Extinguishing the Blaze: Impact of Crop Residue Management on Stubble Burning in India *

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Abstract

Crop residue burning is a major source of air pollution in India, driven by the short window between rice harvesting and wheat sowing, and limited awareness of sustainable alternatives. This study evaluates the impact of subsidizing early-maturity variety rice seeds (EMV) and providing technical training on residue management, using a randomized controlled trial in Punjab, India. Relative to the control group, providing subsidies alone increases sustainable harvesting by 3.57 acres (123% increase over the control group). When combined with training, the effect rises to 4.60 acres (a 158% improvement relative to the control mean). Training enhances the impact of subsidies by promoting greater EMV adoption and addressing knowledge gaps in sustainable residue management. Treated farmers reported improved awareness and confidence in alternatives to burning, with some learning occurring even in the subsidy-only group. Instrumental variable estimates suggest that adopting EMVs on one additional acre increases sustainable harvesting by 1.35 acres. These findings offer the first causal evidence that India's policy push for EMV adoption can effectively curb residue burning. I also find that the effects are stronger for farmers who were more aware of alternate methods of residue management at the baseline, and weaker for larger farmers. A cost-benefit calculation suggests that each $1 spent generates $32.28 of social benefits in the *Seed Subsidy Only* group and $28.35 in the *Subsidy and Training* group, highlighting the environmental and economic efficiency of scaling this policy intervention.

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1 Introduction

Air pollution is one of India's most pressing health challenges. Pandey et al. (2021) estimate that in 2019, nearly 17% of deaths in India were attributable to poor air quality. In North India, more than 40% of peak winter pollution originates from crop residue (stubble) burning by farmers clearing fields between the rice and wheat seasons (Lan et al., 2022; Bikkina et al., 2019). Despite substantial attention from policymakers, the practice persists. Farmers face a narrow window of two to three weeks to manage residue through labor or machine-intensive alternatives (Kant et al., 2022; Agarwala et al., 2022). These challenges are compounded by limited access to and awareness about sustainable alternatives (Raza et al., 2022; Erbaugh et al., 2024). Whether policies designed to alleviate these constraints can meaningfully reduce burning, and which combinations of interventions are most effective, remain open questions.

In recent years, the Government of Punjab has promoted early-maturity variety (EMV) rice seeds as a potential solution to crop residue burning. Developed by the Punjab Agricultural University, these seeds mature 20–25 days earlier than long-duration varieties, easing the time pressure between the rice harvest and wheat sowing. EMVs are also shorter and produce less residue, potentially lowering the burden of residue management. Yet despite widespread promotion, there is limited causal evidence on whether EMV adoption, whether alone or paired with complementary support, reduces burning in practice.

This paper addresses that gap by evaluating two interventions: (i) a targeted seed subsidy designed to encourage EMV adoption, and (ii) technical training on sustainable residue management. Using a randomized controlled trial with 1,000 farmers in Punjab, India, I compare three groups: a control group, a *Seed Subsidy Only* group receiving a 50 percent subsidy on EMV seeds, and a *Seed Subsidy and Training* group receiving both the subsidy and training. I also use an instrumental variable (IV) strategy to isolate the causal effect of EMV adoption on residue burning.

The *Seed Subsidy Only* treatment tested whether financial incentives for EMV seed purchases could reduce burning by inducing adoption. Farmers in this group were offered a 50 percent subsidy—approximately ₹225 ($2.60) per acre for up to 10 acres, conditional on verified adoption. The offer was communicated before sowing (April–May), and reimbursements were issued after adoption was verified on the farmer's plots. By lowering the private cost of adoption, this intervention complements ongoing government efforts and can reduce burning through two channels. First, EMV varieties shorten the crop cycle, freeing up valuable time between harvest and sowing and relaxing the binding time constraint that drives burning. Second, they produce less residue per acre, facilitating residue management both *in situ* (on-farm practices such as mulching or incorporation) and *ex situ* (off-farm uses such as baling and removal for fodder or fuel) (Kemanth et al., 2024).

The *Seed Subsidy and Training* treatment tests whether combining financial incentives with technical support magnifies the program's impact. Training was delivered in two phases: pre-harvest (August–September) and post-harvest (November–December). Pre-harvest sessions focused on best practices for EMV cultivation, cost and time comparisons of alternative residue management methods, and local options for residue management machinery and service providers. Post-harvest sessions addressed issues such as weeds and pests that arise under no-burn conditions. Training could reduce burning by filling knowledge and skill gaps, strengthening farmers' market linkages to access residue management machinery, and increasing their confidence in using EMV seeds effectively.

While EMV seeds are designed to relieve the tight turnaround time between rice harvesting and wheat sowing, their real-world effectiveness in curbing crop residue burning is uncertain. Farmers could use the extra time to plant an additional crop or delay sowing of paddy rice, resulting in little to no reduction in burning. Even those who adopt EMVs may continue to burn residue if they lack the awareness, incentives, or access to sustainable alternatives. I evaluate whether and how these channels translate into actual reductions in burning.

To measure EMV adoption and burning behavior, I collected detailed field observation data from all cultivated plots. EMV adoption was classified using a simple height-based criterion distinguishing the shorter EMV varieties from traditional varieties. Enumerators conducted unannounced visits to each geo-coded plot every two to three days during the harvest months (October–November), recording any evidence of burning to ensure no event was missed. In addition to the binary measure of burning (the extensive margin), enumerators recorded the intensity of burning (the intensive margin), distinguishing between *partial burning*, in which only the upper residue was burned, and *full burning*, in which both the upper residue and basal stalk were burned. This distinction is important: shifting from full to partial burning can substantially reduce emissions even if burning is not entirely eliminated. I combine these high-frequency observations with survey data to examine the mechanisms underlying reductions in burning.

My headline result is that both interventions significantly reduced residue burning, with larger effects in the *Seed Subsidy and Training* arm. On average, the *Seed Subsidy Only* treatment increased sustainably harvested area by 3.57 acres —a 123 percent increase relative to the control mean, while the *Seed Subsidy and Training* treatment increased it by 4.6 acres, corresponding to a 158 percent increase. Both treatments also expanded total cultivated area by roughly 2.5 acres on average (a 27 percent increase over the control mean). I find no detectable effects on partial burning: control farmers partially burned about 3 acres on average, and the point estimates for both treatment arms are negative but imprecisely estimated. In contrast, full burning declined sharply. Relative to a control mean of 3.13 acres, the *Seed Subsidy Only* arm reduced full burning by about 1 acre, and the *Seed Subsidy and Training* arm by roughly 1.5 acres. These two effects, however, are not statistically distinguishable from each other.

