaining soil health and improving rice-wheat productivity: A review. *Journal of Pharmacognosy and Phytochemistry*, *7*(1), 585–597.

Lohan, S. K., Jat, H., Yadav, A. K., Sidhu, H., Jat, M., Choudhary, M., Peter, J. K., & Sharma, P. (2018). Burning issues of paddy residue management in north-west states of India. *Renewable and Sustainable Energy Reviews*, *81*, 693–706.

Mal, T., & Chaudhary, A. (2024). Maize-based diversification options for rice-wheat cropping system. Indian Farming, 73(12), 23–26.

Malasa, R., & Roguel, S. (2002). Social impact assessment of rice hull burning and stale seedbed technique of IPM CRSP. *Philippine Journal of Crop Science (Philipines)*, *27*(supplement1).

Malik, J. S., & Kumar, S. (2019). Crop residue burning: issue and management for climate-smart agriculture in NCR region, India. *Asian Journal of Agricultural Extension, Economics & Sociology*, *36*(1), 1–11.

Ministry of Agriculture and Farmers Welfare. (2018). *Operational guidelines: Promotion of agricultural mechanization for in-situ management of crop residue in the states of Punjab, Haryana, Uttar Pradesh and NCT of Delhi*. Government of India.

Miura, Y., & Kanno, T. (1997). Emissions of trace gases (CO2, CO, CH4, and N2O) resulting from rice straw burning. *Soil Science and Plant Nutrition*, *43*(4), 849–854.

Mohammadi, A., Cowie, A. L., Cacho, O., Kristiansen, P., Mai, T. L. A., & Joseph, S. (2017). Biochar addition in rice farming systems: Economic and energy benefits. *Energy*, *140*, 415–425.

Mohanty, M. (2004). Rice residue-management options and effects on soil properties and crop productivity.

Naser, H. M., Nagata, O., Tamura, S., & Hatano, R. (2007). Methane emissions from five paddy fields with different amounts of rice straw application in central Hokkaido, Japan. *Soil Science and Plant Nutrition*, *53*(1), 95–101.

Negi, V. S., Tiwari, D. C., Singh, L., Thakur, S., & Bhatt, I. D. (2022). Review and synthesis of climate change studies in the Himalayan region. *Environment, Development and Sustainability*, *24*(9), 10471–10502.

Nicolétis, É., Caron, P., El Solh, M., Cole, M., Fresco, L. O., Godoy-Faúndez, A., Kadleciková, M., Kennedy, E., Khan, M., & Li, X. (2019). Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security.

Ojo, M., Nmadu, J., Tanko, L., & Olaleye, R. (2013). Multinomial logit analysis of factors affecting the choice of enterprise among small-holder yam and

cassava farmers in Niger State, Nigeria. *Journal of Agricultural Sciences*, *4*(1), 7–12.

Oraby, G. A. E. M., Putra, F., Natsir, M. H., Siswanto, D., Abdullah, M. M., & Abulibdeh, A. (2025). Straw Burning Dilemma in Modern Agriculture: A Systematic Review of Driving Factors, Environmental Impacts, and Sustainable Solutions. *Rice Science*, *32*(5), 637–648.

Pandey, K., & Sahu, L. (2014). Emissions of volatile organic compounds from biomass burning sources and their ozone formation potential over India. *Current science*, 1270–1279.

Pathak, H. (2023). Impact, adaptation, and mitigation of climate change in Indian agriculture. *Environmental Monitoring and Assessment*, *195*(1), 52.

Patton, M. Q. (2002). Qualitative research & evaluation methods. *(No Title)*.

Paudel, G. P., Chamberlin, J., & Nguyen, T. T. (2024). Can sustainable intensification boost agricultural productivity and fertilizer use efficiency? Insights from wheat systems in the eastern Indo-Gangetic Plains.

PIB. (2025, December 2). *Paddy harvesting season 2025 concludes with significant reduction in farm fire incidents across Punjab and Haryana* [Press release]. Press Information Bureau, Government of India.

