SUSTAINABLE AGRICULTURAL RESIDUE MANAGEMENT OPTIONS FOR SMOG REDUCTION

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ABSTRACT

Air pollution, notably the smog issue, has become a recurring environmental and public health crisis in Pakistan where emissions increase during the post-harvest period. Amongst these sources, the open burning of rice residue continues to be a major contributor to fine particulate matter, smoke, and smog formation. Despite policy and enforcement efforts, residue burning continues due to certain constraints faced by farmers, including narrow sowing-time windows, cost, and limited access to machinery. The existing policies and programs are primarily enforcement-based, while focus on enabling farmer-centric sustainable transition and promoting valorization-based entrepreneurial pathways is limited. Because smog and residue burning are multifaceted problems, a multidimensional study, holistically integrating social, economic, environmental, and policy aspects of the problem, to identify sustainable and scalable solutions and devise data-driven policy recommendations is needed. However, such a systematic research for Pakistan is currently absent in the scientific and policy literature. To bridge this gap, the overarching aim of this study was to identify scalable and sustainable agricultural residue management and valorization solutions for Pakistan through conducting a multidimensional study comparing the baseline scenario (open burning) with alternative on-farm and off-farm rice residue management and valorization scenarios. Accordingly, the study evaluates alternative on-farm and off-farm rice residue management and valorization options using an integrated environmental, economic, and social assessment. Five scenarios were studied: open burning, shredder-based residue incorporation, direct sowing using a super seeder, composting, and pyrolysis. Environmental impacts were assessed with a focus on air quality and climate and health impacts, while economic analysis studied costs incurred by farmers and enterprises. A farmer survey was conducted to determine demographics, knowledge, attitudes, practices, satisfaction, and practical barriers related to residue management. The results of these multidimensional individual assessments were eventually integrated to acquire a holistic evidence for policy recommendations. The results show that open burning performs worst across environmental impacts relevant to smog and public health. Amongst on-farm alternatives, the super seeder appeared as the most environmentally effective and least costly option, though its adoption is constrained by a number of barriers including tractor availability and power requirements. Enterprise-based composting and pyrolysis offer economic potential and environmental benefits but require organized supply chain and product markets. The findings suggest that residue burning continues due to misalignment between policy instruments, farmer realities, and available alternatives, demanding a phased, inclusive, and equitable policy approach enabling on-farm transition via a mix of subsidies, concessional financing, and penalties along with complementary off-farm entrepreneurial pathways for sustainable and scalable agricultural residue management and associated smog mitigation.

PREFACE

Smog has become a serious environmental and public health challenge in Pakistan, particularly in Punjab. Amongst its key contributors, the open burning of agricultural residues, especially rice residue, following the Kharif harvest, has been widely identified as one of the significant sources of ozone precursors, fine particulate matter, and greenhouse gas emissions. Despite policy attention, residue burning continues due to economic, technical, institutional, and behavioral constraints faced by farmers. Addressing this problem therefore necessitates integrated solutions that are environmentally effective, economically viable, and socially acceptable.

Accordingly, the present study was conducted to generate evidence-based policy insights into alternative rice residue management pathways for Pakistan. Recognizing the limitations of enforcement-driven approaches, the study adopts a holistic and multidimensional framework that integrates environmental life cycle assessment (e-LCA), economic analysis (including cost accounting and cost–benefit analysis), and social assessment based on farmers' knowledge, attitudes, and practices (KAP). By holistically assessing environmental impacts, financial feasibility, and farmer behavior, the study aims to support informed and practical policy decision-making.

The study's scope includes rice residue management in Punjab, with Gujranwala District selected as a representative case due to its high rice acreage and prevalent practice of open burning. Five residue management scenarios were assessed, covering both on-farm (farmer-based) and off-farm (enterprise-based) pathways: open burning as the baseline, shredder-based residue incorporation, super seeder–based direct sowing, compost production through windrow composting, and biochar production through pyrolysis. Environmental impacts were evaluated using life cycle assessment approach, while economic analyses were conducted under locally realistic assumptions reflecting prevailing farming and enterprise conditions. A social survey captured farmers' perceptions, constraints, and decision-making factors related to residue management.

The main goal of this work is to provide a data-driven assessment of sustainable agricultural residue management options that can contribute to smog reduction in Pakistan. Beyond scenario comparison, the study aims to inform policy by identifying trade-offs, co-benefits, and implementation challenges associated with different pathways, thereby enabling the design of interventions that are environmentally friendly, economically viable, and socially acceptable.

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ABBREVIATIONS

ac	Acre
BCR	Benefit–Cost Ratio
CBA	Cost–Benefit Analysis
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2-eq	Carbon Dioxide Equivalent
CRF	Capital Recovery Factor
CS-1	Cost of Scenario-1 (baseline cost term used in normalization)
I-CVI	Item-Content Validity Index
DALY	Disability-Adjusted Life Year
DPBP	Discounted Payback Period
e-LCA	Environmental Life Cycle Assessment
EAC	Equivalent Annual Cost
EEI	Eco-Efficiency Index
E_{Eco}	Normalized ecosystem endpoint term used in eco-efficiency aggregation
E_{HH}	Normalized human-health endpoint term used in eco-efficiency aggregation
EPD	Environment Protection Department
FU	Functional Unit
GHG	Greenhouse Gas
GOP	Government of Pakistan
GWP	Global Warming Potential
ha	Hectare

HP	Horsepower
IBI	International Biochar Initiative
IPCC	Intergovernmental Panel on Climate Change
IRB	Institutional Review Board
IRR	Internal Rate of Return
ISO	International Organization for Standardization
KAP	Knowledge, Attitudes, and Practices
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
MoCC	Ministry of Climate Change
N_2O	Nitrous Oxide
NMHC	Non-Methane Hydrocarbons
NMVOC(s)	Non-Methane Volatile Organic Compound(s)
NO_x	Nitrogen Oxides
NO_2	Nitrogen Dioxide
NPV	Net Present Value
O_3	Ozone
PAHs	Polycyclic Aromatic Hydrocarbons
PBS	Pakistan Bureau of Statistics
PCA	Profit-Cost Analysis
PCR	Profit-cost Ratio
PKR	Pakistani Rupee
PM	Particulate Matter

$PM_{2.5}$	Fine Particulate Matter (≤ 2.5 μm)
PM_{10}	Particulate Matter (≤ 10 μm)
RAG	Ratio of Above-Ground residue dry matter to harvested product yield
ReCiPe	ReCiPe life-cycle impact assessment method
RPR	Residue-to-Product Ratio
S-1 to S-5	Scenario 1 to Scenario 5
SimaPro	SimaPro (life-cycle assessment software)
SO_2	Sulfur Dioxide
SPSS	Statistical Package for the Social Sciences
USEPA	United States Environmental Protection Agency
USDA	United States Department of Agriculture
VOCs	Volatile Organic Compounds

INTRODUCTION

1.1. Background

Pakistan is one of the world's largest rice growers with an annual production of 9.9 million tonnes in 2023–2024 (Rehman et al., 2020; Fatima & Zeeshan, 2024). However, rice residue management continues to be a challenge. Open field burning is the most prevalent practice due to its convenience and low cost, but it contributes heavily to air pollution and smog (Ahmed et al., 2015; Raza et al., 2022). During October and November, burning residues in Punjab releases large amounts of carbon monoxide (CO), nitrogen oxides (NOx), particulate matter (PM), sulfur dioxide (SO_2), and volatile organic compounds (VOCs), which combine with vehicular and industrial emissions to generate harmful smog episodes (Mahmood & Gheewala, 2020; Majeed et al., 2024). Emissions from agricultural residue burning contributes ~4%–20% to Pakistan's overall smog (FAO, 2020; The Urban Unit, 2020, 2024). Its effects intensify during October–November due to atmospheric stagnation, and regional evidence identifies rice paddy fire smoke, rather than fog, as a key driver of reduced visibility (Majeed et al., 2024). The smog episodes cause serious health impacts, e.g., respiratory and cardiovascular ailments, and economic losses due to reduced visibility and disruptions in transportation. Primary reason for agriculture's part of this problem is the non-accessibility to affordable, scalable, and farmer-friendly alternatives to open burning (Rafiq et al., 2019).

Rice residue is notably challenging to manage because of its high silica content, low nutritional value, and poor digestibility, which restrain its usage as animal feed or in other industrial applications (Raza et al., 2022; Krishna & Mkondiwa, 2023). While in-situ (on-farm) technologies such as shredders and super seeders are available, their adoption has been limited due to high costs, operational challenges, and equipment requirements (Kaur et al., 2022; Lohan, 2018). Off-farm options like composting or pyrolysis have the potential for soil health improvement and greenhouse gas mitigation (Goswami et al., 2020; Bushra & Remya, 2024; Patel & Panwar, 2023), however, demand organized collection and processing facilities.

Life cycle assessment (LCA) is an approach that can be used to evaluate the environmental trade-offs of residue management strategies (ISO, 2006a, 2006b). However, such studies are scarce in Pakistan, with little attention to local barriers and farmer realities (Mahmood & Gheewala, 2020). Additionally, cost accounting for in-situ options and cost-benefit analyses (CBA) of ex-situ options are also important to evaluate the economic viability, yet remain underexplored (Kashif et al., 2020). Social aspects, including farmers' knowledge, attitudes, and practices, are equally crucial but often ignored in policymaking (Abdullah et al., 2021).

Policy landscape in Pakistan has recognized open burning as a contributor to air pollution and smog and thus introduced blanket bans, subsidies as a solution, and enforcement measures (EPD, 2017; LHC, 2018; Government of Punjab, 2018, 2024a, 2024b; GOP, 2023; NDMA, 2024). However, these approaches largely rely on top-down enforcement with limited farmer engagement, inadequate inclusion of LCA or CBA assessments, and negligible consideration of ex-situ enterprise-based alternatives such as composting and pyrolysis. Hence, policy efforts have remained insufficient in addressing key causes.

Accordingly, this study aims to holistically integrate environmental, economic, and social dimensions to identify sustainable rice residue management and valorization pathways for Pakistan. By integrating environmental, economic, and farmer-centered social analysis, the study aims to deliver evidence-based recommendations for scalable, sustainable, and farmer-centric interventions.

1.2. Problem Statement

Because smog and residue burning are multifaceted problems, a multidimensional study, holistically integrating social, economic, environmental, and policy aspects of the problem, to identify sustainable and scalable solutions and devise data-driven policy recommendations is needed. However, such a systematic research for Pakistan is currently absent in the scientific and policy literature.

1.3. Research Objectives

To identify scalable and sustainable agricultural residue management and valorization solutions for Pakistan through conducting a multidimensional study comparing the baseline scenario (open burning) with alternative scenarios through achieving the following sub-objectives:

i. to determine environmental-friendly agricultural residue management and valorization options;
ii. to determine economically viable agricultural residue management and valorization options;
iii. to examine farmers' existing knowledge, attitudes, and practices related to agricultural residue management; and
iv. to integrate and translate findings into data-driven policy recommendations.

LITERATURE AND POLICY REVIEW

Pakistan is amongst the world's leading rice growers, with recent production averaging nearly 9 to 10 million tonnes annually, which generate a substantial amount of post-harvest residues (Rehman et al., 2020; Fatima & Zeeshan, 2024). The prevalent practice for managing the residues is open-field burning, because it is fast and incurs negligible costs to farmers, thereby enabling rapid preparation of fields for the subsequent crop (Ahmed et al., 2015). However, burning causes the depletion of soil organic matter, generates greenhouse gas emissions, and continues to be one of the notable contributors to winter air pollution and smog episodes in Punjab through considerable emissions of particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NOx), sulfur dioxide (SO_2), and volatile organic compounds (VOCs) (Raza et al., 2022; Mahmood & Gheewala, 2020; Majeed et al., 2024).

Rice residue is tricky to utilize because of its high silica content, low nutritional value, and poor digestibility, which make it inappropriate for animal feed and constrain its industrial applications (Raza et al., 2022; Krishna & Mkondiwa, 2023). The literature broadly suggests two pathways to deal with this: on-farm management and off-farm valorization.

On-farm management involves dealing with the residues directly at the field level. For example, tractor-mounted shredders chop and spread residue across the field for subsequent incorporation into soil (Government of Punjab, 2024a, 2024b; Kaur et al., 2022). While this prevents open burning, shredders involve upfront capital cost which is not always affordable for all farmers. Besides, residue incorporation into soil can lead to nitrogen immobilization which adversely affects yields (Lohan et al., 2018). Another option is the super seeder, which combines residue cutting, mixing, and sowing of the subsequent crop in a single run, thereby addressing the short sowing window after rice harvest (Government of Punjab, 2024a, 2024b). Despite its technical promise, adoption has been limited primarily due to high upfront cost and requirement for high-horsepower tractors (Kaur et al., 2022).

Off-farm valorization includes removing and collecting residues for processing outside the field. Composting is a biological process of controlled aerobic bioconversion that produces a stable organic soil conditioner capable of enhancing soil's physical, chemical, and biological properties (USEPA, 2025; Goswami et al., 2020). Although composting is considered low-cost and relatively simple, it requires longer processing times, often require co-substrate, and typically managed by enterprises. Pyrolysis, on the other hand, is a thermochemical process in which biomass is thermally treated in the absence of oxygen to produce biochar. Biochar has the ability to improve nutrient retention, enhance water holding capacity, and sequester carbon in soils for extended periods (Bushra & Remya, 2024; IBI, 2015; Patel & Panwar, 2023). However, off-farm valorization approaches remain underutilized in Pakistan, primarily because of lack of awareness or logistical constraints (Kashif et al., 2020).

To evaluate the environmental footprint of different options, environmental life cycle assessment (e-LCA), a standardized methodology for quantifying environmental impacts across the life cycle of products and processes (ISO, 2006a, 2006b) can be used. It could allow for fair comparison among different scenarios across multiple impact categories, including global warming which causes climate change, ozone formation which causes photochemical smog, and particulate matter formation which causes health issues (Mahmood & Gheewala, 2020). While alternatives demonstrate improvements but could also involve trade-offs. Composting reduces smoke but demands labor and time; soil incorporation avoids open burning yet generates nitrous oxide emissions; and pyrolysis sequesters carbon effectively but may involve financial risks (Mahmood & Gheewala, 2020; Lohan et al., 2018; Goswami et al., 2020; Patel & Panwar, 2023). Pakistan-specific life cycle assessments are limited, which are otherwise useful for evidence-based policy (Mahmood & Gheewala, 2020).

Besides, economic viability is an important determinant of adoption. Cost-Benefit Analysis (CBA) evaluates the economic feasibility of options by comparing costs, including equipment, labor, and fuel, with benefits such as fertilizer savings, yield improvements, and revenues from products (Kashif et al., 2020). For resource-constrained farmers, high up-front costs remain a major barrier, which highlights the importance of local evidence and financial incentives. From a societal perspective, avoided externalities, such as reduced healthcare costs from improved air quality and climate-related savings, further necessitate for alternatives. However, unless policies are complemented with sufficient financial instruments (subsidies or penalties), adoption at scale is unlikely to occur (EPD, 2017; GOP, 2023, Government of Punjab, 2018).

Surveys have showed that, despite awareness of the harms of burning, many farmers continue the practice due to time constraints, lack of affordable equipment, small landholdings, and poorly developed rental markets (Ahmed et al., 2015; Abdullah et al., 2021). When neighboring farmers continue burning and enforcement remains weak, individuals have little incentive to change their practices (Goswami et al., 2020).

Pakistan's policy framework in this regard is largely dominated by command-and-control approaches. The Policy on Controlling Smog (EPD, 2017) recognized open burning as a major contributor and suggested bans, administrative notifications, and short-term advisories. However, it lacks mechanisms for farmer engagement or incentives to promote adoption of alternatives. The Smog Commission Report (LHC, 2018) widened the scope by advising stakeholder consultations and promotion of technologies, e.g., super seeder. While this represented progress, the report continued to rely on administrative enforcement and hardly made any usage of LCA or CBA for systematically assessing alternatives such as composting and pyrolysis.