My second set of results provides evidence that the Punjab government's policy of promoting EMV seed adoption could yield substantial reductions in residue burning. Excluding the *Seed Subsidy and Training* arm due to concerns about potential violation of the exclusion restriction and comparing only the control and *Seed Subsidy Only* groups, I estimate the causal effect of EMV adoption using an instrumental variable approach. The results show that adoption of EMV seeds on one additional acre reduces burning on 0.42 acres, with the majority of this reduction driven by declines in full burning (0.38 acres) rather than partial burning (0.04 acres). I also find that EMV adoption on one additional acre increases sustainable harvesting by 1.35 acres on average. The per-acre effect exceeding unity is consistent with two mechanisms that operate beyond the directly treated plot. First, the shorter growing cycle and lower residue burden associated with EMV cultivation may encourage farmers to exploit economies of scale (for example, employing residue management machinery on neighboring non-EMV plots as well). Second, EMV adoption in the *Seed Subsidy Only* arm may lead to adoption-triggered self-learning, improving farmers' knowledge of residue management practices and thereby reducing burning even on non-EMV plots.

I find evidence supporting the role of training in reducing residue burning. Farmers in both treatment groups reported greater skills and confidence in sustainable residue management methods. Even subsidy-only farmers acquired knowledge independently, suggesting adoption itself triggered learning. Training further strengthened market linkages for farmers to access residue management machinery, thus strengthening the enabling environment for residue management. Lastly, I also find evidence that combining training with subsidy led to an incremental impact on reducing burning through the channel of higher adoption of EMVs.

To further examine the mechanisms underlying the reduction in burning, I find clear evidence of higher EMV adoption and lower self-reported time constraints during the residue management period. Relative to a control group mean of 3.1 acres under EMV cultivation, the *Seed Subsidy Only* treatment increased EMV adoption by an additional 2.6 acres, while the *Seed Subsidy and Training* treatment increased it by 3.6 acres, with the latter effect significantly larger. Consistent with the shorter maturity period of EMV seeds easing the time pressure between harvests, farmers in both treatment groups were 8–10 percentage points less likely to report facing time constraints for residue management compared to the control group. Moreover, the reduced residue volume from EMV varieties made both *in situ* and *ex situ* residue management more feasible for treated farmers, further contributing to the decline in burning.

Lastly, I also examine heterogeneity in treatment effects along two dimensions pre-specified in the pre-analysis plan filed with the AEA RCT Registry (Gandhi, 2024): baseline planned cultivation area and baseline awareness of sustainable residue management practices. Both factors could plausibly shape farmers' responses. Larger farmers might exhibit stronger effects if economies of scale make residue management more cost-effective, or weaker effects if logistical constraints limit their ability to manage residue sustainably. Similarly, the impact could be stronger for more informed farmers if awareness alone is insufficient and training helps overcome learning costs, or weaker if there are diminishing returns to information. In practice, I find that treatment effects on burning are weaker among larger farmers but stronger among those with higher baseline awareness. I find no significant heterogeneity in EMV adoption along either dimension, suggesting that the interventions were broadly effective in encouraging EMV uptake across farmer types.

To assess welfare implications, I evaluate cost-effectiveness in two ways. First, I calculate benefits based on avoided CO_2 emissions and India-specific estimates of the social cost of carbon. Each dollar of program spending generated roughly $32.28 in social benefits in the *Seed Subsidy Only* arm and $28.35 in the *Seed Subsidy and Training* arm, indicating high cost-effectiveness. The cost-effectiveness is likely to further improve under a state-wide scale-up of the program. Second, I benchmark these results against a Payments for Ecosystem Services (PES) program evaluated by Jack et al. (2025), which offered conditional transfers for verified non-burning. Relative to PES, my interventions achieve an additional unburned acre at least 53-60% more cheaply. Together, the results show that modest, well-targeted input-based subsidies can deliver large environmental benefits at low cost.

This paper contributes to several strands of literature. First, it relates to research on barriers to sustainable crop residue management. Prior studies document that farmers burn crop residue because of the narrow time window between rice harvesting and wheat sowing (Kant et al., 2022; Agarwala et al., 2022), as well as limited knowledge of and access to residue management machinery (Raza et al., 2022; Erbaugh et al., 2024; Shaikh, 2022). However, much less is known about the effectiveness of interventions explicitly designed to relax these constraints. I contribute to this literature by providing causal evidence on the impact of programs designed to alleviate both time and information constraints faced by farmers.

Second, this study contributes to the broader literature on the role of incentives and information in promoting sustainable agricultural practices. Financial incentives such as payments for ecosystem services have been shown to encourage adoption of conservation agriculture (Ward et al., 2021), while combinations of price subsidies and information treatments have been found effective in stimulating the uptake of beneficial agricultural technologies (Vu et al., 2020; Campenhout, 2021; Larochelle et al., 2017). Closely related to this paper, Jack et al. (2025) use a randomized controlled trial to evaluate conditional cash transfers for verified non-burning of crop residue. They find that partial up-front payments reduce burning by 7.7–11.5 percentage points relative to the control group, while purely ex-post payments have no measurable effect. I extend this literature by focusing on a previously unexplored dimension —subsidizing EMV seeds, both alone and in combination with training on sustainable residue management methods —to assess their effectiveness in reducing burning. This approach is important because residue management depends not only on post-harvest practices but also on upstream input choices at the cultivation stage. I further contribute by measuring outcomes along the intensive margin, distinguishing between *partial* and *full* burning. Capturing these nuances provides a more complete understanding of how interventions shift burning behavior, for example from full to partial or no burning.

Finally, this paper contributes to the extensive literature examining the role of subsidies in promoting technology adoption in agriculture in developing countries (Duflo et al., 2011; Carter et al., 2016; Omotilewa et al., 2019). While most existing studies focus on agricultural or productivity outcomes as the primary objective of technology adoption, I extend this work by treating these agricultural outcomes as an intermediate mechanism to evaluate downstream environmental impacts. Specifically, I examine how subsidizing EMV seeds influences adoption decisions that, in turn, reduce crop residue burning and associated emissions. I further contribute to this literature by assessing whether and how information provision complements subsidies in promoting adoption and amplifying their environmental benefits.