Porichha, G. K., Hu, Y., Rao, K. T. V., & Xu, C. C. (2021). Crop residue management in India: Stubble burning vs. other utilizations including bioenergy. *Energies*, *14*(14), 4281.

Poungchompu, S., Kobayashi, T., & Chantanop, S. (2013). Factors affecting farmers' decisions on utilization of rice straw compost in Northeastern Thailand. *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, *114*(1), 21–27.

Pradhan, P., Sinha, A. K., & Pandit, T. K. (2024). The effect of stubble burning and residue management on soil properties: A review. *International Journal of Plant & Soil Science*, *36*(6), 36–49.

PRSC. (2024). *Data on stubble-burning hotspots and district-wise fire incidents*. Punjab Remote Sensing Centre / Punjab Pollution Control Board.

Punjab Department of Agriculture and Farmers' Welfare. (2024, November 26). *Status report of the State of Punjab in OA No. 63 of 2024: Report on stubble-burning incidents and residue management efforts*. Chandigarh, India.

Rahman, M. A., Chikushi, J., Saifizzaman, M., & Lauren, J. G. (2005). Rice straw mulching and nitrogen response of no-till wheat following rice in Bangladesh. *Field Crops Research*, *91*(1), 71–81.

Ramanathan, V., & Carmichael, G. (2008). Global and regional climate changes due to black carbon. *Nature Geoscience*, *1*(4), 221–227.

Rathod, A., Jagtap, M., Kinge, S., & More, P. (2021). Effect of tillage and crop residue management practices on yield and economics of wheat (*Triticum aestivum* L.) under conservation agriculture. *International Journal of Chemical Studies*, *9*(1), 841–843.

Rehman, A., Farooq, M., Lee, D.-J., & Siddique, K. H. (2022). Sustainable agricultural practices for food security and ecosystem services. *Environmental Science and Pollution Research*, *29*(56), 84076–84095.

Rosenberg, S., Brim-DeForest, W., Linquist, B., Leinfelder-Miles, M. M., Espino, L., Pittelkow, C. M., & Al-Khatib, K. (2025). Addressing economic barriers to crop diversification in rice-based cropping systems. *Npj Sustainable Agriculture*, *3*(1), 62.

Rosmiza, M., CR, R. A., Mazdi, M., & MJ, J. (2014). Farmers' knowledge on potential uses of rice straw: an assessment in MADA and Sekinchan, Malaysia. *Geografia*, *10*(5).

Roy, P., & Kaur, M. (2015). Status and problems of paddy straw management in West Bengal. *Int. J. Adv. Agric. Environ. Eng*, *2*(1), 44–48.

Sahai, S., Sharma, C., Singh, S., & Gupta, P. K. (2011). Assessment of trace gases, carbon and nitrogen emissions from field burning of agricultural residues in India. *Nutrient Cycling in Agroecosystems*, *89*(2), 143–157.

Sandhu, L. K., Rampal, M., & Singh, N. (2019). An economic analysis of paddy stubble management technology in Amritsar District of Punjab. *OIDA International Journal of Sustainable Development*, *12*(08), 47–58.

Sidhu, B., & Beri, V. (1989). Effect of crop residue management on the yields of different crops and on soil properties. *Biological Wastes*, *27*(1), 15–27.

Sidhu, H., Humphreys, E., Dhillon, S., Blackwell, J., & Bector, V. (2007). The Happy Seeder enables direct drilling of wheat into rice stubble. *Australian Journal of Experimental Agriculture*, *47*(7), 844–854.

Sidhu, H., Singh, M., Singh, Y., Blackwell, J., Lohan, S. K., Humphreys, E., Jat, M., Singh, V., & Singh, S. (2015). Development and evaluation of the Turbo Happy Seeder for sowing wheat into heavy rice residues in NW India. *Field Crops Research*, *184*, 201–212.