The Punjab Clean Air Action Plan (Government of Punjab, 2018) suggested awareness campaigns, enforcement measures, and subsidies for residue management machinery. Still, the document relied heavily on top-down enforcement and subsidy dissemination, with negligible focus on participatory decision-making or evaluation of promoted technologies. The National Clean Air Policy (GOP, 2023) reinforced bans and highlighted co-benefits of pollution control. However, its focus on top-down enforcement, limited ground-level consultation, and lack of utilization of LCA-based evidence restricted its effectiveness.

The Roadmap for Smog Mitigation 2024–2025 (Government of Punjab, 2024a) presented a relatively more structured framework, focusing on large-scale distribution of super seeders and shredders under a 60% subsidy model. While ambitious, it lacked ground-reality data on adoption rates, challenges faced by small-scale farmers, and long-term sustainability. Likewise, the Smog Control Strategy 2024–25 (Government of Punjab, 2024b), Winter Smog Guidelines (NDMA, 2024), and

Punjab’s SMOG Prevention and Control Rules (EPD, 2023) proposed enforcement efforts and public advisories but continued to ignore valorization-based off-farm options.

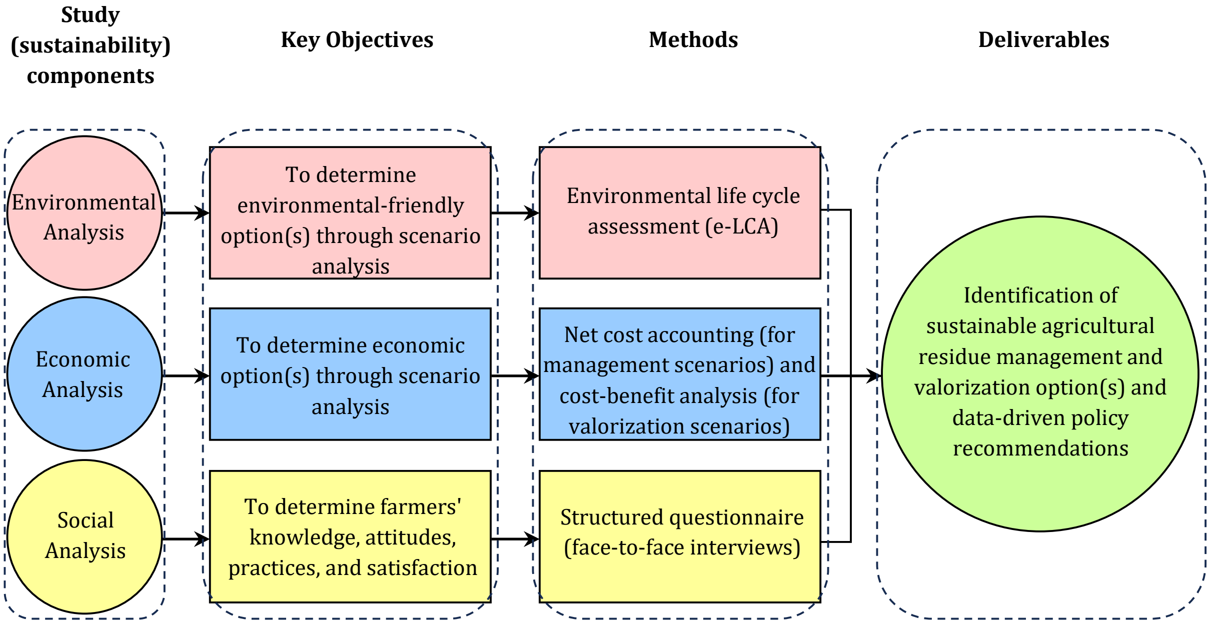
The literature body and existing policies show common shortcomings: limited farmer participation in policymaking, negligible incorporation of LCA and CBA evidence, incentives misaligned with farmers’ needs, and weak cross-sectoral coordination. Data-driven approaches, e.g., environmental LCAs, economic CBAs, and social assessments remain largely absent from policymaking, while valorization pathways, e.g., composting and pyrolysis continue to be disregarded. Resolving these issues requires a transition toward data-driven, evidence-based, and participatory approaches that integrate environmental, economic, and social aspects in residue management policy- and decision-making (ISO, 2006a, 2006b; Mahmood & Gheewala, 2020; Kashif et al., 2020; Abdullah et al., 2021).

RESEARCH METHODOLOGY

3.1. Scope of the Study

An overview of the scope and framework of this study, comprising social, environmental, and economic components, is illustrated in Figure 1.

Figure 1. Overview of Scope and Framework of the Study



Source: Authors' compilations.

3.1.1 Study Area

Given that it is one of the largest rice producers in Pakistan (>25% rice acreage of total rice-wheat system in Punjab) and having prevalent practice of open burning of rice residues (Azhar et al. 2019), Gujranwala, Punjab was selected as the representative study area.

3.1.2. Agricultural Residue

Rice crop residue was chosen as the representative agricultural residue for this study because its on-farm open burning is a major contributor to air-quality deterioration and smog formation. The term "residue" collectively refers to rice straw (cut stems left after combine harvesting) and stubble (the rooted lower stem). The remainder of the report uses the umbrella term "residue" because further distinguishing of straw and stubble are unnecessary from study objectives' viewpoint.

3.1.3. Functional Unit

The functional unit of the study is 1 tonne of rice residue managed or valorized. Using the 5-year average rough product (grain) yield for Punjab (3.85 t/ha) (USDA, 2025) and the residue-to-product ratio of 1.4 (IPCC, 2019), it is established that 1 tonne of residue corresponds to 0.714 tonnes of product (grains), requiring 0.186 hectares (0.458 acres) of land and representing a total harvested biomass of about 1.714 tonnes (Table 1).

In other words, on a per-hectare basis, rice cultivation produces approximately 3.85 tonnes of grain (product) and 5.39 tonnes of residue, giving a total harvested biomass of about 9.24 tonnes per hectare. This is equivalent to approximately 1.56 tonnes of grain and 2.18 tonnes of residue per acre, representing a total of 3.74 tonnes of biomass per acre. Environmental results will be consistently reported per tonne of residue, while economic calculations are first carried out on a per-acre basis (reflecting local farming practice) and subsequently converted into per-tonne values.

Table 1. Relationships Corresponding to the Functional Unit (1 Tonne Residue)

Item	Value	Remarks
Residue[1] (tonne)	1	Functional unit
Product[2] (tonne)	0.714	Product (tonne) = Residue (tonne) × RPR[3]
Total harvested biomass (tonne)	1.714	Total harvested biomass (tonne) = Residue (tonne) + Product (tonne)
Area (ha)	0.186	Area (ha) = Product (tonne) / Average product yield[4] (tonne/ha)
Area (ac)	0.458	Area (ac) = Area (ha) × 2.471[5]

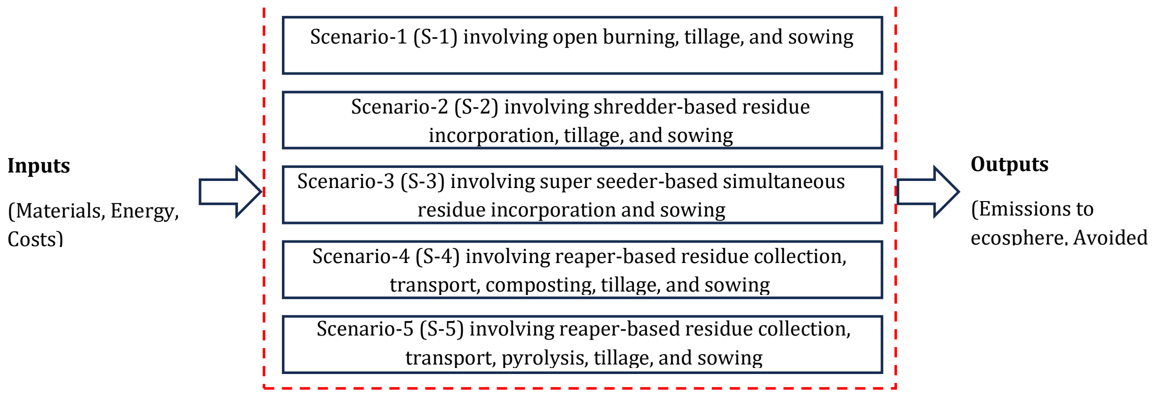
Notes: [1] Residue is used as an umbrella term encompassing straw and stubble. [2] Product refers to the rice grains excluding straw and stubble. [3] Residue-to-product ratio (RPR) = 1.4, referred to as the ratio of above-ground residue dry matter to harvested product yield (RAG) in IPCC (2019). [4] 5-year average product yield = 3.85 tonne/ha for Punjab, Pakistan from 2020-25 (USDA, 2025). [5] Unit conversion: 1 ha = 2.471 ac, where ha = hectare and ac = acre.

Source: Authors' compilations.

3.1.4. System Boundary and Scenarios

The scenarios and the system boundary used in this study are illustrated in Figure 2 and described further in the following paragraphs.

Figure 2. System Boundary Diagram also Showing Scenarios Used in the Study



Source: Authors' compilations.

Scenario 1 (S-1): After harvest, residues are openly burnt, followed by field preparation and wheat sowing using a disc plow, rotavator, and seed drill. The scenario serves as the baseline (reference) scenario with which all other scenarios are compared.

Scenario 2 (S-2): Residues are shredded and incorporated into soil using a tractor-mounted shredder. After shredding, the field is prepared using a disc plow and rotavator, followed by sowing with a seed drill.

Scenario 3 (S-3): All post-harvest operations till seeding are carried out by a super seeder machine. This machine is available locally in Pakistan and has been deployed in the field already in many areas of Pakistan. Super seeder integrates residue management, tillage, and crop sowing in one single run.

Scenario 4 (S-4): Rice residues are managed through windrow composting. After harvest, residues are collected using a tractor-mounted reaper and transported 450 m to a composting site, with cow dung used a co-substrate to achieve the required feedstock composition and moisture content. Windrows are formed using a tractor-mounted front loader and aerated weekly with a windrow turner.

Scenario 5 (S-5): Rice residues are converted into char using the Kon-Tiki flame-curtain pyrolysis method. Residues are transported to the pyrolysis facility and fed into an open-top conical kiln, where controlled flaming minimizes smoke and methane emissions.

3.2. Environmental Life Cycle Assessment (e-LCA)

The environmental life cycle assessment (e-LCA) was carried out following the International Organization for Standardization (ISO) framework (ISO, 2006a, 2006b), as further described as follows.

3.2.1. Life Cycle Inventory Analysis (LCI) and Life Cycle Impact Assessment (LCIA)

The LCI included compilation of relevant emissions (e.g., CO_2, CH_4, N_2O, NO_x, SO_2, NH_3, particulate matter, NMVOCs, and PAHs) from open burning, in-field residue management operations, residue collection and transport, composting, and pyrolysis processes, as well as avoided emissions from fertilizer substitution in enterprise-based scenarios. Data were collected from relevant sources, including research articles, official reports, companies' profiles, local manufacturers, and standard databases, including *Ecoinvent* v3.10 and *Agri-footprint* v6.3. All inventory flows were normalized to the functional unit of 1 tonne of rice residue.

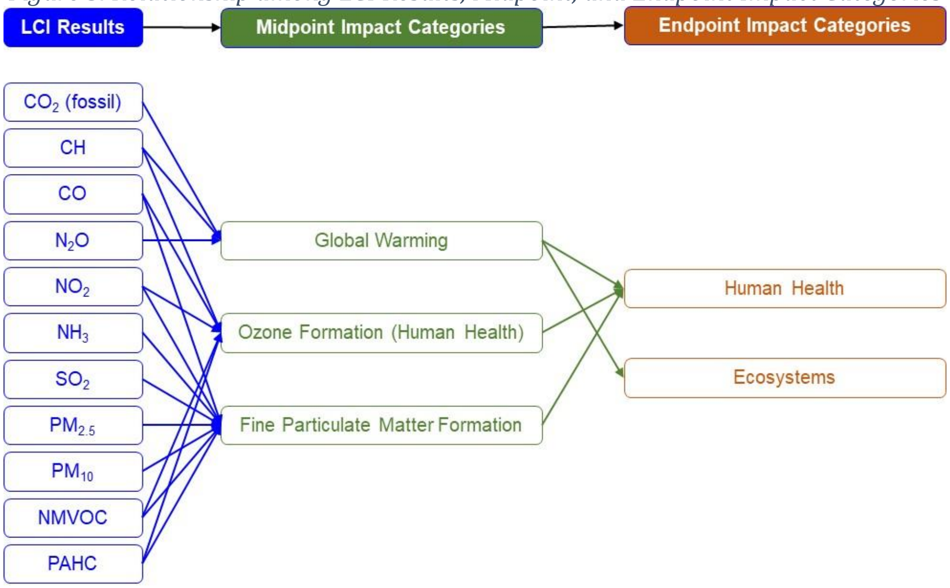
The LCIA was carried out through the *SimaPro Craft v9.6* software using the built-in *ReCiPe2016_C V1.1* LCIA method. Specifically, the LCI results were transformed into midpoint impact categories (global warming, ozone formation, and particulate matter) based on established cause–effect pathways using substance-specific characterization factors, converting heterogeneous flows into common equivalence units at the midpoint level. Finally, the midpoint results were aggregated into endpoint impact categories (human health and ecosystems) using the damage assessment framework embedded within the *ReCiPe2016_C V1.1* LCIA method (Figure 3). Endpoint indicators quantify potential damage to areas of protection, specifically human health (expressed in disability-adjusted life years, DALY) and ecosystems (expressed in species·year).

All the three midpoint impact categories, i.e., *global warming*, *ozone formation,* and *fine particulate matter formation,* contribute to the endpoint category of *human health* through specific pathways (Goedkoop et al., 2009; Huijbregts et al., 2017). Specifically, global warming increases malnutrition while both ozone formation and fine particulate matter formation increase respiratory diseases, and hence, through these pathways, all these three midpoint impact categories collectively contribute to the endpoint impact category of *human health*. For the *ecosystems* endpoint category, only *global warming* is the contributor out of the three midpoints used in this study, and it affects the ecosystems through the pathway of damage to terrestrial and aquatic species (Goedkoop et al., 2009; Huijbregts et al., 2017).

3.3. Economic Assessment

The economic assessment comprised a scenario-wise cost accounting and cost–profit analysis. Capital costs were annualized at a 17% discount rate using the Capital Recovery Factor (CRF) method, and total cost per scenario was divided into ownership (fixed) and operating (variable) components. For on-farm scenarios (S-1 to S-3), farmers incurred full machinery ownership and operating costs, including depreciation, repair and maintenance, fuel, and labor. For off-farm enterprise scenarios (S-4 and S-5), enterprises managed residue collection, transport, and processing, while paying farmers a residue procurement price. Composting and pyrolysis incorporated yield assumptions, product selling prices, and land lease costs. No subsidies or concessional financing were assumed. Enterprise-level feasibility was evaluated over a 20-year project life using discounted cash flow analysis. Financial performance was assessed using Net Present Value (NPV), Internal Rate of Return (IRR), Profit–Cost Ratio (PCR), and Discounted Payback Period (DPBP). Detailed methodology for economic assessment is available in Appendix 1.