The rest of the paper is proceeds as follows. Section 2 describes the study setting and policy background. Section 3 outlines the research design. Section 4 presents data and empirical strategy, with results in Section 5. Section 6 provides cost-benefit analysis, and

Section 7 concludes.

2 Study Setting/Background

This section situates the interventions examined in this study within the broader context of crop residue burning in India. I first outline the structural and farmer-level constraints that sustain crop residue burning. I then review past government efforts and explain why they achieved limited success. Building on this, I turn to the government's recent promotion of early-maturity variety seeds, a policy whose impact on residue burning remains uncertain and is the primary focus of this study.

The persistence of residue burning in Punjab reflects a combination of structural, policy, and farmer-specific constraints that shape the feasibility of alternative management practices. The widespread adoption of mechanized harvesting, particularly through Combine Harvesters, leaves behind greater volumes of residue compared to manual methods, making disposal more challenging (Kumar et al., 2015; Bhushan, 2020). This challenge is further exacerbated by the Punjab Preservation of Subsoil Water Act, 2009, which prohibits paddy transplantation before mid-June to conserve groundwater. The resulting delay shortens the interval between rice harvest and subsequent wheat sowing, making residue burning an expedient solution for farmers pressed for time (Kant et al., 2022; Agarwala et al., 2022). In addition, research points to farmer-specific constraints that reinforce the practice of residue burning, including credit constraints (Jack et al., 2025) and information gaps regarding sustainable residue management (Raza et al., 2022; Erbaugh et al., 2024). Figure 12 illustrates the prevalence of burning across Punjab,[1] highlighting the scale of the problem.

2.1 Initial Government Response to Crop Residue Burning

The government has historically employed a combination of punitive and incentive-based measures to curb crop residue burning. Examining these early interventions sheds light on the challenges of enforcement and adoption, and helps explain why burning has persisted despite policy efforts. These lessons directly inform the design of the intervention examined in this study, which seeks to address the shortcomings of previous policies.

Burning of crop residue is formally prohibited in India under Section 188 of the Indian Penal Code. In December 2015, the National Green Tribunal—the country's statutory body for environmental protection—further imposed fines ranging from $30 to $180 on farmers

[1] The dense red dots northwest of New Delhi represent fire incidences as measured by NASA.

depending on landholding size. However, punitive approaches to deter crop residue burning have shown limited effectiveness due to weak enforcement and sustained resistance from farmer unions (Bhuvaneshwari et al., 2019; Shyamsundar et al., 2019).

On the incentive side, the Government of India introduced a subsidy program covering up to 50% of the cost for individual farmers and up to 80% for cooperatives to purchase in-situ crop residue management equipment such as the Happy Seeder. Yet, the scheme has faced challenges including low awareness among smallholder farmers, inadequate subsidy coverage, and long delays in disbursement (Erbaugh et al., 2024).

Finally, in 2019 the Punjab government announced a policy to pay ₹2500 ($29) per acre to small and marginal farmers who refrained from burning. The program was later suspended due to issues with the verification process and budgetary constraints. (Gupta, 2022)

2.2 Policy Emphasis on Early-Maturity Variety (EMV) Seeds

In recent years, the Government of Punjab has promoted the adoption of early-maturity variety (EMV) paddy seeds as a potential solution to crop residue burning. In this subsection, I review the agronomic, economic, and environmental benefits of EMV seeds and explain how they can reduce residue burning. I then describe the policy measures undertaken by the government to expand EMV cultivation and highlight the constraints to their widespread adoption.

Developed by Punjab Agricultural University between 2013–2016, EMV seeds offer several advantages over traditional long-duration varieties. They mature within 93–110 days of transplanting, compared to about 130 days for widely used long-duration varieties such as Pusa-44. Their shorter duration reduces exposure to abiotic stress and pest infestations, lowering cultivation costs and pesticide use, with estimated savings of over ₹1,500 ($\sim$ $17.6) per acre (PAU, 2024). EMVs are also resistant to diseases such as bacterial blight and are associated with higher profitability (Singh et al., 2022). Beyond private gains, EMVs conserve groundwater by requiring roughly 25% less irrigation than Pusa-44 (PAU, 2024). Reduced groundwater pumping also eases pressure on Punjab's agricultural electricity subsidies, which exceeded $1 billion in 2023–24.

EMV seeds can mitigate crop residue burning in two ways. First, the 25–30 day reduction in maturity time (Singh et al., 2022; Hindustan Times, 2024) lengthens the window between paddy harvest and wheat sowing. This potentially alleviates time pressures and allows farmers to manage residues without jeopardizing wheat yields[2]. Second, EMV plants are

[2] Rice agronomists estimate that a one-week delay in sowing reduces wheat yields by about 1.5 quintals/acre, relative to an

shorter and generate less residue per acre, making it easier to manage using both *in situ* and *ex situ* methods (Kemanth et al., 2024).

To promote adoption of EMV seeds, the Punjab government has employed both restrictions and encouragement. In 2023, it banned the cultivation of select long-duration, water-intensive, and high-residue varieties such as Pusa-44, citing groundwater depletion and residue burning concerns (Agnihotri Chaba, 2025; Kemanth et al., 2024). At the same time, it has promoted EMVs through campaigns and farmer outreach programs.

Despite these policy efforts, EMV adoption is far from universal. Although nearly 70% of paddy area in Punjab, and 49% of paddy area cultivated by the control group of this study, was under short- to medium-duration varieties, several barriers persist. Despite lower input requirements in EMV seeds, farmers continue to favor de-notified long-duration varieties like Pusa-44 for their marginally higher yields (Singh et al., 2022), which remain accessible through informal markets. Seed supply constraints for popular EMV varieties such as PR-126 in 2022 and 2023 further limited adoption, forcing some farmers to cultivate alternative varieties (Kemanth et al., 2024). In addition, my survey data reveal that limited confidence in cultivating relatively new EMV seeds (12% of farmers) and preferences for alternative varieties for self-consumption (9% of farmers) also hinder widespread adoption.