Singh, A., Alagusundaram, K., Kumar, A., Singh, R., Sehgal, V., Chahal, V., Singh, K., Mahal, J., & Singh, S. (2019). In-Situ Crop Residue Management: Key Outcome and Learning. *Division of Agricultural Extension, ICAR, New Delhi*, *30*.

Singh, G., Sachdeva, J., & Walia, G. S. (2022). Paddy straw management in Punjab: An economic analysis of different techniques. *Indian Journal of Ecology*, *49*(1), 302–308.

Singh, G., Singh, P., Sodhi, G. P. S., & Tiwari, D. (2020). Adoption status of rice residue management technologies in south western Punjab. Indian Journal of Extension Education, 56(3), 76–82.

Singh, J., Singh, J., Kumar, H., Singh, S., Sachdeva, J., Kaur, B., Chopra, S., & Chand, P. (2019). Management of paddy straw in Punjab: An economic analysis of different techniques. *Indian Journal of Agricultural Economics*, *74*(3), 301–310.

Singh, R., & Kaur, S. (2023). Adoption pattern of farm-machinery based solutions for in-situ paddy straw management in Punjab. *Indian Journal of Extension Education*, *59*(4), 103–108.

Singh, T., Kaur, M., & Singh, G. (2021). Extent of adoption of happy seeder technology among the farmers of Punjab (India). *Indian Journal of Extension Education*, *57*(4), 75–79.

Singh, Y., & Sidhu, H. (2014). Management of cereal crop residues for sustainable rice-wheat production system in the Indo-Gangetic plains of India. *Proceedings of the Indian National Science Academy*, *80*(1), 95–114.

Sommer, R., Piggin, C., Feindel, D., Ansar, M., van Delden, L., Shimonaka, K., Abdalla, J., Douba, O., Estefan, G., & Haddad, A. (2014). Effects of zero tillage and residue retention on soil quality in the Mediterranean region of northern Syria. *Open Journal of Soil Science*, *4*(3), 44383.

Surekha, K., Padma Kumari, A., Narayana Reddy, M., Satyanarayana, K., & Sta Cruz, P. (2003). Crop residue management to sustain soil fertility and irrigated rice yields. *Nutrient Cycling in Agroecosystems*, *67*(2), 145–154.

Tamburini, G., Bommarco, R., Wanger, T. C., Kremen, C., Van Der Heijden, M. G., Liebman, M., & Hallin, S. (2020). Agricultural diversification promotes multiple ecosystem services without compromising yield. *Science Advances*, *6*(45), eaba1715.

Tirol-Padre, A., Ladha, J., Regmi, A., Bhandari, A., & Inubushi, K. (2007). Organic amendments affect soil parameters in two long-term rice-wheat experiments. *Soil Science Society of America Journal*, *71*(2), 442–452.

Valbuena, D., Erenstein, O., Tui, S. H.-K., Abdoulaye, T., Claessens, L., Duncan, A. J., Gérard, B., Rufino, M. C., Teufel, N., & van Rooyen, A. (2012). Conservation agriculture in mixed crop–livestock systems: scoping crop residue trade-offs in Sub-Saharan Africa and South Asia. *Field Crops Research*, *132*, 175–184.

Verma, N. K., & Pandey, B. K. (2013). Effect of varying rice residue management practices on growth and yield of wheat and soil organic carbon in rice-wheat sequence. *Global Journal of Science Frontier Research Agriculture and Veterinary Sciences*, *13*(3), 32–38.

Yadvinder-Singh, B.-S., Ladha, J., Khind, C., Khera, T., & Bueno, C. (2004). Effects of residue decomposition on productivity and soil fertility in rice–wheat rotation. *Soil Sci Soc Am J*, *68*(3), 854–864.