Figure 3. Relationship among LCI Results, Midpoint, and Endpoint Impact Categories

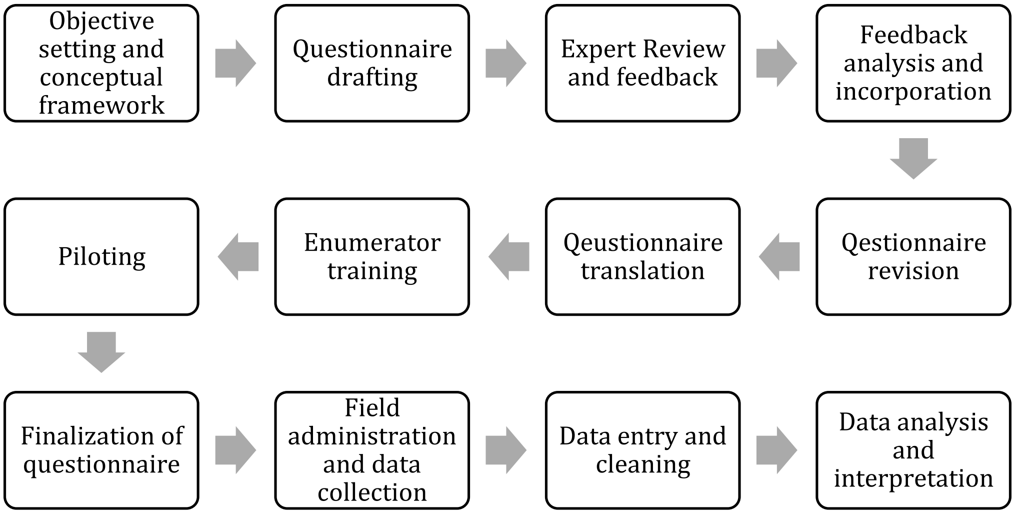


Note: The LCI results are translated into midpoint results, which are subsequently aggregated into endpoints through the ReCiPe2016_C V1.1 LCIA method.
Sources: Goedkoop et al. (2009) and Huijbregts et al. (2017)

3.4. Social Assessment

The overall methodological framework used for the social assessment is illustrated in Figure 4. Based on the objectives, a questionnaire draft was initially developed, covering farmer demographics, satisfaction, knowledge, attitudes, and practices. It was reviewed by six subject experts, and their feedback was utilized to refine the draft, which was then translated into Urdu and finalized in bilingual form. Subsequently, a pilot survey with ten farmers identified issues related to language, length, sensitivity, and coverage, leading to further refinement. The finalized questionnaire is provided in Appendix 2. The finalized questionnaire comprised six sections. Section 1 (Demographics) collected background information, including gender, age, education, language, farming experience, landholding size, cropping pattern, rice variety, and tractor ownership. Section 2 (Satisfaction with Government Policies and Programs) assessed perceptions of government efforts to regulate residue management. Section 3 (Knowledge) examined awareness of air pollution and health impacts, residue burning regulations, compost and char potential, and the Super Seeder. Section 4 (Attitudes) evaluated views on farmer involvement, awareness campaigns, and willingness to adopt alternative methods. Section 5 (Practices) documented current residue management practices, training exposure, and beneficial use of residues. Section 6 (Open-Ended Questions) invited suggestions to improve government policies and support programs. The acquired data were entered into SPSS, cleaned for consistency, and analyzed using frequency analysis to examine trends and chi-square test to examine associations amongst different variables.

Figure 4. Methodological Framework for the Social Study



Source: Authors' compilations.

3.4.1. Sample Size, Sampling Approach, and Surveys

Gujranwala has 109,388 private farms spanning 721,454 acres as per the latest agricultural census (GOP, 2024). This value is used as a proxy for the number of farmers, assuming one owner per farm and district-wide rice cultivation in the Kharif season. While 80–90% of fields are reported to grow rice (Latif et al., 2022), a 100% coverage was assumed to be conservative. The sample size was estimated as (Cochran, 1977; Naing et al., 2006):

$$n = \frac{N \cdot Z^2 \cdot p \cdot (1-p)}{(N-1) \cdot e^2 + Z^2 \cdot p \cdot (1-p)}$$

where N is the population size (109,388 for Gujranwala), Z is the standard normal variate corresponding to the desired confidence level (1.96 for 95%), p is the assumed population proportion (0.5 for maximum variability), and e is the acceptable margin of error (0.06 for ±6%). In survey research, a 5% margin of error at 95% confidence is conventionally used, though margins up to 10% are acceptable if justified (James et al., 2001). In this study, a margin of error of 6% was adopted as a practical balance between statistical rigor and fieldwork feasibility. The issue of rice residue burning in Pakistan is both socially sensitive and legally controversial, making farmer participation difficult to achieeve; thus, a slightly relaxed margin of error was considered. Comparable margins of error, e.g., 7% (Ahad et al., 2024; Dembele et al., 2025) and 10% (Ahmad et al., 2024; Canan, 2023; Juni et al., 2022; Karakaya, 2025; Mensah et al., 2019; Nainggolan et al., 2022; Ngetuny et al., 2025; Shani et al., 2024), have also been used in some of the relevant survey-based farmer studies. The calculation produced a minimum required sample size of 267 respondents.

The farmer survey was carried out by trained enumerators via face-to-face interviews during August 2025 using a nonprobability approach, specifically convenience sampling (Hayat et al., 2022; Kalauni et al., 2024; Latawiec et al., 2017; Mamun et al., 2023; Rathee et al., 2023), which offered a pragmatic means of engaging farmers based on accessibility and willingness to participate in a setting where residue burning is a sensitive topic. Although the calculated minimum sample size was 267 respondents, a larger pool of 450 farmers was approached to account for potential non-responses. Eventually, 300 farmers participated by consent (response rate: ~67%). The final sample not only exceeded the required size but is also consistent with a range, i.e., 150–300 respondents, reported in some of the comparable farmer surveys (Ahmed et al., 2015; Ali et al., 2020; Aslam et al., 2024; Bakhtawer & Afsheen, 2021; Luqman et al., 2024; Rafiq et al., 2019; Rhofita et al., 2024; Usman et al., 2024; Yaseen et al., 2016). To account for variation across Gujranwala District, surveys were conducted in multiple rice-growing locations spanning the tehsils of Gujranwala, Kamoke, and Wazirabad. Ethical requirements were duly fulfilled, including informed and voluntary participation, anonymity and confidentiality safeguards, trained enumerators with cultural sensitivity, ensured field safety, non-interventional design with no environmental risk, and formal ethical approval from NUST's Institutional Review Board.

FINDINGS AND DISCUSSION

4.1. Environmental Life Cycle Assessment (e-LCA)

4.1.1. Results of Life Cycle Inventory Analysis (LCI)

The LCI quantified the total emissions associated with each scenario, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulate matter (PM), non-methane volatile organic compounds (NMVOCs), ammonia (NH_3), and polycyclic aromatic hydrocarbons (PAHs), as summarized in Table 2 (full-length breakdown in Appendix 3). These pollutants are subsequently linked to relevant midpoint impact categories under the ReCiPe framework. Specifically, CO_2 (fossil), CH_4, and N_2O contribute to the global warming category; NO_x and NMVOCs are primarily associated with ozone formation (human health); and PM, SO_2, NO_x, NH_3, and related precursors contribute to fine particulate matter formation. The LCI results, therefore, serve as the input for the subsequent life cycle impact assessment (LCIA), where they are characterized into midpoint indicators (global warming, ozone formation, and fine particulate matter formation) and eventually aggregated into endpoint impact categories, namely human health and ecosystems.

Table 2. Results of Life Cycle Inventory Analysis (LCI)

Pollutant / emission*	S-1	S-2	S-3	S-4	S-5
CO_2 (biogenic)	1188	342.0	–	1200	929
CO_2 (fossil)	22	25.0	6.6	264	0.3
CH_4	2.1	0.4	0.0003	0.04	6.5
N_2O	0.1	0.1	0.0020	0.88	0.8
CO	72.1	–	–	–	22
NO_x	2.0	–	–	–	–
SO_2	1.6	–	–	–	–
PM	10.2	–	–	–	13.4
NMVOC	–	–	–	–	1.3
NMHC	3.1	–	–	–	–
PAHs	0.02	–	–	–	–
Avoided CO_2-eq	–	–	–	−51	−46

*Note: *: All units in kg (pollutant)/tonne (residue), except for avoided emissions which are in kg (CO_2-eq)/tonne (residue).*

Source: Authors' compilations.

4.1.2. Results of Life Cycle Impact Assessment (LCIA)

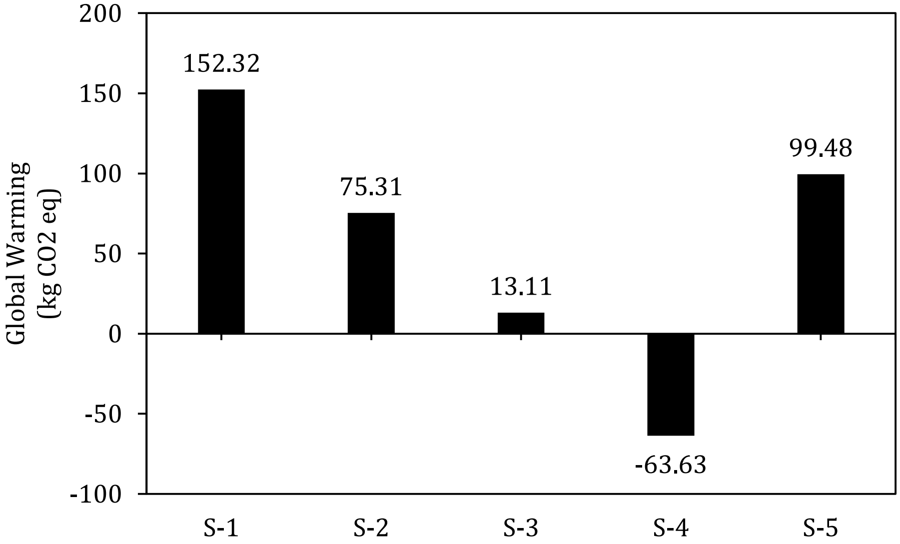
Midpoint Impact Assessment: In Figure 5, scenario 1 (S-1) serves as the baseline (global warming potential (GWP) = 100%)), with impacts dominated by CH_4 and N_2O emissions from open burning, and secondary contributions from diesel use (Table 3). S-2 reduced GWP to 49.4% of the baseline, though CH_4 and N_2O from biodegradation of incorporated residues and multiple field operations keep emissions present. S-3 achieved a large reduction (91.4%), comprising only 8.6% of the baseline, as emissions are only because of diesel-related CH_4 and N_2O. S-4 showed a net negative GWP (−41.8%), indicating that the avoided upstream production of synthetic urea more than offset the composting-related emissions, resulting in a net climate benefit relative to S-1. S-5, while performing better than the baseline, remained net-positive (65.3%), as CH_4 and N_2O emissions from the pyrolysis process and transport outweighed the avoided fertilizer benefit.

Table 3. Results of Life Cycle Impact Assessment (Midpoint Impact Categories)

Scenario	Global Warming		Ozone Formation (Human Health)		Fine Particulate Matter Formation	
	kg CO_2 eq	Normalized %age	kg NOx eq	Normalized %age	kg $PM_{2.5}$ eq	Normalized %age
S-1	152.3	100	11.2	100	13.4	100
S-2	75.3	49.4	0.1	1.1	0.01	0.1
S-3	13.1	8.6	0.004	0.03	0.0004	0.003
S-4	-63.6	-41.8	4.7	41.9	0.5	3.5
S-5	99.5	65.3	0.2	1.9	5.9	44.6

Note: Results reported per functional unit; normalized %ages are relative to baseline (S-1 = 100%)/.
Source: Authors' compilations.

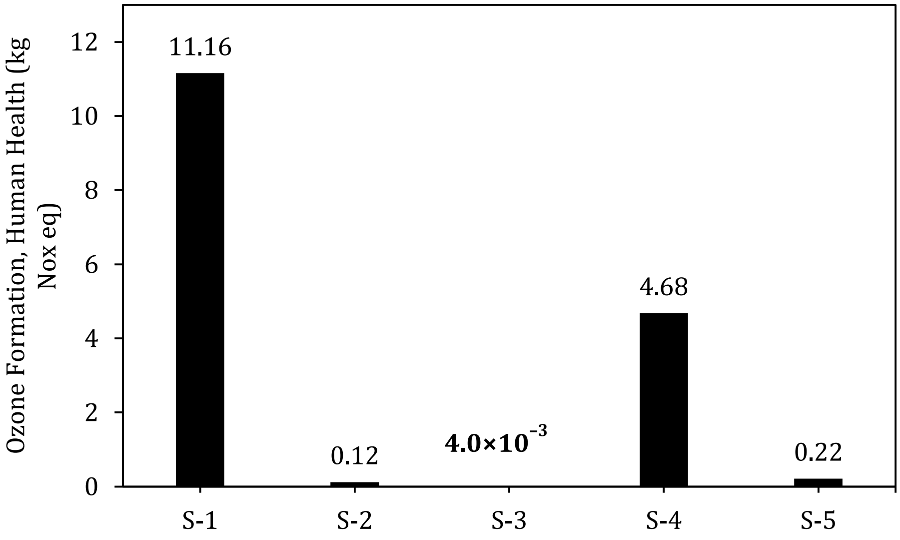
Figure 5. Results of Life Cycle Midpoint Impact (Global Warming Potential) Assessment



Source: Authors' compilations.

Figure 6 shows that S-1 dominated ozone formation impacts (11.16 kg NO_x-eq; 100%), due to high emissions of NO_x, CO, and NMVOCs from open burning, which drive photochemical ozone formation. All alternative scenarios showed strong reductions relative to the baseline (Table 4). S-2 contributed only 1.08% of S-1, and S-3 performed best at 0.04%. S-5 also achieved a considerable reduction (1.93% of S-1), though process-related CO and NMVOC emissions keep it higher than in-situ options. S-4 showed a comparatively higher ozone formation impact (41.9% of S-1), indicating that transport activities and compost management operations contribute notable NO_x-equivalent emissions, even though impacts remained well below the baseline.

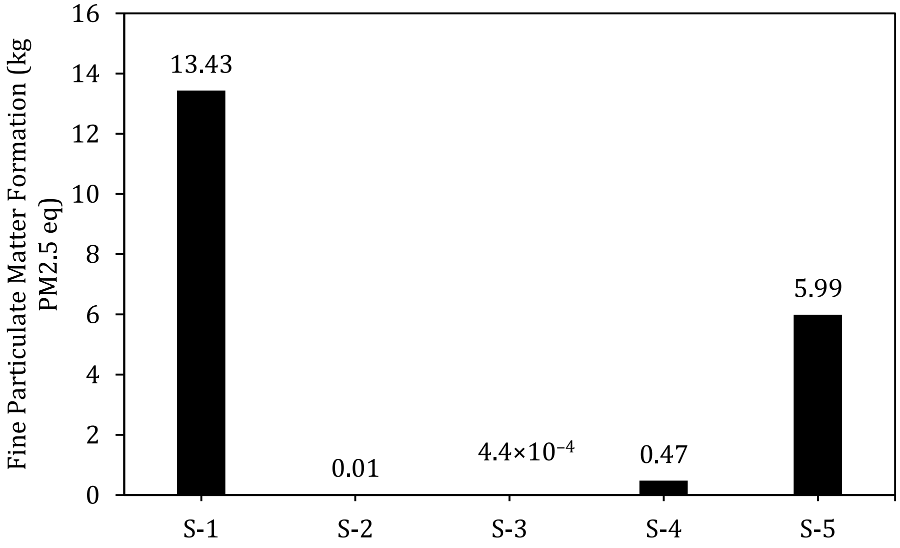
Figure 6. Results of Life Cycle Midpoint Impact (Ozone Formation, Human Health) Assessment



Source: Authors' compilations.

Figure 7 showed that S-1 exhibited the highest fine particulate matter formation potential (13.43 kg $PM_{2.5}$-eq; 100%), driven by direct emissions of primary $PM_{2.5}$ and secondary PM precursors during open burning (Table 4). All alternative scenarios significantly reduced PM impacts. S-3 performed best, contributing only 0.003% of the baseline, followed closely by S-2 at 0.10%, as combustion-related particulate emissions were avoided and diesel use was limited. S-4 reduced $PM_{2.5}$ formation to 3.5% of S-1, with remaining impacts mainly from residue transport and compost handling activities. S-5 showed a lesser reduction (44.6% of S-1), reflecting the influence of process-related PM emissions, albeit it still performed better than open burning.