Taken together, past and current policies have yet to generate large-scale reductions in residue burning. This motivates my focus on an alternative approach that aligns farmer incentives: subsidizing EMV seeds and closing information gaps. I now describe my research design.

3 Research Design

This study uses a randomized controlled trial (RCT) to assess the impact of interventions aimed at easing the time and information constraints farmers face in managing crop residue. Drawing on lessons from prior government efforts, I implement two treatment arms that promote the adoption of EMV seeds while addressing common barriers to implementation. Farmers were randomly allocated to one of three groups: a *control* group, a *Seed Subsidy Only* group, and a *Seed Subsidy and Training* group. The study design is illustrated in Figure 1.

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average yield of 22 quintals/acre (PAU, 2024).

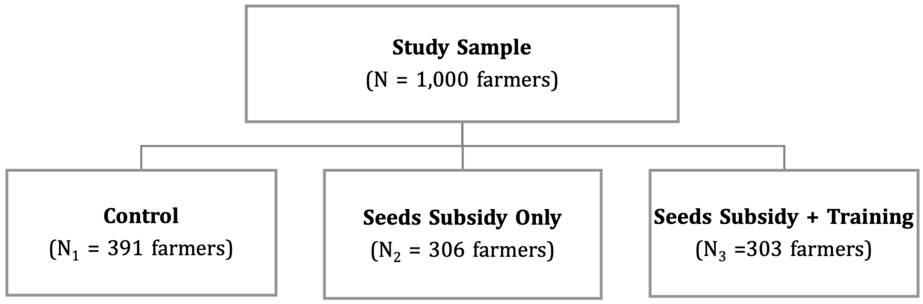

Figure 1: Research Design

3.1 Treatment Groups

3.1.1 *Seed Subsidy Only* Group

The first treatment experimentally varies adoption of EMV seeds through targeted subsidies. Farmers in this group were offered a 50% subsidy (approximately ₹225/$2.6 per acre) for the purchase of EMV seeds, up to a maximum of 10 acres, conditional on adoption. The subsidy offer was communicated prior to sowing (April/May), and payments were made after adoption was verified on the farmer's plots.

This design complements government initiatives to increase EMV adoption in two important ways. First, it lowers the private cost of adoption through direct, conditional support. Second, given concerns about supply constraints for specific EMV varieties, the intervention allowed farmers to adopt any EMV variety and still qualify for the subsidy, thereby minimizing supply-related barriers to participation.

From an implementation standpoint, the study also addresses measurement concerns for various outcomes. Specifically, if the transplant date of each variety is known, it is easier to identify the adoption of EMV seeds, given they take 25-30 days less to mature (Singh et al., 2022). Furthermore, the dwarf nature of EMV plants make it is possible to credibly verify their adoption in the field. In addition, by leveraging the presence of a trusted local NGO, the intervention ensured timely subsidy disbursement, which built farmer confidence in the program. Farmers also agreed to geo-code their fields, enabling accurate measurement of burning outcomes (see Section 4.1).

3.1.2 *Seed Subsidy and Training* Group

The second treatment adds an information component to address the knowledge and skill gaps that often discourage farmers from adopting sustainable residue management. Prior research highlights that farmers lack awareness about alternate methods of residue management (Raza et al., 2022; Bajracharya et al., 2021). Even when the information is available, farmers perceive online or generic information as unreliable and have expressed a preference for in-person guidance and trusted social networks (Erbaugh et al., 2024). Building on this evidence, the intervention in this treatment arm combined the seed subsidy offer with two structured in-person training visits —one before the harvest and one after.

1. The first visit, conducted pre-harvest (August/September), focused on EMV cultivation practices, sustainable residue management, and strengthening market linkages for residue management machinery. During this visit, farmers were provided information on the recommended package of practices developed by Punjab Agricultural University for EMV cultivation, including optimal harvest schedules. They also received details on the costs and time requirements of various residue management options (incorporation, baling, use as cattle feed, etc.) as well as the nearest access points for crop residue management machinery.

2. The second visit, conducted post-paddy harvest (November/December), addressed concerns about maintaining wheat productivity under alternative residue management practices. Farmers often worry that avoiding burning will reduce wheat yields, largely because they are unaware that different residue management methods require complementary adjustments in subsequent cultivation practices—such as irrigation timing, fertilizer application, and pest and weed control (Kemanth et al., 2024). To address these concerns, farmers were provided guidance on the specific adjustments needed to sustain wheat yields when adopting non-burning practices.

This training intervention could reduce burning through three channels. First, training addresses knowledge and skill gaps that limit adoption of sustainable residue management. Second, stronger market linkages improve access to residue management machinery, lowering the cost of alternatives to burning. Third, assurances of technical support during both paddy and wheat cultivation may encourage EMV adoption, indirectly reducing burning.

3.2 Sample Recruitment and Randomization

The study was conducted in Fatehgarh Sahib district of Punjab, which has the state's highest agricultural $PM_{2.5}$ emissions per unit of crop production (Lan et al., 2022). Forty-three villages were identified, and from them, 1,000 farmers planning to cultivate paddy rice in the 2024 *kharif* season (June–October) were screened and enrolled. The study area and villages are illustrated in figure 12.

Randomization was done at the farmer level and stratified within villages. Following (Duflo et al., 2007), the sample was split into groups in a 4:3:3 ratio (control: subsidy only: subsidy + training) to maximize statistical power subject to budget constraints. Table 1 presents baseline characteristics of farmers across groups and checks for balance. I observe slight imbalance in planned acreage for paddy though the F-tests for joint orthogonality indicate that baseline characteristics are well-balanced across treatment groups, with p-values > 0.1 for all three pairwise comparisons. These high p-values suggest that the randomization was successful in creating comparable groups.

At baseline, farmers were on average 42 years old with 21–24 years of farming experience. About 57% owned their cultivated plots and planned to sow paddy on 10–11 acres. More than 70% farmers believed residue was difficult to manage without burning, and over 80% reported needing training in alternate methods of residue management. Between 23–28% farmers reported burning crop residue in the previous paddy harvest season (2023).