Yang, Z., Ueda, K., Umemura, T., Onishi, K., Terasaki, H., Nakayama, T., Matsumi, Y., Vatta, K., Araki, H., Hayashida, S., & Patra, P. K. (2025). Perceptions of air pollution from stubble burning and its health risks in Punjab, India. *Scientific Reports*, 15, 37455. https://doi.org/10.1038/s41598-025-21235-8

Zuo, A., Hou, L., & Huang, Z. (2020). How does farmers' current usage of crop straws influence the willingness-to-accept price to sell? *Energy Economics*, *86*, 104639.

## Appendix A. Coding framework used for thematic analysis

### Table A1. The types and proportions of coded responses

| Theme | Sub-theme | Code | No. of respondents (n=30) |
|---|---|---|---|
| **Environmental** | Soil health | Improved soil fertility | 18 |
| | | Loss of soil nutrients due to burning | 20 |
| | Air quality | Air pollution from burning | 27 |
| | | Reduced smoke through alternatives | 17 |
| | Climate | Greenhouse gas emissions | 20 |
| | Biodiversity | Decline in soil microorganisms | 14 |
| **Socio-economic** | Economic factors | High machinery cost | 23 |
| | | Labour shortage | 20 |
| | | Narrow sowing window | 27 |
| | | Cost savings from burning | 18 |
| | Machinery access | Limited availability of Happy Seeder | 21 |
| | | Difficulty accessing CHCs | 16 |

| | | | |
|---|---|---|---|
| | Adoption | Positive experience with Happy Seeder | 6 |
| | | Residue incorporation | 2 |
| | | Straw baling/biomass use | 2 |
| | Farmer perceptions | Risk of delayed wheat sowing | 22 |
| | | Fear of yield reduction | 15 |
| | | Environmental awareness | 19 |
| **Policy and Institutional** | Government support | Machinery subsidy | 20 |
| | | Delayed subsidy payments | 9 |
| | Extension | Extension training programmes | 17 |
| | | Need for farmer awareness campaigns | 18 |
| | Institutions | Trust in government programmes | 12 |
| | | Weak policy implementation | 16 |
| | | Poor enforcement of burning regulations | 14 |
| | Recommendations | Better machinery access | 21 |

| | | | |
|---|---|---|---|
| | | Strengthen Custom Hiring Centres | 16 |
| | | Promote crop diversification | 13 |
| | | Incentives for sustainable practices | 19 |

**Appendix B. Summary of farmer interview transcripts**

*(Rather than including every verbatim transcript in the main thesis, it is common practice to include either full transcripts or a summary table in an appendix.)*

| Respondent | District | Residue management practice | Main reason for chosen practice | Key quotation/theme |
|---|---|---|---|---|
| Farmer A | Ludhiana | Happy Seeder | Soil moisture, successful previous experience | "The soil stays moist and wheat establishes well." |
| Farmer B | Ludhiana | Happy Seeder | Lower tillage requirement | "Field preparation is easier now." |
| Farmer C | Ludhiana | Happy Seeder | Extension demonstration | "Seeing other farmers succeed convinced me." |
| Farmer D | Ludhiana | Happy Seeder | Lower fuel use | "It saves both time and diesel." |
| Farmer E | Ludhiana | Happy Seeder | Reliable CHC access | "The machine is available when I need it." |
| Farmer F | Ludhiana | Burning | Time pressure | "There isn't enough time to wait." |
| Farmer G | Sangrur | Residue incorporation | Long-term soil fertility | "Residue improves soil over time." |
| Farmer H | Sangrur | Residue incorporation | Soil improvement | "The residue becomes part of the soil." |
| Farmer I | Sangrur | Burning | Fear of delayed sowing | "Late wheat means lower yields." |