Figure 7. Results of Life Cycle Midpoint Impact (Fine Particulate Matter Formation) Assessment



Source: Authors' compilations.

Endpoint Impact Assessment: DALY represents the potential loss of healthy life years in a population, combining years of life lost due to premature mortality and years lived with disability: lower values mean lower human health damage. Species loss over time represents the potential loss of species integrated over time, reflecting damage to biodiversity and ecosystem integrity: lower values mean reduced ecosystem harm. Results are reported per functional unit and normalized relative to the baseline scenario (S-1 = 100%) (Table 4).

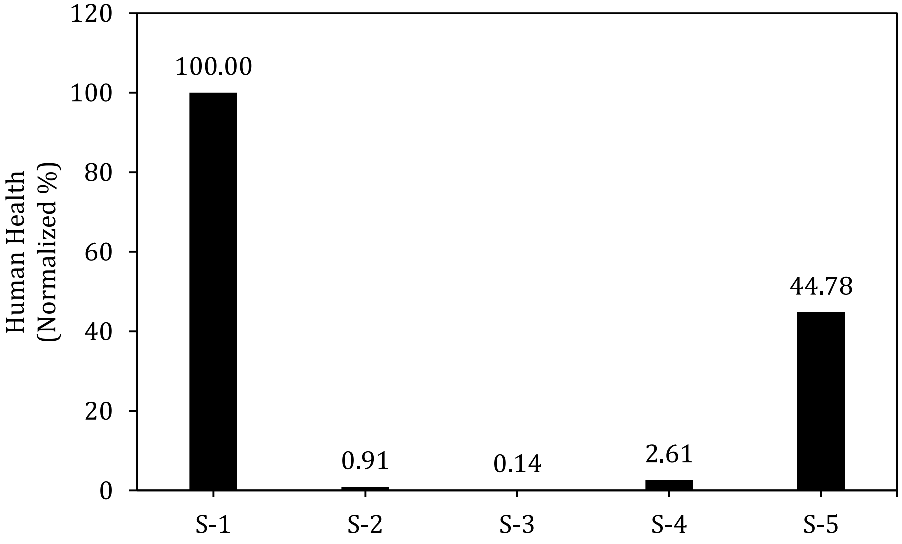
Table 4. Results of Life Cycle Impact Assessment (Endpoint Impact Categories)

Scenario	Human health		Ecosystems	
	DALY	**Normalized %**	**Species.Yr**	**Normalized %**
S-1	8.6×10^{-3}	100	3×10^{-6}	100
S-2	7.8×10^{-5}	0.9	2×10^{-7}	9.2
S-3	1.2×10^{-5}	0.1	4×10^{-8}	1.5
S-4	2.2×10^{-4}	2.6	5×10^{-7}	18
S-5	3.9×10^{-3}	44.8	3×10^{-7}	12.4

Source: Authors' compilations.

Figure 8 shows that S-1 resulted into the highest human health damage (100%). All alternative scenarios showed significant reductions relative to S-1. S-2 reduced human health impacts to 0.91% of the baseline. S-3 performs best, contributing only 0.14%. S-4 also performed significantly better than the baseline (2.61%), though impacts are higher than in-situ options. S-5 showed a relatively higher human health impact (44.78%).

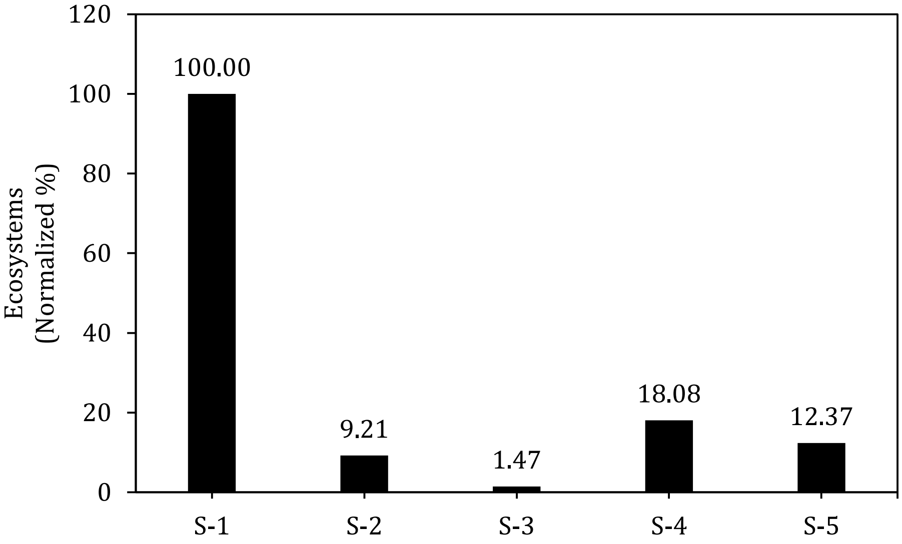
Figure 8. Results of Life Cycle Endpoint Impact (Human Health) Assessment



Source: Authors' compilations.

Figure 9 shows that S-1 remained the worst-performing scenario (100%). All alternative scenarios significantly reduced ecosystem damage relative to the baseline. S-3 showed the lowest impact (1.47% of S-1), followed by S-2 at 9.21%. S-4 reduced ecosystem damage to 18.08%. S-5 performed better than composting at 12.37% of the baseline but still showed higher damage than S-2 and S-3. All alternatives significantly improve ecosystem protection compared to open burning, with in-situ options offering the greatest benefits.

Figure 9. Results of Life Cycle Endpoint Impact (Ecosystems) Assessment



Source: Authors' compilations.

Summary of Life Cycle Impact Assessment (LCIA): At the midpoint level, open burning (S-1) performed worst, particularly for ozone and fine particulate matter formation, which are key drivers of seasonal smog in Punjab. All alternative scenarios reduce these impacts by eliminating open-field burning, with the S-3 achieving the greatest reductions in ozone-forming emissions and $PM_{2.5}$ (over 99% relative to baseline). S-2 also improved air quality but is less effective than S-3. S-4 and S-5 performed better than open burning but showed weaker smog-reduction potential because of associated transport- and process-related emissions. The endpoint results reinforced these patterns, with S-3 showing the lowest human health and ecosystem damage. Although composting delivers environmental benefits and pyrolysis is better than the baseline, their higher endpoint damages implies trade-offs. Considering both damage-based indicators and the project's smog-reduction objective, S-3 emerged as the most environmentally friendly option.

4.2. Economic Assessment

4.2.1. Cost Accounting Analysis

Table 5 shows that the total private cost for scenario 1, in the absence of a penalty, is PKR 4,147 t^{-1}. However, the inclusion of a regulatory penalty substantially increased the total cost to PKR 27,083 t^{-1}, rendering this practice economically unattractive. Primary tillage using a disc plow dominated costs, contributing over 54% of total per-acre expenditure, while the act of burning itself incurred negligible direct cost (PKR 116.15 $acre^{-1}$), hiding its social and environmental risks. The affordability of open burning seems to be enforcement-dependent: once fines are applied, the open burning practice becomes economically inferior to alternate residue management options, endorsing the case for mechanized on-field management and off-field enterprise-based valorization pathways.

Table 5. Per-acre Cost Breakdown and Conversion to Per-Tonne Residue for S-1

Operation / Process	Cost Component	Value (PKR)	Unit
(a) Open Burning (In-Situ)	Ownership Cost	0.00	PKR $acre^{-1}$

	Labour	96.15	PKR acre⁻¹
	Matchstick	20.00	PKR acre⁻¹
	Total Burning Cost	116.15	PKR acre⁻¹
(b) Primary Tillage – Disc Plow	Ownership Cost	554.85	PKR acre⁻¹
	Operating Cost	4,357.81	PKR acre⁻¹
	Total Disc Plow Cost	4,912.66	PKR acre⁻¹
(c) Secondary Tillage – Rotavator	Ownership Cost	537.00	PKR acre⁻¹
	Operating Cost	1,666.80	PKR acre⁻¹
	Total Rotavator Cost	2,203.80	PKR acre⁻¹
(d) Wheat Sowing – Seed Drill	Ownership Cost	429.83	PKR acre⁻¹
	Operating Cost	1,378.28	PKR acre⁻¹
	Total Sowing Cost	1,808.11	PKR acre⁻¹
Total Ownership Cost		1,521.68	PKR acre⁻¹
Total Operating Cost		7,519.05	PKR acre⁻¹
Total Private Cost (Open Burning Scenario)	Ownership Cost + Operating Cost	9,040.73	PKR acre⁻¹
Residue Generation	Conversion Factor	2.18	t acre⁻¹
Cost Per Tonne of Residue (Functional Unit)	Converted Cost	4,147.12	PKR t⁻¹
Cost Per Tonne of Residue (With PKR 50,000/Acre Fine)	Converted Cost	27,082.90	PKR t⁻¹

Notes: Operating costs are reported as aggregated values (including fuel, lubrication, labor, and repair and maintenance, where applicable), while ownership costs represent annualized capital components. The penalty value of PKR 50,000 is adopted from enforcement figures reported in the PDMA Smog Order (PDMA, 2022) and the Lahore High Court decision (Business Recorder, 2020), where this amount is cited as the applied fine for stubble burning. In this study, it is used as an illustrative enforcement-level penalty example to assess how regulatory strictness may influence the private economics of open burning.

Source: Authors' compilations.

Table 6 shows that S-2 significantly increased costs compared to open burning, with a per-tonne cost of PKR 5,736, primarily due to the addition of the shredder operation. While costlier than open burning, this scenario eliminates residue burning, enhances soil organic matter content, and facilitates compliance.

Table 6. Per-acre Cost Breakdown and Conversion to Per-Tonne Residue for S-2

Operation / Process	**Cost Component**	**Value (PKR)**	**Unit**
(a) Shredder Operation	Ownership Cost	740.84	PKR acre⁻¹
	Operating Cost	2,839.43	PKR acre⁻¹
	Total Shredder Cost	3,580.27	PKR acre⁻¹
(b) Primary Tillage – Disc Plow	Ownership Cost	554.85	PKR acre⁻¹
	Operating Cost	4,357.81	PKR acre⁻¹
	Total Disc Plow Cost	4,912.66	PKR acre⁻¹
(c) Secondary Tillage – Rotavator	Ownership Cost	537.00	PKR acre⁻¹
	Operating Cost	1,666.80	PKR acre⁻¹
	Total Rotavator Cost	2,203.80	PKR acre⁻¹
(d) Wheat Sowing – Seed Drill	Ownership Cost	429.83	PKR acre⁻¹
	Operating Cost	1,378.28	PKR acre⁻¹
	Total Sowing Cost	1,808.11	PKR acre⁻¹
Total Ownership Cost (S-2)		2,262.52	PKR acre⁻¹
Total Operating Cost (S-2)		10,242.32	PKR acre⁻¹
Total Private Cost (S-2)	Ownership Cost + Operating Cost	12,504.84	PKR acre⁻¹

Residue Generation	Conversion Factor	2.18	t acre^{-1}
Cost per tonne of residue (Functional Unit)	Converted Cost	5,736.17	PKR t^{-1}

Note: Operating costs are reported as aggregated values (including fuel, lubrication, labor, and repair and maintenance, where applicable), while ownership costs represent annualized capital components.
Source: Authors' compilations.

Table 7 shows that S-3 has the lowest cost amongst all non-burning, farmer-centered options (PKR 2,790 per tonne), outperforming both S-2 and S-1 (without penalty). Although the super seeder has higher upfront cost, this is offset by eliminating primary tillage, secondary tillage, and separate sowing, leading to substantial reductions in fuel use, labor, and operational time. S-3 offers an economic advantage, ensuring regulatory and environmental compliance, and faster field preparation.

Table 7. Per-acre Cost Breakdown and Conversion to Per-Tonne Residue for S-3

Operation / Process	**Cost Component**	**Value (PKR)**	**Unit**
Super Seeder Operation	Ownership Cost	1,643.18	PKR acre^{-1}
	Operating Cost	4,440.10	PKR acre^{-1}
	Total Super Seeder Cost	6,083.28	PKR acre^{-1}
Total Private Cost (S-3)	Ownership Cost + Operating Cost	6,083.28	PKR acre^{-1}
Residue Generation	Conversion Factor	2.18	t acre^{-1}
Cost per tonne of residue (Functional Unit)	Converted Cost	2,790.49	PKR t^{-1}

Note: Operating costs are reported as aggregated values (including fuel, lubrication, labor, and repair and maintenance, where applicable), while ownership costs represent annualized capital components.
Source: Authors' compilations.

For the enterprise-centered scenarios (S-4 and S-5), residue management is undertaken entirely by an external enterprise, with farmers providing only post-harvest field access. The enterprise performs mechanized cutting, collection, and transport using a tractor-mounted reaper and trolley. The transport distance was derived using a circular catchment approach from biomass supply literature (Stürmer, 2020; Overend, 1982), relating annual demand to recoverable residue density and adjusting for road routing through a circuity factor. A modest farm-gate price for rice residue (PKR 1,000 t^{-1}) was assumed because literature shows that rice straw is commonly treated as surplus waste with negligible economic value at the farm level (Khan et al., 2022; Sutradhar et al., 2021; Bentzen et al., 2018), which was also reflected in our informal field interactions with farmers. This assumption may be revised if a formal residue market develops in the future. Cow dung price was obtained from literature average value (WHO, 2005; Rasheed et al., 2016) and adjusted to current terms. Since residue supply is identical for S-4 and S-5, it is modeled as a common upstream module, with cutting and collection accounting for ~70% of total supply cost (Table 8).

Table 8. Cost of reaper-based Residue Supply

Operation / Cost item	**Cost category**	**Value (PKR)**	**Unit**
Reaper cutting & collection	Ownership cost	1,983.96	PKR acre^{-1}
	Operating cost	3,464.27	PKR acre^{-1}
	Total reaper operation cost	5,448.23	PKR acre^{-1}
Residue generation	Conversion factor	2.18	t acre^{-1}
Reaper cutting & collection	Converted cost	2,499.19	PKR t^{-1}
Rice residue (farm-gate price)	Feedstock procurement	1,000.00	PKR t^{-1}
Transport to decentralized processing facility	Operating cost	78.75	PKR t^{-1}

Total residue supply cost	3,577.94	PKR t^{-1}

Note: Ownership and operating costs for reaper cutting and collection are estimated using the same capital recovery and operating cost framework applied to farm machinery in S-1 to S-3.
Source: Authors' compilations.

Table 9 shows that ownership costs accounted for about 71.9% of total composting costs, while operating costs contributed 28.1%, with cow dung acquisition and repair and maintenance as the key operating cost drivers. The large gap between the production cost (PKR 29.24 kg^{-1}) and the selling price (PKR 80 kg^{-1}) is due to high yield of composting process (Table 9). The notable profit margin seems to make composting a financially attractive alternative to open burning. However, practical implementation depends on reliable co-substrate availability, organized residue collection, working capital, and effective marketing and distribution arrangements.

Table 9. Composting Process Cost (Per Tonne of Rice Residue)

Cost Category	Cost Component	Value	Unit
Ownership Costs	Machinery ownership (annualized)	4,763,276.61	PKR yr^{-1}
	Land lease (annualized)	1,457,968.87	PKR yr^{-1}
	Total annual ownership cost	6,221,245.48	PKR yr^{-1}
	Ownership cost per tonne (FU)	13,824.99	PKR t^{-1}
Operating Costs	Cow dung (co-substrate)	2,000.00	PKR t^{-1}
	Labour	190.00	PKR t^{-1}
	Diesel / energy	466.67	PKR t^{-1}
	Repair & maintenance	2,656.69	PKR t^{-1}
	Miscellaneous	89.00	PKR t^{-1}
	Total operating cost	5,402.00	PKR t^{-1}
Total Process Cost (Excluding Residue Supply)	Ownership + operating	19,227.24	PKR t^{-1}
Residue Supply (Common Upstream Module)	Total residue supply cost (Table 8)	3,577.94	PKR t^{-1}
Total System Cost	Total cost per tonne of residue	22,805.18	PKR t^{-1}

Note: Ownership costs were annualized using the capital recovery factor (CRF) and combined with annual land lease. Ownership cost per tonne (functional unit) was obtained by allocating total annual ownership cost over annual throughput (tonnes day^{-1} × operating days). Operating costs were calculated on a per-tonne basis and added to derive total process cost.
Source: Authors' compilations.