Table 1: Balance on Baseline Characteristics

	(1)	(2)	(3)	(1)-(2)	(1)-(3)	(2)-(3)
	Control Group	Seed Subsidy Only	Seed Subsidy & Training	Pairwise t-test		
	Mean/(SD)	Mean/(SD)	Mean/(SD)	P-value	P-value	P-value
Age	42.88	42.02	42.53	0.343	0.708	0.617
	(11.75)	(11.72)	(12.77)			
Experience (years)	24.34	21.61	22.78	0.307	0.567	0.237
	(45.09)	(11.58)	(12.59)			
Owner of Cultivated Land	0.57	0.59	0.58	0.691	0.849	0.847
	(0.50)	(0.49)	(0.49)			
Planned area under paddy cultivation (acres)	9.63	10.33	11.57	0.325	0.041	0.234
	(9.16)	(9.35)	(15.32)			
=1 if difficult to manage residue without burning	0.75	0.70	0.74	0.131	0.649	0.327
	(0.43)	(0.46)	(0.44)			
=1 if requires training in alternate methods to burning	0.81	0.81	0.84	0.961	0.360	0.410
	(0.39)	(0.39)	(0.37)			
=1 if requires support to access residue management machinery	0.83	0.79	0.81	0.155	0.410	0.581
	(0.37)	(0.41)	(0.39)			
=1 if burnt residue in previous year (2023)	0.28	0.24	0.23	0.198	0.136	0.839
	(0.45)	(0.43)	(0.42)			
F-test for joint orthogonality (p-value)				0.888	0.999	1.000
Number of observations	384	301	293			

Notes: This table presents mean values and standard deviations (in parentheses) for baseline characteristics across the three groups—Control, Seed Subsidy Only, and Seed Subsidy & Training. The columns (1)-(2), (1)-(3), and (2)-(3) report p-values from pairwise t-tests. The F-test for joint orthogonality tests whether all baseline characteristics are jointly balanced between treatment groups. * p<0.1, ** p<0.05, *** p<0.01.

4 Data and Empirical Strategy

4.1 Data Collection

The empirical analysis relies on two complementary sources of data: farmer surveys and direct field observations. Together, these allow me to measure not only adoption of EMVs but also actual burning outcomes on cultivated plots. Figure 11 illustrates the agricultural and data collection timelines.

4.1.1 Survey Data

The surveys were conducted in three rounds: baseline, midline and endline.

Baseline surveys were conducted during the pre-sowing months (April/May 2024). I collected data on farmer demographics, farming practices, seeds preferences and barriers to sustainable residue management. I also recorded the geocoordinates of the plots farmers planned to cultivate. At the end of the survey, treatment status was announced, and treated farmers were informed of the subsidy offer (to be paid after verifying adoption of EMV seeds).

Midline surveys were conducted in the middle of the rice growing season (August/September 2024) where I collected data on self-reported adoption of EMV seeds and the geocoordinates of the actual plots cultivated. This distinction is important because baseline surveys captured intended plots for cultivation, while many farmers finalize rental contracts for their actual plots closer to sowing, which can shift the actual location of cultivation.

Endline surveys were conducted after the harvesting of paddy crop and sowing of the subsequent wheat crop (December 2024). The survey gathered data on agricultural production, self reported burning behavior and the crop residue management practices. To measure the impact of training intervention, I also collected information about farmer awareness, confidence and reported constraints in using alternate methods of crop residue management.

4.1.2 Field Observation Data

To complement self-reports, enumerators visited all cultivated plots to directly measure adoption and burning outcomes.

Using plot geocoordinates, enumerators accompanied farmers to measure crop height once plants had reached maturity. Drawing on estimates from (Mann and Dhillon, 2023; Singh et al., 2019), EMV varieties in my sample typically did not exceed a height of 115.75 cm, compared to up to 128.6 cm for long-duration varieties. As a simple verification rule, a plot was classified as EMV if the farmer reported EMV adoption *and* measured crop height was below 115.75 cm.[3]

For burning outcomes, enumerators again relied on geocoordinates to conduct unannounced visits every 2–3 days during the harvest season (September–December 2024). Since burn traces are visible only for a short period, repeated visits were necessary to capture outcomes reliably. Plots were categorized as no burn, partial burn (burning only the upper

[3]Since purchase receipts or other forms of proof were rarely available, height-based verification provided a practical and credible way to confirm adoption.

part of crop residue), or full burn (burning both the upper part of residue and basal stalk). Importantly, this exercise could be completed from outside the farmer's field, allowing independent observation without farmers being present. Figure 13 illustrates each type of burning outcome.

I successfully collected both field observation and endline survey data for the vast majority of farmers, with minimal attrition across treatment groups. Table 8 reports attrition rates between the baseline and endline surveys. Attrition in the control group was approximately 1.8%, and there is no evidence of differential attrition in either treatment group relative to the control.

4.2 Empirical Specification

4.2.1 Intent-to-Treat Estimates

To address the question—"How does offering subsidies for EMV adoption and training in sustainable residue management affect crop residue burning?"—I first estimate the Intent-to-Treat (ITT) effects. Specifically, I compare farmers randomly assigned to either *seed subsidy only* or *seed subsidy and training* treatments relative to the control group. This specification also allows me to explore the potential mechanisms underlying the results. Formally, I estimate:

$$Y_i = \beta_0 + \beta_1 SeedSubsidyOnly_i + \beta_2 SeedSubsidy\&Training_i + \gamma X_j + \epsilon_i \qquad (1)$$

where Y_i denotes the outcome for farmer i (e.g., acres burnt, acres planted with EMV, or adoption of residue management practices). $SeedSubsidyOnly_i$ and $SeedSubsidy\&Training_i$ are treatment assignment indicators that take the value 1 if the farmer is assigned to the *seed subsidy only* treatment and the *seed subsidy and training* treatment, respectively. X_j includes strata (village) fixed effects, and robust standard errors are used throughout. β_1 captures the effect of being assigned to the *seed subsidy only* treatment, while β_2 captures the effect of being assigned to the *seed subsidy and training* treatment. I also test the equality of treatment effects, $\beta_1 = \beta_2$.

4.2.2 Instrumental Variable Estimates

To estimate the causal impact of EMV seed adoption on burning outcomes, I employ an instrumental variables (IV) approach. Because adoption is endogenous, I use random treatment assignment as an instrument for EMV adoption. The identification strategy rests on two key assumptions.

First, the relevance condition requires that treatment assignment influences EMV adoption. As discussed in Section 3.1, there are multiple channels that make this plausible. I also present the first-stage results in Section 5.3.1, which confirm a strong and statistically significant relationship between treatment assignment and EMV adoption.