| | | | | |
|---|---|---|---|---|
| Farmer J | Sangrur | Burning | Machinery shortage | "Machines are booked everywhere." |
| Farmer K | Sangrur | Burning | Operational convenience | "Burning clears everything immediately." |
| Farmer L | Sangrur | Burning | Labour shortage | "Finding labour is difficult." |
| Farmer M | Mansa | Happy Seeder | Better moisture retention | "The field remains moist for longer." |
| Farmer N | Mansa | Straw baling | Income from straw | "Selling straw gives extra income." |
| Farmer O | Mansa | Straw baling | Biomass utilisation | "The straw has value instead of being burned." |
| Farmer P | Mansa | Burning | Protect wheat yield | "I cannot risk delaying sowing." |
| Farmer Q | Mansa | Burning | Immediate field clearance | "Burning is still the fastest option." |
| Farmer R | Mansa | Burning | Limited machinery availability | "Burning is the quickest option." |

## Appendix C. Interview guide

The interviews were semi-structured. The guide below lists the themes and the open-ended questions used as prompts; the wording and order of questions were adapted to each respondent and follow-up questions were asked to explore issues as they arose. Before each interview, participants were informed about the purpose of the study and that participation was voluntary and anonymous (Section 3.7).

**Part 1. Introduction and background (all respondents)**

1. Could you tell me about your role and experience in relation to paddy residue management? (For farmers: farm size, cropping pattern and how long you have grown paddy and wheat.)

2. How is paddy residue usually managed in your area, and how have practices changed in recent years?

**Part 2. Residue burning, environment and soil (all respondents)**

3. Why do farmers in your area burn or not burn paddy residue?

4. What effects of residue burning on air quality, health, soil and the wider environment have you noticed or heard about?

5. What is your view of the effect of burning, retention or incorporation of residue on soil health and later crop yields?

**Part 3. Practices, technologies and economics**

6. Which residue-management practices or technologies have you used or been involved with (for example Happy Seeder, Super SMS, Super Seeder, incorporation, mulching, baling, biomass use)? What was your experience?

7. What are the main costs involved (machinery hire, diesel, labour, repairs), and how do they compare with burning?

8. How important is the time between paddy harvest and wheat sowing in your decisions?

9. What risks do you associate with alternatives to burning (delayed sowing, pests and rodents, decomposition, yield)?

**Part 4. Machinery access, subsidies, extension and institutions**

10. How easy is it to obtain residue-management machinery when you need it, including through Custom Hiring Centres?

11. What is your experience of government subsidies and schemes, such as the Crop Residue Management Scheme (application, delay, cost, fairness)?

12. What training, demonstration or advice have you received or provided, and how useful was it?

13. How well do farmers, machinery providers, extension services and government agencies coordinate with each other?

**Part 5. Longer-term change and recommendations**

14. Do you think changes in the cropping system, such as crop diversification, could reduce residue burning? What would be needed to make this possible?

15. What are the main challenges to wider use of sustainable residue management in Punjab?

16. What would you recommend to farmers, to government and to other stakeholders?

**Additional prompts by stakeholder group**

Farmers: farm-level decision-making, residue management in the last season, constraints in production and economics, willingness to try alternatives.

Machinery providers and Custom Hiring Centre representatives: machinery demand and availability in the harvest season, booking and scheduling, costs and maintenance, farmer uptake and challenges in operating the service.

Extension officers: farmer awareness, demonstrations and training, farmers' concerns about alternatives, challenges in implementation.

Policy and institutional stakeholders: government policies and subsidy programmes, institutional coordination, enforcement mechanisms and future policy directions.

**Publishing and archiving**

Approved students' theses at SLU can be published online. As a student you own the copyright to your work and in such cases, you need to approve the publication. In connection with your approval of publication, SLU will process your personal data (name) to make the work searchable on the internet. You can revoke your consent at any time by contacting the library.

Even if you choose not to publish the work or if you revoke your approval, the thesis will be archived digitally according to archive legislation.

You will find links to SLU's publication agreement and SLU's processing of personal data and your rights on this page:
https://libanswers.slu.se/en/faq/228318

YES, I, Shubkaran Singh , have read and agree to the agreement for publication and the personal data processing that takes place in connection with this.