Based on the compost yield of 780 kg per tonne of rice residue, the unit production cost is 29.24 PKR kg^{-1}. At a market selling price of 80 PKR kg^{-1}, composting yields notable profit margin (Table 10).

Table 10. Compost Yield and Economics

Parameter	Value
Product yield (compost)	780 kg t^{-1} residue
Total system cost (including residue supply)	22,805.18 PKR t^{-1} residue
Unit production cost	29.24 PKR kg^{-1}
Selling price	80.00 PKR kg^{-1}
Revenue per tonne of residue	62,400.00 PKR t^{-1} residue
Net profit per tonne of residue	39,595 PKR t^{-1} residue
Net profit per kg of compost	50.76 PKR kg^{-1}

Source: Authors' compilations.

In the case of S-5, a single Kon-Tiki kiln processes about 80 kg day^{-1} (40 kg per batch, two batches per day); thus, 13 kilns are required to process 1 tonne day^{-1}. All ownership, operating, and land costs are aggregated for the 13-kiln system and normalized per tonne. The biochar yield is 22.5% (equivalent to 225 kg biochar per tonne of residue). Pyrolysis processing costs are dominated by ownership costs associated with kiln capital recovery, while operating costs remain relatively modest due to low mechanization intensity and limited labor requirements (Table 11). Feedstock acquisition costs are incorporated at the system level through the common upstream residue supply module.

Table 11. Pyrolysis Process Cost (Per Tonne of Rice Residue)

Cost Category	Cost Component	Value	Unit
Ownership Costs	Kiln ownership (annualized)	6,944.73	PKR t^{-1}
	Land lease (annualized)	482.75	PKR t^{-1}
	Total ownership cost	7,427.48	PKR t^{-1}
Operating Costs	Labour	480.77	PKR t^{-1}
	Repair & maintenance	1,116.67	PKR t^{-1}
	Water	500.00	PKR t^{-1}
	Miscellaneous	125.00	PKR t^{-1}
	Total operating cost	2,222.44	PKR t^{-1}
Total Process Cost (Excluding Residue Supply)	Ownership + operating	9,649.92	PKR t^{-1}
Residue Supply (Common Upstream Module)	Total residue supply cost (Table 8)	3577.94	PKR t^{-1}
Total System Cost	Total cost per tonne of residue	13,227.86	PKR t^{-1}

Note: Ownership costs were annualized using the capital recovery factor (CRF) and combined with annual land lease. Ownership cost per tonne (functional unit) was obtained by allocating total annual ownership cost over annual throughput (tonnes day^{-1} × operating days). Operating costs were calculated on a per-tonne basis and added to derive total process cost.

Source: Authors' compilations.

Table 12 shows that S-5 yielded a net profit of PKR 2,522 per tonne of residue. Comparatively, composting remains more profitable (with a net profit of PKR 39,595 t^{-1} residue) than pyrolysis because it produces a greater product mass per tonne of residue (i.e., higher mass yield) and has a higher product price (PKR 80 kg^{-1}) compared to biochar (PKR 70 kg^{-1}).

Table 12. Biochar Yield and Economics

Parameter	Value
Product yield (biochar)	225 kg t^{-1} residue
Total system cost (including residue supply)	13,227.86 PKR t^{-1} residue
Unit production cost	58.79 PKR kg^{-1}
Selling price	70.00 PKR kg^{-1}
Revenue per tonne of residue	15,750.00 PKR t^{-1} residue
Net profit per tonne of residue	2,522.14 PKR t^{-1} residue
Net profit per kg of biochar	11.21 PKR kg^{-1}

Source: Authors' compilations.

4.2.2. Comparative Stakeholder-wise Scenario Analysis

Table 13 presents the stakeholder-wise distribution of costs and profits across rice residue management scenarios. The results indicated that all on-farm scenarios (S-1 to S-3) impose a net cost on farmers, with the super seeder (S-3) representing the least-cost option. Under the enterprise-centered scenarios (S-4 and S-5), farmers provide access to residue to enterprises and receive a compensation of PKR 1,000 t^{-1}, which partially offsets their residue management cost and reduces their financial burden. From the enterprise perspective, both off-farm pathways generate positive financial returns. Composting (S-4) yields substantially higher net returns than pyrolysis (S-5), reflecting its higher product yield and stronger revenue performance.

Table 13. Stakeholder-wise Summary of Net Cost/Profit of Scenarios (PKR Per Tonne)

Scenario	Farmer			Enterprise		
	Cost	Revenue	Net cost or profit	Cost	Revenue	Net cost or profit
S-1	4,147	–	−4,147	–	–	–
S-2	5,736	–	−5,736	–	–	–
S-3	2,790	–	−2,790	–	–	–
S-4	4,094	1,000	−3,094	22,805	62,400	+39,595
S-5	4,094	1,000	−3,094	13,228	15,750	+2,522

Notes: Net cost (or profit) = Cost – Revenue. Negative values indicate net cost; positive values indicate net profit.
Source: Authors' compilations.

4.2.3. Cost-profit Analysis (CPA) of Enterprise-centered Scenarios

From a financial perspective, a project is attractive when it shows a positive NPV, a PCR above 1, an IRR higher than the discount rate, and a short DPBP. Both enterprise-centered scenarios meet these criteria but differ in performance (Table 14). Composting (S-4) demonstrates strong viability, with an NPV of PKR 42.20 million, PCR of 2.69, IRR of 47.55%, and a payback period of 2.46 years. Pyrolysis (S-5) is also viable, with a positive NPV (PKR 1.65 million), PCR of 1.19, and IRR of 20.60%, though its longer payback (5.57 years) and lower returns indicate comparatively modest performance.

Table 14. Results of Cost-profit Analysis of Enterprise-centered Scenarios

Indicator	Unit	S-4	S-5
Net Present Value (NPV)	PKR million	42.20	1.65
Profit-Cost Ratio (PCR)	–	2.69	1.19
Internal Rate of Return (IRR)	%	47.55	20.60
Discounted Payback Period (DPBP)	years	2.46	5.57

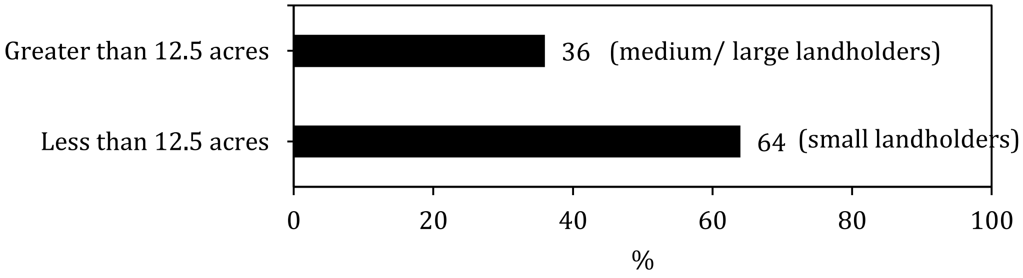
Source: Authors' compilations.

4.3. Social Assessment

4.3.1. Respondents' Demographics

As per the results of item A 1 (Table 15), all the participants of the study were males. The age of about 24% of the participants was equal to or less than 32 years, while the remaining ~76% were above 32 years of age (A 2). For the education levels, 18% of respondents were totally illiterate, and up to 58% of farmers had an education level of up to matriculation (A 3). This indicates that most farmers were literate, with 13% having an intermediate level of education, and ~10% having a literacy level of graduation or higher (A 3). Whereas the native language of all the farmers was Punjabi (A 4), ~16% of the surveyed farmers were unable to read and understand that national language, Urdu (A 5). In farming experience, ~64% of farmers had more than 15 years of rice farming experience, while only 36% of respondents had less than 15 years of farming experience (A 6). Regarding landholdings (A 7), 64% of farmers were small landholders and had a farm area less than 12.5 acres while 36% of participants were medium or large landholders (Figure 10). Rice-wheat cropping system was the prevalent rabi-kharif cropping system across all (100% of) the respondents (A 8), and majority (95% of the respondents) cultivated the basmati variety of rice (A 9).

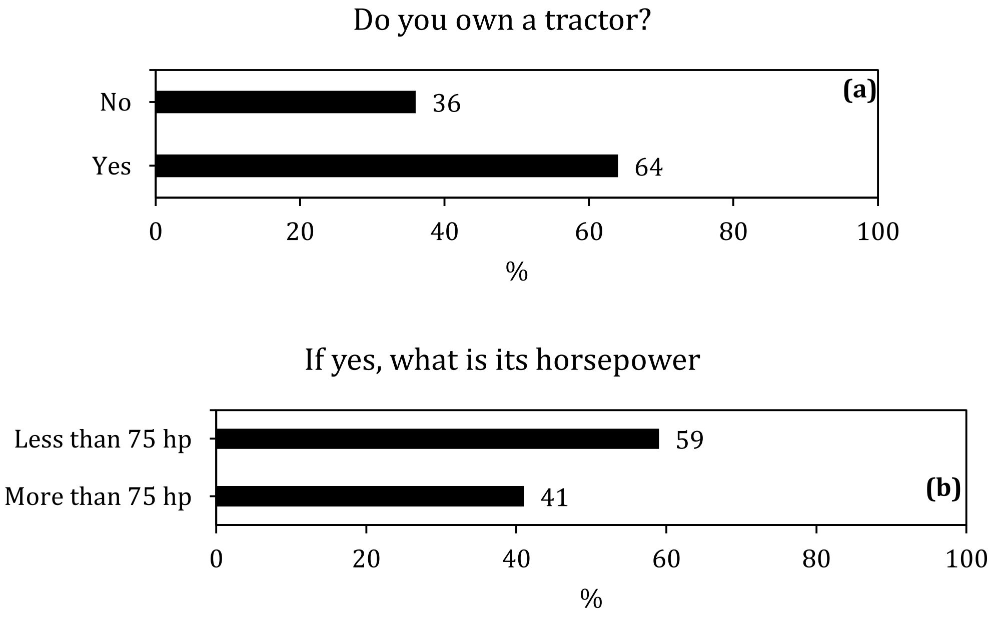
Figure 10. Results of Farm Profile Data (Item A 7 of Questionnaire)



Source: Authors' compilations.

Regarding tractor ownership (A 10), 64% of the respondents owned a tractor, while 36% of the farmers did not have a tractor (Figure 11a). As per Figure 11b, out of these tractor owners, majority, i.e., 59%, had tractors having horsepower equal to or less than 75 hp (A 11). Although the eligibility criterion for acquiring government's subsidy on the purchase of super seeders and shredders in Pakistan is to own a tractor of 65 hp, farmers informed that 65 hp tractor is insufficient to optimally operate this machine in a field laden with residue (this information was not part of the questionnaire, and is acquired from enumerators' reflections and also from their side notes which they recorded on the questionnaire). The same observation of the incapability of 65 hp tractors and the necessity of higher hp tractors, preferably 85 hp, has also been reported in the literature (Latif et al., 2024; Latif et al., 2020; Shah,2025).

Figure 11. Results of tractor-related questionnaire items: (a) item A 10 and (b) item A 11



Source: Authors' compilations.

Table 15. Frequency and Percentage Description of Respondents' Demographics

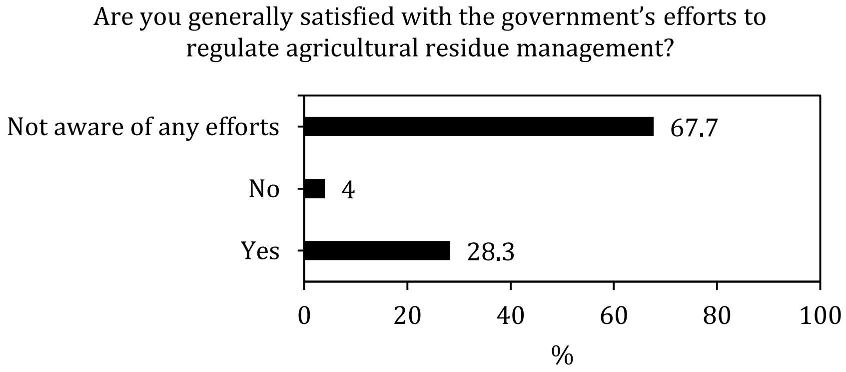
Id No.	Item	Options	Frequency	Percentage
A 1	Gender	Male	300	100
		Female	0	-
A 2	Age	18 – 32	73	24.3
		33 - 46	86	28.7
		47 – 60	91	30.3
		61 – 74	39	13
		75 - 90	11	3.7
A 3	Highest level of education completed	No Formal Education	54	18
		Primary (up to 5th grade)	27	9
		Secondary (up to 10th)	149	49
		Intermediate (up to 12th)	39	13
		Graduation or above	31	10.3
A 4	Native language	Urdu	0	-
		Punjabi	300	100
		Seraiki	0	-
		Others	0	-
A 5	Read and understand Urdu	Yes	251	83.7
		No	49	16.3
A 6	How many years have you been growing rice?	2 – 15 Years	109	36.3
		16 – 29 Years	69	23
		30 – 43 Years	84	28
		44 – 57 Years	31	10.4
		58 – 70 Years	7	2.3
A 7	Total agricultural landholding	Less than 12.5 acres	192	64
		Greater than 12.5 acres	108	36
A 8	Which Kharif and Rabi crops you regularly grow?	Rice–wheat	300	100
		Other	0	-
A 9	Rice variety	Basmati	285	95
		Non-Basmati	15	5
A 10	Do you own a tractor?	Yes	192	64
		No	108	36
A 11	If yes, what is its horsepower?	Less than 40 hp	11	5.7
		40 to 50 hp	66	34.4
		51 to 60 hp	29	15.1
		61 to 75 hp	07	3.6
		More than 75	79	41.1

Source: Authors' compilations.

4.3.2. Respondents' Satisfaction with Government Policies and Programs

The results of Section 2 of the questionnaire show that 28.3% of the respondents were satisfied, while 4.0% were not satisfied (Figure 12). However, the majority, 67.7%, reported being unaware of any government initiatives to regulate agricultural residue management.

Figure 12. Results of Farmer Satisfaction Levels (Item B 12 of Questionnaire)

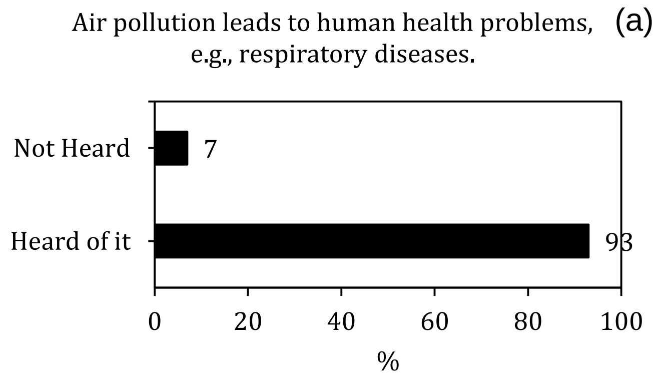


Source: Authors' compilations.