Second, the exclusion restriction requires that treatment assignment affect burning outcomes only through its effect on EMV adoption. I argue that random assignment to the *seed subsidy only* group plausibly satisfies this condition and serves as a valid instrument. A potential concern arises if treated farmers use the savings from subsidized seeds to alter their cultivation behavior, for example, by expanding acreage or adopting alternative residue management methods. However, because the subsidy is conditional on EMV adoption, any changes in total cultivated area or residue management practices are likely to operate only through the adoption channel. Moreover, given the small subsidy amount (approximately $2.6 per acre, compared to about $800 in revenue per acre)[4], any independent behavioral effect is expected to be minimal.

By contrast, assignment to the *seed subsidy and training* group may violate the exclusion restriction. Specifically, the training component could directly influence outcomes beyond EMV adoption such as improving farmers' knowledge of sustainable residue management. Nonetheless, using this group as an instrument yields a distinct interpretation: the estimated coefficient can be understood as the effect of per EMV adoption acre impact on burning. I report both sets of IV results in Section 5.

More formally, the IV specification is:

First stage:

$$Adoption_i = \pi_{10} + \pi_{11} SeedSubsidyOnly_i + \gamma_{1j} + \eta_{1i}$$

Reduced form:

$$Burning_i = \pi_{20} + \pi_{21} SeedSubsidyOnly_i + \gamma_{2j} + \eta_{2i}$$

Assuming the exclusion restriction holds, the causal effect of EMV adoption on burning can be estimated as:

$$IV\ Estimate = \frac{\pi_{21}}{\pi_{11}}$$

[4] Assuming an average yield of 30 quintals per acre (Kemanth et al., 2024), sold at the 2025 minimum support price of $27.38 per quintal.

4.2.3 Heterogeneity Estimates

A natural question on the effects across farmers is how do these effects vary with levels of land cultivation and baseline awareness about alternate methods of residue management. I answer this question by estimating pre-registered heterogeneous treatment effects along these two dimensions, as specified in the pre-analysis plan (Gandhi, 2024). I estimate the regression equation:

$$\begin{aligned} Y_i = \beta_0 &+ \beta_1 \, \text{Seed Subsidy Only}_i + \beta_2 \, \text{Seed Subsidy \& Training}_i \\ &+ \beta_3 \, \text{Seed Subsidy Only}_i \times \text{Covariate}_i + \beta_4 \, \text{Seed Subsidy \& Training}_i \times \text{Covariate}_i \\ &+ \beta_5 \, \text{Covariate}_i + \gamma X_j + \varepsilon_i \end{aligned} \tag{2}$$

The planned area of paddy cultivation is a self-reported measure by farmer at the baseline, before the treatment status was revealed. $Covariate_i = 1$ if the planned acreage is above median and 0 otherwise. To create a measure of awareness about alternate crop residue management methods, I use the baseline response to the question: Which of the following alternatives for managing crop residue are you aware of? Farmers selected the options from the list, and the awareness measure is a simple count of how many options they chose. The maximum number of options were 8. A higher score implies awareness about more alternate methods of residue management. $Covariate_i = 1$ if the number of alternatives known are above median and 0 otherwise.

5 Results

This section presents the impacts of the interventions on crop residue burning and related outcomes. I begin with overall effects on cultivation and burning, then turn to the causal role of EMV adoption using the IV strategy described earlier. Finally, I unpack the channels driving the results, focusing on EMV adoption, the incremental role of training, and pre-registered heterogeneity by baseline cultivated area and awareness of residue management methods.

5.1 Total Area Under Cultivation and Burning Outcomes

I begin by examining the effects of the interventions on cultivated area and residue burning practices. Table 2 presents the results: column 1 reports impacts on total paddy area cultivated, column 2 on partial burning (only the upper part of residue), column 3 on full burning (both the upper part and basal stalk of residue), column 4 on total burning (partial + full), and column 5 on total area harvested using sustainable methods.

Both treatment arms significantly expand cultivated area by roughly 2.46–2.50 acres, about a 27% increase relative to the control mean. The effects are statistically indistinguishable across arms. For burning outcomes, I find no detectable effects on partial burning: control farmers partially burn about 3 acres, and point estimates for both arms are negative but imprecise. By contrast, full burning falls substantially: relative to a control mean of 3.13 acres, the *Seed Subsidy Only* arm reduces full burning by about 1 acre and the *Seed Subsidy and Training* arm by about 1.5 acres; though these two effects are not statistically different from each other. Aggregating to total burning yields negative estimates for both arms, statistically significant only for *Seed Subsidy and Training* arm. This is consistent with larger and more precisely estimated reductions when training complements the subsidy.

Sustainable harvesting, defined as total cultivated acres minus total burned acres, rises by 3.57 acres in the *Seed Subsidy Only* arm (a 123% increase over the 2.9-acre control mean) and by 4.6 acres in the *Seed Subsidy and Training* arm (a 158% increase). Although the point estimates differ by more than one acre, the two effects are statistically indistinguishable.

As a robustness exercise, Table 8 expresses burning as a share of total cultivated area. I find statistically significant reductions in partial, full, and total burning. Relative to a 41% control mean for partial burning, the *Seed Subsidy Only* and *Seed Subsidy and Training* arms reduce partial burning by 11 and 15 percentage points, respectively, though the two effects are not statistically different. For full burning, over a control mean of 22.4%, the corresponding reductions are 7.8 and 12 percentage points, again not statistically different across arms. Summing to total burning, the control group burns about 63% of cultivated area; the *Seed Subsidy Only* and *Seed Subsidy and Training* arms reduce this by 19 and 26 percentage points, respectively. The reduction in total burning is larger in the *Seed Subsidy and Training* arm than in the *Seed Subsidy Only* arm, with the difference significant at the 10% level. By construction, the share of land sustainably harvested is the complement of total burning, and the coefficients mirror those for total burning.

Self-reported burning outcomes from the endline survey (Table 9) align with these patterns. In the control group, 43% of farmers report burning. The *Seed Subsidy Only* arm reduces self-reported burning by 27 percentage points and the *Seed Subsidy and Training* arm reduces it by 32 percentage points, a statistically larger effect than the subsidy-only arm.