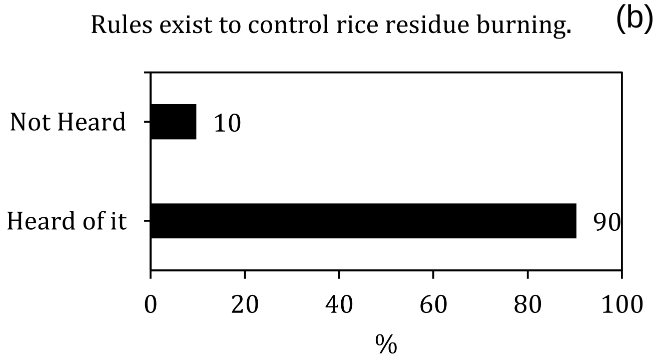
4.3.3. Knowledge, Attitudes, and Practices (KAP)

Figure 13a illustrates that 93% of the respondents had heard that air pollution leads to human health problems, whereas 7% had not heard about it. Additionally, only 10% of the participants were unaware of the existing rules that control rice residue burning (Figure 13b). The results suggest that while general awareness of burning restrictions (Figure 13b) is high (90% have heard about it), satisfaction (only 4% satisfied) and awareness (68% unaware) regarding structured governmental initiatives and support mechanisms remains comparatively limited (Figure 12). While 45% of respondents indicated awareness that compost or char can be made from rice residue, the majority, 55%, lacked knowledge about that process (Figure 13c). Furthermore, 21% of the respondents had not heard about the advanced rice residue management technology, the Super Seeder, which integrates shredding, incorporation, tillage, and seeding in a single operation (Figure 13d).

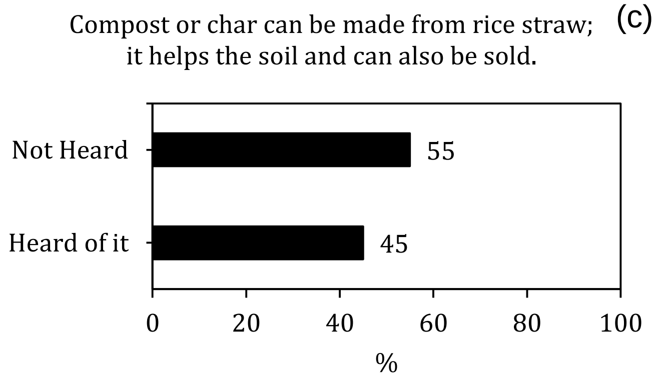
Figure 13. Results of Knowledge Section of Questionnaire: (A) Item C 13; (B) Item C 14; (C) Item C 15; and (D) Item C 16


(a)

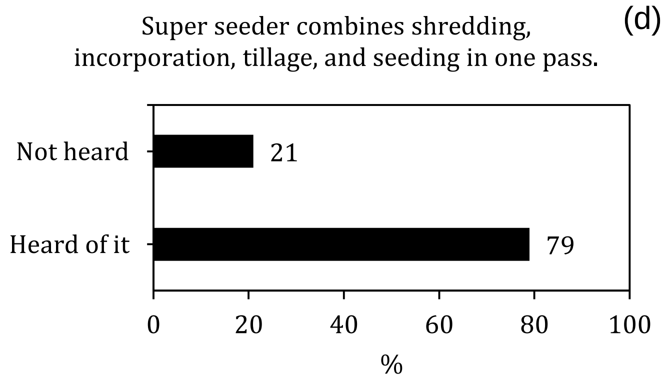
Air pollution leads to human health problems, e.g., respiratory diseases.


(b)

Rules exist to control rice residue burning.


(c)

Compost or char can be made from rice straw; it helps the soil and can also be sold.


(d)

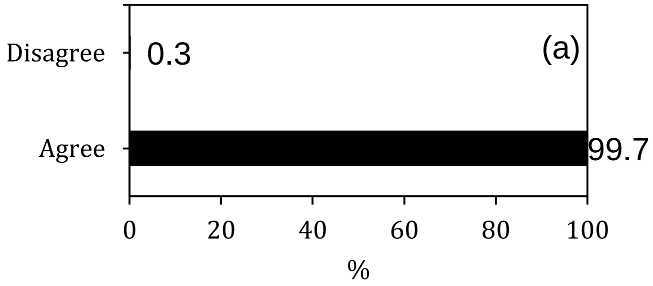
Super seeder combines shredding, incorporation, tillage, and seeding in one pass.

Source: Authors' compilations.

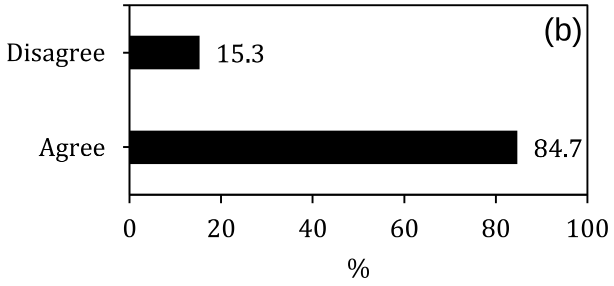
Figure 14a shows a positive attitude, as 99.7% of farmers agreed that farming community should be involved in planning and policy decisions, while 0.3% of farmers disagreed. Furthermore, 15.3% of respondents disagreed, while 84.7% agreed that awareness campaigns can help reduce residue burning (Figure 14b). Meanwhile, only 1.3% of the respondents were not willing to try new or alternative methods even though support is provided, e.g., training, subsidies, or machines (Figure 14c).

Figure 14. Results of Attitudes Section of Questionnaire: (A) Item D 17; (B) Item D 18; and (C) Item D 19 Of Questionnaire

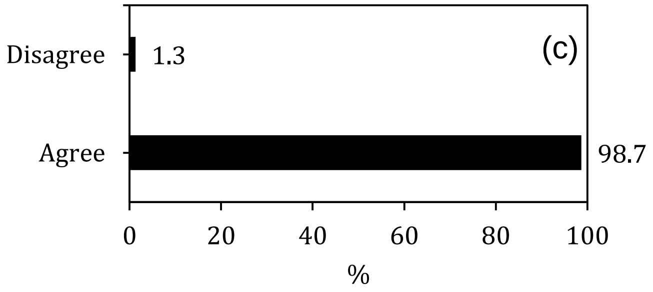
Farmers should be involved in planning and policy decisions.



Awareness campaigns can help reduce residue burning



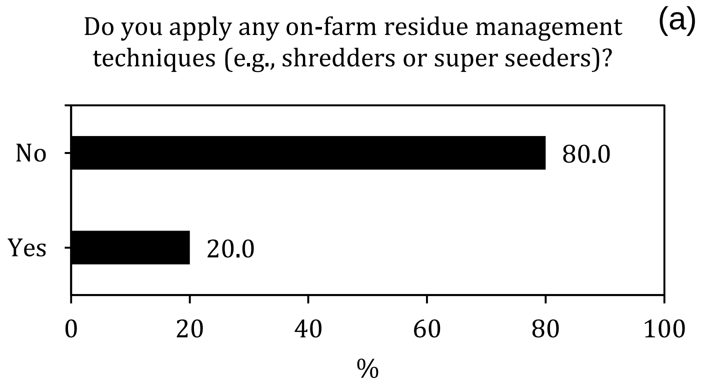
I am willing to try new or alternate methods if support is provided, e.g., training, subsidy, or machines.

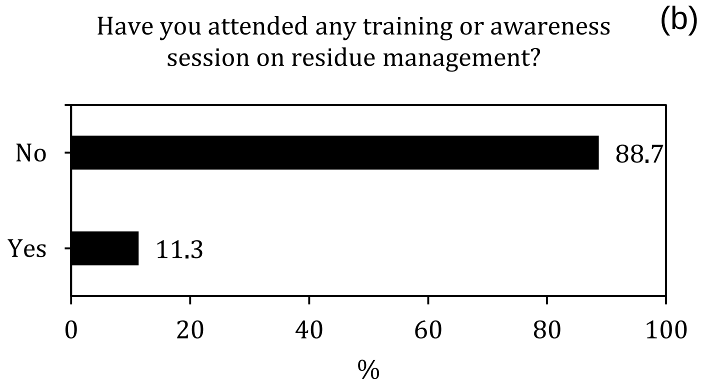


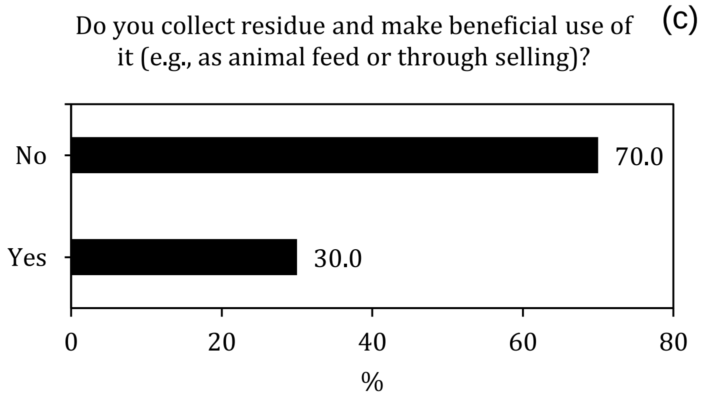
Source: Authors' compilations.

Figure 15 presents the farmers' practices related to residue management. The findings reveal that only 20% of farmers apply on-farm residue management techniques, e.g., shredders or super seeders, while 80% do not practice them (Figure 15a). Additionally, only 11.3% of respondents reported attending any training or awareness sessions on residue management (Figure 15b). Furthermore, 30% of the respondents collect crop residue for beneficial use, such as selling or fodder preparation, whereas the majority leave it unutilized (Figure 15c).

Figure 15. Results of Practices Section of Questionnaire: (A) Item E 20; (B) Item E 21; and (C) Item E 22







Source: Authors' compilations.

4.3.4. Open-ended Suggestions by Farmers

In the open-ended section (section 6) of the questionnaire, most farmers suggested that the government should provide machinery (tractors, super-seeders, and shredders) with training and subsidies fairly. All agricultural pesticides and fertilizers should be available at low prices and of good quality. Some of the respondents asked to lower the prices of electricity and fuel for agricultural activities and that proper training of machinery and awareness sessions should be held in the villages. A large fraction of farmers mentioned that crop prices should be fair enough to meet the expenses of agricultural activities. While these suggestions reflect the practical constraints faced by farmers and their broader policy preferences regarding the agricultural sector, several extend beyond the scope of the present study. Moreover, their implementation would require careful evaluation within realistic fiscal limits, market dynamics, and long-term sustainability objectives.

4.3.5. Associations amongst KAP Variables

Table 16 presents cross-tabulation and Chi-square results for selected KAP variables, showing that awareness and technology exposure are strongly associated with positive behavioral outcomes. Awareness of air-pollution health impacts is significantly linked with willingness to try alternatives, while super seeder awareness and campaign exposure are associated with on-farm technology use and training attendance. In contrast, awareness of rules or general compost and biochar concepts shows no significant relationship with behavior, indicating that regulatory awareness alone is insufficient. These findings suggest that residue-burning mitigation policies should emphasize behavior-oriented approaches, combining targeted awareness with hands-on technology exposure to promote adoption of sustainable residue management practices.

Table 16. Associations between KAP Items of the Questionnaire

Independent Variable	Dependent Variable	χ^2	p-value	Significant ($p \leq 0.05$)?
Air pollution causes health problems	Farmers should be involved in planning	0.076	0.783	No
Air pollution causes health problems	Awareness campaigns reduce residue burning	9.012	0.003	Yes
Air pollution causes health problems	Willing to try new or alternative methods	11.515	0.001	Yes
Rules exist to control residue burning	Farmers should be involved in planning	0.107	0.743	No
Rules exist to control residue burning	Awareness campaigns reduce residue burning	0.709	0.400	No
Rules exist to control residue burning	Willing to try new or alternative methods	0.434	0.510	No
Compost/char knowledge	Farmers should be involved in planning	0.821	0.365	No
Compost/char knowledge	Awareness campaigns reduce residue burning	1.420	0.233	No
Compost/char knowledge	Willing to try new or alternative methods	3.317	0.069	No
Super Seeder awareness	Farmers should be involved in planning	3.774	0.052	No

Super Seeder awareness	Awareness campaigns reduce residue burning	8.338	0.004	Yes
Super Seeder awareness	Willing to try new / alternative methods	2.055	0.152	No
Compost/char knowledge	Use of on-farm residue management technology	8.418	0.004	Yes
Super Seeder awareness	Use of on-farm residue management technology	19.937	<0.001	Yes
Awareness campaigns	Use of on-farm residue management technology	6.169	0.013	Yes
Awareness campaigns	Attendance in training sessions	4.536	0.033	Yes
Willingness to try new methods	Use of on-farm residue management technology	0.063	0.801	No
Willingness to try new methods	Training attendance	0.518	0.472	No

Source: Authors' compilations.

4.3.6. Associations between Demographics and KAP items

The studied associations between education, landholding size, and selected KAP variables related to rice residue management are shown in Table 17. Education is significantly associated only with actual technology use and shows no meaningful relationship with awareness or willingness. Contrarily, landholding size is significantly associated with technology awareness, use, and beneficial residue utilization, indicating that farm size is a stronger driver of adoption than education. The findings indicate that policies should adopt capacity-sensitive, practice-oriented interventions, particularly for smallholders, through tailored subsidies rather than uniform approaches.

Table 17. Associations between Demographics and KAP Items

Variable Pair Tested	**χ^2**	**p-value**	**Significant ($p \leq 0.05$)?**
Education × Air-pollution health impacts	7.01	0.135	No
Education × Rules on residue burning	4.06	0.397	No
Education × Compost/Biochar knowledge	9.11	0.058	No
Education × Super Seeder awareness	2.37	0.668	No
Education × Farmers' involvement in policy	1.02	0.907	No
Education × Awareness campaigns	1.57	0.814	No
Education × Willingness to adopt alternatives	3.35	0.501	No
Education × Use of residue-management technologies	21.79	<0.001	Yes
Education × Training attendance	7.09	0.131	No
Education × Beneficial residue use	2.94	0.568	No
Landholding × Air-pollution health impacts	6.56	0.087	No
Landholding × Rules on residue burning	8.58	0.036	Yes
Landholding × Compost/Biochar knowledge	12.68	0.005	Yes
Landholding × Super Seeder awareness	20.10	<0.001	Yes
Landholding × Farmers' involvement in policy	2.01	0.571	No
Landholding × Awareness campaigns	1.39	0.708	No
Landholding × Willingness to adopt alternatives	1.80	0.615	No
Landholding × Use of residue-management technologies	37.65	<0.001	Yes
Landholding × Training attendance	3.87	0.276	No
Landholding × Beneficial residue use	10.50	0.015	Yes

Source: Authors' compilations.

The social assessment revealed a gap between high environmental awareness and low adoption of sustainable residue management. While most farmers recognize health impacts and support alternatives to burning, only 20% use on-farm sustainable technologies and 11.3% have received training, implying that barriers are mainly financial and structural. Adoption was significantly linked to technology-specific awareness, campaign exposure, and landholding size, suggesting that policy should focus on equitable machinery access and practical training rather than generic awareness campaigns or blanket measures.