Finally, a post–double-selection LASSO procedure selects no additional controls beyond treatment indicators and village fixed effects, indicating that observable farmer characteristics add little predictive power for sustainable harvesting once within-village and treatment differences are accounted for. Results are also robust to randomization inference (Table 12), alleviating concerns about finite-sample inference under farmer-level randomization.

Table 2: Area Under Cultivation and Burning Outcomes

Outcomes	Total Acres Under Paddy	Partial Burning (Acres)	Full Burning (Acres)	Total Burning (Acres)	Total Land Sustainably Harvested (Acres)
	(1)	(2)	(3)	(4)	(5)
Seeds Only	2.46***	-0.10	-1.01**	-1.11	3.57***
	(0.73)	(0.51)	(0.51)	(0.73)	(0.58)
Seeds + Training	2.50***	-0.70	-1.49***	-2.10***	4.60***
	(0.72)	(0.48)	(0.49)	(0.70)	(0.64)
N	978	978	978	978	978
Control Mean	9.067	3.025	3.136	6.162	2.905
p-val Seeds Only = Seeds + Training	0.964	0.235	0.292	0.119	0.164

Heteroskedasticity-robust standard errors in parenthesis. * p<0.1, ** p<0.05, *** p<0.01

5.2 Does Adopting EMV Seeds Reduce Burning?

The Government of Punjab has recently promoted early-maturity varieties (EMVs) as a potential solution to curb crop residue burning. The causal effect of EMV adoption on burning, however, is ex ante unclear. Using an instrumental variable approach, I provide the first causal evidence on this relationship. Table 3 reports the estimates. As outlined in Section 4.2.2, the analysis compares only the *Control* and *Seed Subsidy Only* groups, excluding the *Seed Subsidy and Training* group due to concerns about violation of the exclusion restriction.

EMV adoption has no detectable effect on partial burning (column 1). In contrast, each additional acre planted with EMVs reduces full burning by 0.38 acres on average, significant at the 10% level (column 2). Aggregating partial and full burning, the point estimate implies a 0.42-acre reduction in total burning per acre of EMV adoption, although this estimate is imprecise and not statistically significant. Turning to sustainable harvesting, an additional acre of EMV adoption increases land area harvested sustainably by 1.35 acres, a statistically significant effect. The per-acre effect exceeding one is consistent with mechanisms that extend beyond the directly treated plot. For example, shorter growing cycle of EMVs potentially provide farmers more time to manage residue in the harvest–sowing window and reduce residue volume, enabling sustainable management on adjacent non-EMV plots. Consistent with this interpretation, section 5.3.1 shows that sustainably harvested area rises by more than EMV acreage. A complementary channel is learning: adoption in the *Seed Subsidy Only* arm may catalyze self-learning about residue management, with supportive evidence for this discussed in section 5.3.2.

Taken together, these results indicate that EMV adoption can substantially reduce burning. The evidence is consistent with policy efforts in Punjab that restrict long-duration varieties and promote the uptake of EMV seeds.

Table 3: Impact of an Additional Acre of EMV Seed Adoption on Burning (in Acres)

Outcomes	IV estimate Partial Burn (Acres)	IV estimate Full Burn (Acres)	IV estimate Total Burn (Acres)	IV Estimate Total Sustainable Harvesting (Acres)
	(1)	(2)	(3)	(4)
EMV Adoption (Acres)	-0.040	-0.38*	-0.42	1.35***
	(0.19)	(0.20)	(0.28)	(0.28)
N	685	685	685	685

Heteroskedasticity-robust standard errors in parenthesis. * $p<0.1$, ** $p<0.05$, *** $p<0.01$

5.3 Why Did Treatment Farmers Reduce Burning?

Reductions in burning plausibly operate through two channels: higher adoption of EMV seeds, which relaxes the harvest–sowing time constraint and lowers residue volume; and additional gains from training that mitigate information frictions around sustainable residue management. I examine each channel in turn.

5.3.1 Higher EMV Adoption

Table 4 shows that both treatments substantially increased EMV adoption. Farmers in the *Seed Subsidy Only* arm adopted 2.64 additional EMV acres on average (an 84% increase relative to control), while the *Seed Subsidy and Training* arm adopted 3.56 additional acres (a 114% increase). The latter effect is significantly larger, suggesting that the assurance of training boosted EMV adoption beyond the impact of the subsidy alone. This is consistent with the training content, which emphasized optimal harvesting schedules and residue management practices for EMVs, thereby encouraging farmers to adopt them.

Table 4: EMV Seeds Adoption and Self-Reported Time Constraints

Outcomes	EMV Adoption (in Acres)	Insufficient Time for Residue Clearing (Dummy)
	(1)	(2)
Seeds Only	2.64***	-0.099***
	(0.41)	(0.016)
Seeds + Training	3.56***	-0.080***
	(0.57)	(0.017)
N	978	978
Control Mean	3.117	0.109
p-val Seeds Only = Seeds + Training	0.0840	0.143

Heteroskedasticity-robust standard errors in parenthesis. * p<0.1, ** p<0.05, *** p<0.01

As discussed in Section 2.2, EMVs can reduce burning by extending the interval between paddy harvest and wheat sowing and by generating less residue, which facilitates both in-situ and ex-situ residue management. By in-situ methods, I refer to practices that manage residue within the field, for example mulching, soil incorporation, or on-field composting. By ex-situ methods, I mean removing crop residue from the field for external uses, for example baling for sale, animal feed, or off-farm composting/energy.

The evidence is consistent with both pathways: The share of farmers citing time constraints for residue management falls by 9.9 and 8 percentage points in the *Seed Subsidy Only* and *Seed Subsidy and Training* arms, respectively (Table 4, column 2), suggesting that EMVs alleviated a key barrier often cited as a reason for burning. Table 5 further indicates that treated farmers reported significantly lower reliance on burning and greater adoption of alternative residue management methods. While 41.4% of control farmers reported burning, the *Seed Subsidy Only* and *Seed Subsidy and Training* arms reduced self-reported burning by 27 and 32 percentage points, respectively, with the latter effect statistically larger. Both arms also report greater use of in-situ methods (mulching, incorporation, composting) and ex-situ methods (baling, animal feed). Taken together, the results suggest that EMVs not only give farmers more time to manage residue but also lower their residue handling costs, making non-burning strategies more feasible on EMV plots and, potentially, adjacent non-EMV acreage.