4.4. Integration of Findings

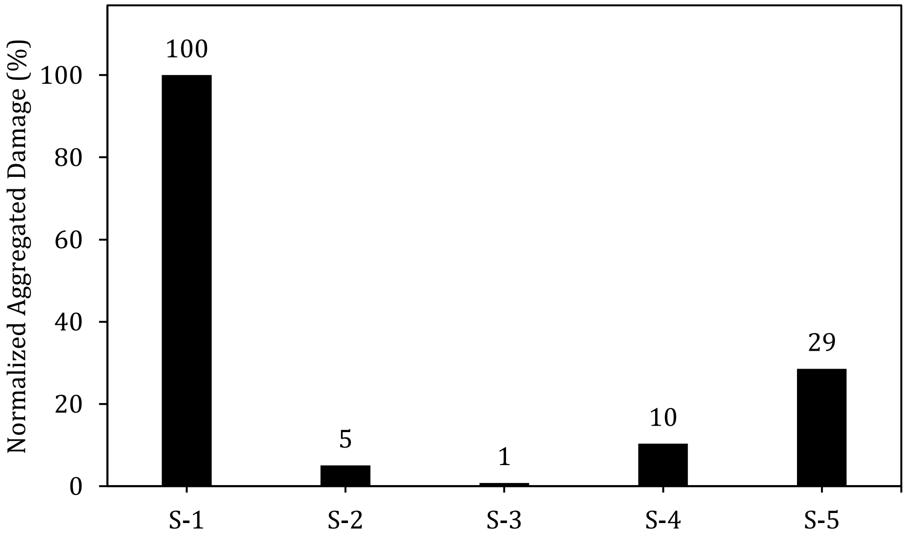
Environmental performance of the rice residue management scenarios was first evaluated using endpoint indicators representing impacts on human health and ecosystems. For each scenario, both endpoint results were normalized with respect to the baseline scenario (S-1), which was assigned a value of 100% (Table 18). To obtain a single environmental indicator suitable for joint analysis with economic performance, the two normalized endpoint results were aggregated using an equal-weight arithmetic mean (Table 18):

$$E_{agg,i} = \frac{(E_{HH,i} + E_{Eco,i})}{2}$$

where, $E_{agg,i}$ is the aggregated environmental damage of scenario i (%), $E_{HH,i}$ is the normalized human health endpoint (%), and $E_{Eco,i}$ is the normalized ecosystem endpoint (%).

Aggregation of the human health and ecosystem endpoints shows that all alternative scenarios substantially reduce overall environmental damage compared to the baseline (Figure 16).

Figure 16. Normalized Aggregated Environmental Damage (%), with All Scenarios Expressed Relative to Scenario 1 (S-1 = 100%)



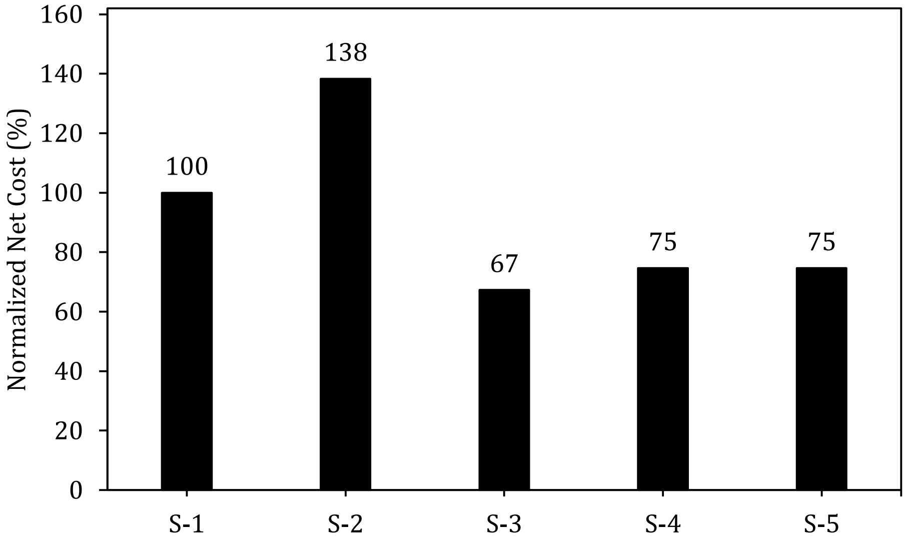
Source: Authors' compilations.

Economic performance was represented by the net cost incurred by farmers under each scenario. Economic costs were normalized relative to the baseline scenario (Figure 17):

$$C_i = \frac{C_i}{C_{S-1}} \times 100$$

where, C_i is the net cost incurred under scenario i and C_{S-1} is the net cost incurred under the baseline scenario (S-1).

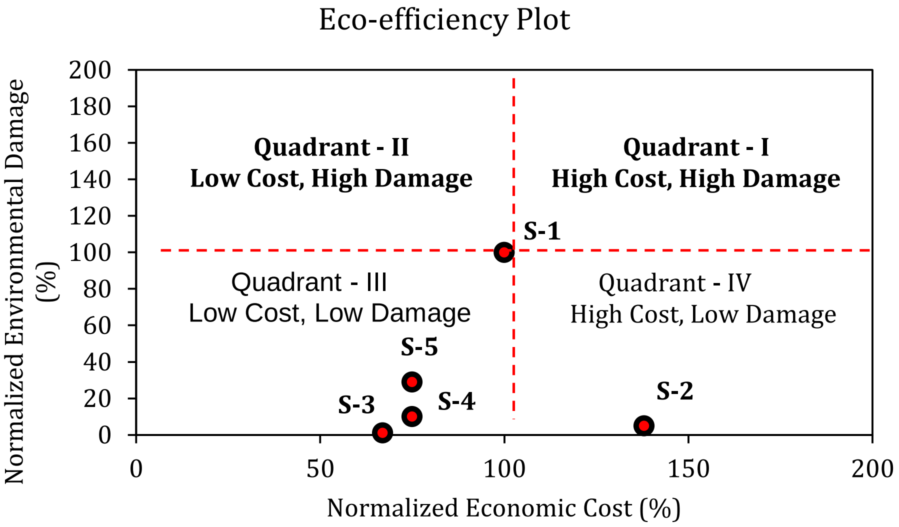
Figure 17. Normalized Net Cost for Farmers (%), with All Scenarios Expressed Relative to Scenario 1 (S-1 = 100%).



Source: Authors' compilations.

An eco-efficiency plot was constructed using normalized economic cost (x-axis) and aggregated environmental damage (y-axis), with reference lines at 100% representing the baseline. The plot (Figure 18) indicates that S-3 performs best, achieving both the lowest cost and environmental damage. S-4 shows balanced improvement at relatively low cost, while S-5 offers similar economics but weaker environmental benefits. S-2 provides strong environmental gains at higher cost, and the baseline S-1 performs worst overall.

Figure 18. Eco-efficiency Plot for Rice Residue Management Scenarios (S-1 = 100%) Where Lower-Left Positions Indicate Higher Eco-Efficiency



Source: Authors' compilations.

For quantitative comparison and ranking, Eco-Efficiency Index (EEI) was calculated. First, normalized ratios for economic cost and environmental damage were calculated:

$$c_i = \frac{C_i}{100}$$

$$e_i = \frac{E_i}{100}$$

The Eco-Efficiency Index was then computed as:

$$EEI_i = \frac{1}{\sqrt{c_i \times e_i}}$$

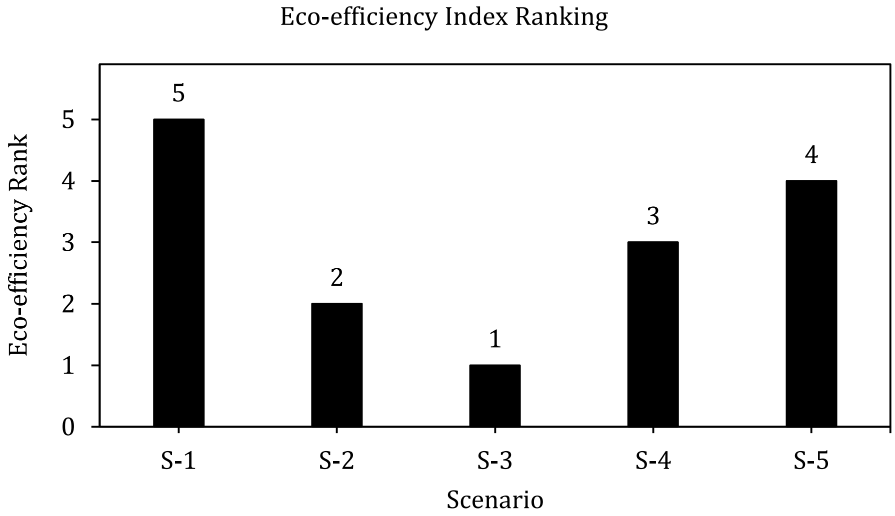
For ease of interpretation, the EEI values were scaled such that the baseline scenario has a value of 100.

$$EEI_i^{100} = EEI_i \times 100$$

Higher EEI values indicate better combined economic and environmental performance.

Ranking of scenarios was done using the EEI scores (Table 18 and Figure 19). S-3 achieved the highest EEI value and ranks first, indicating the most favourable combined economic and environmental performance. S-2 and S-4 follow, reflecting trade-offs between cost and environmental benefit, while S-5 ranks lower due to comparatively higher environmental damage. Both the eco-efficiency plot and the EEI ranking consistently identify S-3 as the most eco-efficient option.

Figure 19. Eco-efficiency Ranking of Rice Residue Management Scenarios Based on the Eco-Efficiency Index (EEI), with Rank 1 Indicating the Most Eco-Efficient Scenario



Source: Authors' compilations.

Integrating the environmental and economic findings with the findings of social assessment, it is concluded that farmers demonstrate high awareness of the harms of residue burning and express willingness to adopt alternatives, but actual uptake of sustainable practices is limited primarily by access to machinery, capital constraints, and tractor power rather than lack of motivation. This explains the gap between the strong eco-efficiency performance of S-3 and its limited adoption in reality. Additionally, Shah (2025) reported that many small and tenant farmers never even enter the process of balloting (for subsidy) because subsidy information does not reach them clearly and the need for a (high-powered) tractor along with a 40% upfront payment feels unaffordable; those who do apply often get discouraged by last-minute paperwork requirements and unclear ballot procedures, and even successful applicants face delivery delays, limited practical training, and extra costs such as tractor upgrades or vendor mark-ups, all of which slow or discourage actual adoption. Likewise, the promising ranking of composting aligns with ground farming realities for enterprise-based solutions that reduce on-farm operational burden of farmers. The ongoing practice of open burning seems to reflect convenience under constrained conditions rather than social desire or acceptance. The integrated findings conclude that the most eco-efficient options could be socially acceptable and suitable, provided enabling conditions are generated to eliminate economic and structural barriers to adoption and environmental compliance.

Unlike existing Pakistan-specific studies that primarily examine residue-to-energy pathways (Mahmood & Gheewala, 2020; Kashif et al., 2020; Abdullah et al., 2021) or explain burning behavior but without comparing alternative scenarios (Ahmed et al., 2015), this study systematically evaluates both on-farm and off-farm options within the agricultural system itself. International literature has either assessed environmental or economic dimensions separately (Keck & Hung, 2019; Hsu, 2021) or focused on technologically-complex pathways such as bio-ethanol, di-methyl ether, or mushroom production (Silalertruksa & Gheewala, 2013; Sander et al., 2019). In contrast, the present study integrates environmental life cycle assessment and economic analysis through an eco-efficiency framework, previously applied in other sectors (Woon & Lo, 2016) but remain unutilized in agricultural sector, and interprets results alongside farmer-level social realities. By combining environmental, economic, and social evidence within a single context-specific framework aligned with current provincial technologies (Government of Punjab, 2024a, 2024b), the study provides a structured and policy-relevant basis for prioritizing residue management and valorization pathways under Pakistan's conditions.

Table 18. Eco-efficiency Index Ranking Results

Scenario	**Normalized Human Health Endpoint (%)**	**Normalized Ecosystem Endpoint (%)**	**Aggregated Environmental Damage (%)**	**Normalized Net Economic Cost (%)**	c_i	e_i	**EEI (S-1=1)**	**EEI (S-1=100)**	**EEI Rank**
S-1	100	100	100	100	1.00	1.00	1.00	100	5
S-2	0.91	9.21	5	138	1.38	0.05	3.81	380.69	2
S-3	0.14	1.47	1	67	0.67	0.01	12.22	1221.69	1
S-4	2.61	18.08	10	75	0.75	0.10	3.65	365.15	3
S-5	44.78	12.37	29	75	0.75	0.29	2.14	214.42	4

Source: Authors' compilations.

CONCLUSIONS

Rice residue open burning remains a major contributor to air pollution and smog episodes in Punjab. The environmental life cycle assessment showed that open burning performs worst across environment-, climate-, and health-related impact categories, while all alternative scenarios significantly reduce environmental impacts. Among on-farm residue management options, direct sowing using the super seeder showed the lowest aggregated environmental damage. Enterprise-based off-farm valorization pathways, particularly composting, also demonstrated environmental benefits compared to the baseline.

The economic analysis indicated that, under the study assumptions and annualized cost framework, the super seeder emerged as the lowest-cost option for farmers. However, its adoption at farm level is constrained primarily by operational feasibility (constraints of tractor availability and tractor horsepower) identified through the field survey. Enterprise-based off-farm valorization pathways, particularly composting, also showed net profit at the enterprise level. However, such enterprise-led models are largely absent from the current policy landscape.

The social assessment showed that continued residue burning is driven primarily by economic and operational constraints rather than lack of awareness. Most farmers reported awareness of the harms of open burning and expressed willingness to adopt alternatives. However, practical barriers limit implementation. A clear mismatch was observed between existing policies and ground realities. Subsidy eligibility for implements such as super seeders and shredders requires possession of a 65 hp tractor, whereas 36% of surveyed farmers do not own a tractor and are therefore unable to benefit from such schemes. Field engagement further indicated that these machines operate effectively only with high-powered tractors, preferably 85 hp. Meanwhile, about 60% of tractor owners possess tractors with horsepower equal to or less than 75 hp. Under such conditions, farmers may likely revert to open burning due to sub-optimal machine performance and the narrow sowing window, leading to ineffective subsidy utilization and reduced confidence in government programs.

While alternatives may be feasible for relatively well-off farmers, small landholders face greater constraints in adopting machinery-based options. Penalizing them without first addressing access limitations may therefore be ineffective. Off-farm initiatives, such as composting and pyrolysis plants operated by external enterprises, could provide a complementary pathway in which residue is collected and valorized outside the farm. Under such arrangements, farmers would be relieved of residue-related operational burden and could potentially receive compensation for providing access to residue; however, such enterprise-based systems remain limited within existing policies.

Overall, integration of the environmental, economic, and social findings indicates that sustainable residue management is achievable when environmental performance, cost feasibility, and farm-level conditions are considered together. Sustainable agricultural residue management and associated smog reduction require policies grounded in field evidence, enabling access to workable alternatives and supporting transition before strict enforcement measures are applied.

RECOMMENDATIONS AND POLICY IMPLICATIONS

Based on the findings, this study recommends a phased policy framework focusing on subsidies, loans, and penalties applied in an equitable and sequenced manner. Because these instruments are already in use in the country to an extent, only optimization in their design and deployment is primarily proposed here as a minimal intervention to overcome the misalignment with ground realities without asking for a complete overhaul. The scope and intensity of these recommendations are intentionally kept modest as a pragmatic measure to be feasible for the relevant authorities to adopt and implement. The goal is to first enable and empower, then scale, and eventually consolidate long-term behavioral change regarding sustainable agricultural residue management or valorization (Table 19).

During the *transition phase*, policy and programs should prioritize enabling farmers to transition away from burning by minimizing entry barriers. For farmers with no or low-powered tractors, subsidies and concessional loans should focus on increasing access to high-powered (≥85 hp) tractors (which are a critical prerequisite to successful operation of residue management machinery, e.g., super seeders) while for farmers owning adequate-powered tractors, these incentives should be available for residue management implements, e.g., super seeders and shredders. Considering some farmers may not be able to afford the full co-payment amount for subsidy at once, introducing an installment-based payment option would make the subsidy more accessible and reduce the immediate financial burden. Penalties should apply only to farmers who already have adequate technical and financial capacity to adopt alternatives. This entails meticulous scrutiny of eligibility of candidates for these incentives or penalties.

The *scaling phase* should gradually minimize subsidies while increasing enforcement as alternatives become largely accessible. Enterprise-based initiatives, e.g., composting and pyrolysis, should be actively promoted, e.g., through concessional finance and tax rebates, allowing off-farm valorization pathways to flourish so that resource-constrained farmers could transfer residue management responsibility to enterprises.

The *consolidation phase* aims for a matured system in which non-burning practices are feasible for most, if not all, farmers. During this stage, subsidies can be gradually withdrawn, loans can shift toward market terms, and penalties for burning can be applied across the board.

Across all phases, policies should remain farmer-inclusive by systematically incorporating farmer feedback to adjust implementation over time. Although S-3 was found to have the lowest total annualized cost, adoption barriers may be related to upfront capital access and machinery availability rather than long-term cost inefficiency. Alongside technology-based compliance monitoring (e.g., remote sensing and GIS tools for tracking burning), regular field engagement through agricultural extension departments, digital feedback mechanisms, and supervised student outreach programs can provide real-time insights into machinery performance, liquidity constraints, and adoption stability. This would enable support measures to be adjusted based on field realities and sustained uptake, rather than relying solely on time-bound phase implementation or compliance surveillance.

Agriculture–related air quality improvement and smog minimization are achievable when policies reflect farmer realities, enable equitable transition before blanket enforcement, and leverage enterprise-based off-farm valorization pathways. This phased and equitable deployment of subsidies, loans, and penalties, offers a pragmatic and evidence-based policy pathway toward sustainable residue management and associated smog reduction in Pakistan.

Table 19. Phased Policy Framework for Rice Residue Management

Phase	**Time Horizon**	**Target Farmers**	**Penalty**	**Subsidy**	**Loan / Financing**
Transition Phase	Short term (≤2 years)	Low-power tractor farmers	No	For high-powered tractors	Concessional loans for tractors
		High-power tractor farmers	Yes	For implements	Loans for implements
Scaling Phase	Medium term (≤5 years)	Low-power tractor farmers	Limited	Gradual reduction	Continued access to loans
		High-power tractor farmers	Yes	Targeted only	Market-linked loans
Consolidation Phase	Long term (≥10 years)	All farmers	Uniform enforcement	Gradual withdrawn	Commercial financing

Source: Authors' compilations.

LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

This study provides an integrated comparison of five rice-residue management and valorization scenarios for Gujranwala using environmental life cycle assessment, farm/enterprise economic analysis, and a farmer survey. However, several limitations should be noted to interpret results appropriately and guide the next phase(s) of research.

Firstly, the economic component is intentionally farm- and enterprise-centric, and does not provide an aggregate public policy-level costing of proposed instruments, e.g., how many farmers would be supported, subsidy levels per farm, and total fiscal burden. Addressing whether public support is justified would require an externality-based life cycle costing approach that monetizes climate, environmental, and health impacts and compares these enviro-societal benefits against government expenditures.

Secondly, the finding that S-3 is least cost yet not widely adopted suggests that constraints beyond modeled cost efficiency are at play. Barriers may exist related to capital access, tractor horsepower limitations, and machinery availability. Labor market dynamics warrant investigation, e.g., whether family labor underemployment leads farmers to favor more labor-intensive conventional practices (S-1).

Thirdly, several assumptions used in the enterprise scenarios (S-4 and S-5) should be further validated under field conditions. For example, the transport distance (~450 m) is derived using a geometric catchment approach and reflects a small decentralized plant configuration; the implied number of sites at district scale becomes very large. Real-world roll-out would likely require larger (clustered) facilities covering larger catchment areas. Institutional and financial mechanisms such as public–private partnerships (PPP) for cluster-based facilities, custom hiring centers and cooperative machinery-sharing models to improve access without requiring individual ownership, and carbon credit or climate finance instruments to monetize avoided burning emissions could be explored.

Fourthly, several assumptions in the cost analysis remain market-dependent, e.g., residue price paid by enterprises, dung price, penalties, discount rate, and product prices. Future research should prioritize: market surveys of compost and char demand, prices, and quality requirements; and enterprise-side evidence on achievable capacity utilization and supply chain risks, to better represent the gap between modelled viability and operational viability. Sensitivity testing and uncertainty analysis would strengthen robustness.

Fifthly, empirical investigation is needed to examine how valorization pathways perform under regional agro-climatic and market conditions. Although composting and pyrolysis are internationally tested technologies, context-specific assessments and field-based trials would help validate technical performance, financial outcomes, and operational feasibility. Such investigation is also essential to better understand practical constraints, such as limited technical knowledge, access to capital, and underdeveloped supply chains and product markets, that often restrict real-world adoption (Pergola et al., 2018; Rhofita et al., 2024; Viaene et al., 2016; Ahmed et al., 2015; Muliarta, 2019).

Finally, the recommended phased policy pathway requires empirical evidence on what makes transitions durable. Future research should include longitudinal tracking of adoption, and assessment of whether and how quickly farmers revert if machinery performance is sub-optimal, including whether and when transitional support can be reduced without loss of adoption.

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APPENDICES

Appendix 1: Economic Assessment Methodology

The economic assessment was a comparative cost accounting and cost-benefit analysis of alternative rice residue management pathways applicable to Punjab, Pakistan. The ownership (fixed) costs, operating (variable) costs, unit production costs and revenues associated with each residue management scenario are quantified on a consistent basis. The scope focuses on residue-related machinery and technological items and thus excludes rice cultivation, harvesting, agrochemicals application, irrigation, and wheat crop management.

All costs were normalized to a functional unit of 1 tonne of post-harvest rice residue and reported in PKR, with capital costs annualized using a 17% discount rate via the Capital Recovery Factor (CRF). For in-situ scenarios (S-1 to S-3), analysis began post-harvest with residues managed on-field, assuming a 65 HP tractor, trained operators, standard efficiencies, and stable fuel and labor prices; full ownership costs, including depreciation, salvage value, repair and maintenance, diesel, and lubrication, were incurred by farmers. For ex-situ enterprise scenarios (S-4 and S-5), enterprises handled residue collection, short-distance transport (450 m), and processing, paying farmers 1,000 PKR t^{-1} of residue. Composting invovled mechanized windrows, a fixed residue–cow dung mix, 780 kg compost yield t^{-1} residue, land lease costs, and a selling price of 80 PKR kg^{-1} compost, while pyrolysis used Kon-Tiki kilns with a 22.5% char yield and a selling price of 70 PKR kg^{-1} char. Taxes followed FBR regulations, with no subsidies or financing schemes assumed.

Cost Accounting Framework

The methodology comprised standard agricultural engineering cost accounting practice, with all costs normalized to the functional unit of 1 tonne (1,000 kg) of rice residue managed. For each scenario, total cost per functional unit is calculated as the sum of ownership (fixed) costs and operating (variable) costs:

$$C_{\text{total, tonne}} = C_{\text{own, tonne}} + C_{\text{op, tonne}}$$

where, $C_{\text{total, tonne}}$ is the total cost per tonne of residue managed (PKR/tonne); $C_{\text{own, tonne}}$ is the ownership (fixed) cost per tonne (PKR/tonne); and $C_{\text{op, tonne}}$ is the operating (variable) cost per tonne (PKR/tonne).

Ownership costs are the annualized cost of capital assets and land use required to operate each scenario. These costs are independent of short-term production variability and are allocated to the functional unit based on annual throughput. Capital assets, e.g., tractor, shredder, super seeder, composting machinery, Kon-Tiki kiln, were annualized using the Capital Recovery Factor (CRF):

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

where, i is the nominal discount rate (17%) and n is the economic life of the asset (years). The Equivalent Annual Cost (EAC) of each asset was calculated as:

$$EAC = (P - S) \times CRF$$

where, P is the initial capital cost (PKR) and S is the salvage value (PKR).

Total annual machinery ownership cost was obtained by summing EAC values for all assets used in a given scenario. Annual ownership costs were allocated to the functional unit using throughput-based cost allocation. The ownership cost per tonne of rice residue was calculated as:

$$C_{\text{own,tonne}} = \frac{C_{\text{own,annual}}}{M_{\text{annual}}}$$

where, $C_{\text{own,annual}}$ is the total annual ownership cost (PKR/year) and M_{annual} is the total quantity of rice residue handled annually (tonnes/year). For enterprise-centered scenarios (composting and pyrolysis), land use costs are also factored in. Annual land lease cost is computed based on required operational area and allocated per tonne of residue processed using the same throughput-based allocation method.

Operating (variable) costs were computed based on the quantity of residue handled. These included feedstock procurement, labor based on operating hours, and fuel and energy use for machinery and transport. Repair and maintenance were estimated as a share of capital cost. Short-distance transport costs were also factored in for enterprise-based scenarios.

Cost-profit Analysis

A discounted cost–benefit analysis was conducted over a 20-year project life and discounted at a uniform nominal rate of 17%. Capital costs were considered to occur upfront, while operating costs and revenues were evaluated annually through net cash flows. A salvage value equal to 30% of the initial capital cost was assumed at the end of the project life. Economic feasibility was judged using indicators including, Net Present Value (NPV), Internal Rate of Return (IRR), Profit–Cost Ratio (PCR), and Discounted Payback Period (DPBP).

Net Present Value (NPV): The annual net cash flows were derived from unit-level net profit and scaled to annual processing capacity, and were assumed constant over the project life, except in the final year when salvage value was added. NPV was calculated as:

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t}$$

where, CF_t is the net cash flow in year t, r is the nominal discount rate, and n is the project life. Year 0 cash flow is negative and equals the initial capital investment, while cash flows from Year 1 onward represents annual net benefits.

Profit-Cost Ratio (PCR): The profits comprised discounted annual net cash flows, including salvage value, while costs included the initial capital investment since operating costs are already netted out. Based on present values, PCR was calculated as:

$$PCR = \frac{PV(Profits)}{PV(Costs)}$$

Internal Rate of Return (IRR): The IRR cash-flow series includes the initial capital cost at Year 0, uniform annual net cash inflows during operation, and a higher final-year inflow including salvage value. A project is acceptable if its IRR exceeds the discount rate. It was calculted as:

$$0 = \sum_{t=0}^{n} \frac{CF_t}{(1+IRR)^t}$$

Discounted Payback Period (DPBP): It was calculated as:

$$DPBP = Y^{-} + \frac{|\ Cumulative\ DCF_{Y^-}\ |}{DCF_{Y^+}}$$

where, $Y^{-}$is the year immediately preceding payback, $Cumulative\ DCF_{Y^-}$ is the cumulative discounted cash flow at that year, and $DCF_{Y^+}$is the discounted cash flow in the subsequent year.

Appendix 2: Questionnaire for Farmers

Section 1: Demographics

For each question, select all options that apply to you.

Id no.	Question (English Version)	Options (English Version)
A 1.	Respondent Gender	☐ Male ☐ Female
A 2.	How old are you?	_____ (Years)
A 3.	Highest level of education completed	☐ No Formal Education ☐ Primary (up to 5th grade) ☐ Secondary (up to 10th) ☐ Intermediate (up to 12th) ☐Graduation or Above
A 4.	What is your native language? (mother tongue)? *(Select only one option)*	☐ Urdu ☐ Punjabi ☐ Seraiki ☐ Other (specify) ___________
A 5.	Can you read and understand Urdu?	☐ Yes ☐ No
A 6.	How many years have you been growing rice?	_____ year(s)
A 7.	What is your total agricultural landholding (in acres)?	☐ Less than 2.5 acres ☐ 2.5 to 5 acres ☐ Greater than 5 to 12.5 acres ☐ Greater than 12.5 acres
A 8.	Which Kharif and Rabi crops do you regularly grow?	☐ Rice–wheat ☐ Other (specify): _____
A 9.	Which rice variety do you grow? (e.g., Basmati)	_____
A 10.	Do you own a tractor?	☐ Yes ☐ No

A 11.	If yes, what is its horsepower?	☐ Less than 40 hp ☐ 40 to 50 hp ☐ 51 to 60 hp ☐ 61 to 75 hp ☐ More than 75 hp ☐ Not sure

Section 2: Satisfaction with Government Policies and Programs

Please share your views about government efforts.

Id no.	Question (English Version)	Options (English Version)
B 12.	Are you generally satisfied with the government's efforts to regulate agricultural residue management?	☐ Yes ☐ No ☐ Not aware of any efforts

Section 3: Knowledge

Please answer whether you have heard of each of the following.

Id no.	Question (English Version)	Options (English Version)
C 13.	Air pollution leads to human health problems, e.g., respiratory diseases.	☐ Heard of it ☐ Not Heard
C 14.	Rules exist to control rice residue burning.	☐ Heard of it ☐ Not Heard
C 15.	Compost or char can be made from rice residue; it helps the soil and can also be sold.	☐ Heard of it ☐ Not Heard
C 16.	The Super Seeder combines shredding, incorporation, tillage, and seeding in one pass.	☐ Heard of it ☐ Not Heard

Section 4: Attitudes

Please say whether you agree or disagree with each statement.

Id no.	Question (English Version)	Options (English Version)
D 17.	Farmers should be involved in planning and policy decisions.	☐ Agree ☐ Disagree
D 18.	Awareness campaigns can help reduce residue burning.	☐ Agree ☐ Disagree
D 19.	I am willing to try new or alternate methods if support is provided, e.g., training, subsidy, or machines.	☐ Agree ☐ Disagree

Section 5: Practices

Please answer Yes or No for each statement.

Id no.	Question (English Version)	Options (English Version)
E 20.	Do you apply any on-farm residue management techniques (e.g., shredders or super seeders)?	☐ Yes ☐ No
E 21.	Have you attended any training or awareness sessions on residue management?	☐ Yes ☐ No
E 22.	Do you collect residue and make beneficial use of it (e.g., as animal feed or through selling)?	☐ Yes ☐ No

Section 6: Open-Ended Questions

Please share your suggestions to improve government policies and support programs.

Id no.	Question (English Version)	Response Space
F 23.	What suggestions do you have for improving government policies and support programs on rice residue management?	

Appendix 3: Scenario-wise Breakdown of LCI Results

Activity		Pollutant	Emission*
Scenario 1			
Emission due to open burning	-	CO_2 (biogenic)	1188
		CH_4	2.1
		N_2O	0.06
		CO	72
		NOx	1.96
		SO_2	1.7
		$PM_{2.5}$	10.2
		NMHC	3.1
		PAHs	0.02
Emissions due to diesel combustion	Primary Tillage	CH_4	0.0008
		CO_2 (fossil)	14
		N_2O	0.005
	Secondary tillage	CH_4	0.0003
		CO_2 (fossil)	4.5
		N_2O	0.002
	Sowing	CH_4	0.0002
		CO_2 (fossil)	3.4
		N_2O	0.0013
Scenario 2			
Emission due to biodegradation of residues	-	CH_4	0.4
		CO_2 (biogenic)	342
		N_2O	0.1
Emissions due to diesel combustion	Use of shredder	CH_4	0.0004
		CO_2 (fossil)	6.5
		N_2O	0.003
	Primary Tillage	CH_4	0.0008
		CO_2 (fossil)	14
		N_2O	0.005
	Secondary tillage	CH_4	0.0003
		CO_2 (fossil)	4.5
		N_2O	0.002
	Sowing	CH_4	0.0002
		CO_2 (fossil)	3.4
		N_2O	0.0013
Scenario 3			
Emission due to diesel combustion due to the use of super seeder	-	CH_4	0.0003
		CO_2 (fossil)	7
		N_2O	0.002

Scenario 4			
Emissions during the compost process	-	CH_4	0.02
		N_2O	0.8
		CO_2 (biogenic)	1200
Emission due to diesel consumption	Transport	CH_4	0.00002
		CO_2 (fossil)	0.26
		N_2O	0.0001
	Formation & Management of windrows	CH_4	0.02
		CO_2 (fossil)	264
		N_2O	0.1
Avoided emissions (if compost is used back in the soil)	-	Avoided urea	20
		CO_2 eq	51
Scenario 5			
Emissions during the pyrolysis process	-	CO_2 (biogenic)	929
		CO	22
		CH_4	6.5
		PM_{10}	13
		NMVOC	1.3
		N_2O	0.8
Emission due to diesel consumption	Transport	CH_4	0.00002
		CO_2 (fossil)	0.3
		N_2O	0.0001
Avoided emissions (if biochar is used back in the soil)	-	Avoided urea	23
		CO_2 eq	46

*Note: *: All units are in kg/tonne.*