Table 5: End Use of Crop Residue

Outcomes	Burning	Mulching	Incorporation	Composting	Baling	Animal Feed
	(1)	(2)	(3)	(4)	(5)	(6)
Seeds Only	-0.27***	0.030**	0.046	0.062***	0.17***	0.0044
	(0.031)	(0.013)	(0.030)	(0.013)	(0.025)	(0.012)
Seeds + Training	-0.32***	0.018	0.27***	0.0068	0.14***	0.065***
	(0.029)	(0.012)	(0.032)	(0.0063)	(0.025)	(0.018)
N	978	978	978	978	978	978
Control Mean	0.414	0.0130	0.385	0	0.237	0.0234
p-val Seeds Only = Seeds + Training	0.0890	0.447	0	0	0.150	0.00100

Heteroskedasticity-robust standard errors in parenthesis. * p<0.1, ** p<0.05, *** p<0.01

5.3.2 Role of Training Intervention

I next examine whether the training component independently reduced burning. As discussed in Section 3.1.2, training can operate by closing knowledge gaps, strengthening market linkages for residue-management services, and indirectly by raising EMV adoption. I present evidence consistent with each channel.

Table 6 reports estimates for various outcomes relating to farmer ability in sustainable crop residue management. I find evidence that both treatments improved self-reported farmer skills for residue management, confidence in handling post-harvest issues under no burning (e.g. pests), and self-reported perceived ease of using alternatives. Interestingly, the magnitudes are quite similar and I find no significant differences between the two treatments on these dimensions. Given that only the *Seed Subsidy Training* group received formal training, this pattern suggests that the EMV adoption itself may induce substantial self-learning to support sustainable residue management.

By contrast, training had clear effects on machinery access. Columns 4–5 show that only the *Seed Subsidy and Training* group reported improved awareness of nearby sources of residue management machinery (an increase of 8.4 percentage points over a control mean of 82%) and fewer delays in obtaining access to residue management machinery (a 12 percentage point reduction relative to a control mean of 19%). In both cases, the difference between the training and subsidy-only groups is significant. These results suggest that training reduces burning partly by improving timely access to residue-management services.

To quantify training's incremental contribution at the intensive margin, I estimate IV models using random assignment to the *Seed Subsidy and Training* arm as an instrument for EMV adoption (Table 7). Interpreting coefficients as effects per acre of EMV adoption,

Table 6: Awareness and Input Availability

Outcomes	Skills in managing crop residue without burning	Confidence in dealing with issues due to no burn	Easiness in crop residue management without burning	Aware of nearby sources of residue management machinery (Dummy)	Delays in accessing crop residue management machinery (Dummy)
	(1)	(2)	(3)	(4)	(5)
Seeds Only	0.36***	0.40***	0.10***	0.038	0.043
	(0.056)	(0.059)	(0.039)	(0.025)	(0.027)
Seeds + Training	0.31***	0.43***	0.17***	0.084***	-0.12***
	(0.058)	(0.059)	(0.043)	(0.024)	(0.023)
N	978	978	978	978	978
Control Mean	2.781	2.648	2.060	0.820	0.190
p-val Seeds Only = Seeds + Training	0.375	0.634	0.123	0.0760	0

Heteroskedasticity-robust standard errors in parenthesis. * p<0.1, ** p<0.05, *** p<0.01
Columns 1,2 and 3 represent answers to endline questions asked on a likert scale 1-5, with 5 being highest level of skill, confidence and easiness respectively. Columns 4 and 5 represent dummy variable outcomes.

partial burning declines by about 0.2 acres per adoption acre of EMV, though not statistically significant. By contrast, the reduction in full burning is roughly twice as large and statistically significant. Aggregating to total burning, the estimated reduction in burning is 0.57 acres per EMV acre —larger than the 0.42 acres in the subsidy-only IV. The sustainably harvested area also rises significantly by 1.28 acres per EMV acre. As discussed in Section 5.2, per-acre effects exceeding one are consistent with mechanisms that extend beyond the directly treated plot (fr example, time saved and lower residue volumes enabling sustainable management on adjacent fields).

Taken together, evidence suggests that training has an incremental effect on reducing burning through two pathways —first, by increasing EMV adoption and second, by amplifying the per-acre reduction in (especially full) burning per adoption acre of EMV.

Table 7: Impact on Burning (in Acres) for an Additional Acre of Adoption of EMV Seeds (Control vs Subsidy + Training Group)

Outcomes	IV estimate Partial Burn (Acres)	IV estimate Full Burn (Acres)	IV estimate Total Burn (Acres)	IV Estimate Total Sustainable Harvesting (Acres)
	(1)	(2)	(3)	(4)
EMV Adoption (Acres)	-0.20	-0.40***	-0.57***	1.28***
	(0.14)	(0.15)	(0.22)	(0.27)
N	677	677	677	677

Heteroskedasticity-robust standard errors in parenthesis. * p<0.1, ** p<0.05, *** p<0.01

5.4 Heterogeneity by Planned Area and Awareness

This section examines treatment heterogeneity along two pre-registered margins: baseline planned cultivation area (acres) and baseline awareness of crop residue management (CRM) techniques. These variables were identified prior to analysis as potentially important moderators of treatment effects. The first proxy captures differences in operational scale while the second reflects initial knowledge and familiarity with non-burning alternatives.

Theoretically, the direction of heterogeneity along these dimensions is ambiguous. Farmers with above-median cultivation area might respond more strongly to the intervention if they have lower financial constraints for adopting sustainable residue management methods or if they can leverage economies of scale in adopting EMV seeds and residue management machinery. On the other hand, larger farmers must clear greater residue volume within the same weather window and often face tighter labor/logistics bottlenecks, making burning the time-dominant method of residue management. Smallholders may respond more if absolute residue volumes are manageable, but less if fixed charges, credit limits, or minimum-acre service thresholds render alternatives unviable. Similarly, above-median awareness can amplify impacts because learning costs are lower, training material is more readily absorbed, and pre-existing networks (peers, input dealers, extension agents) help convert training into practice. On the other hand, effects may be weaker at high awareness due to diminishing returns to information or binding non-informational constraints (e.g., machine queues).

Table 8 reports heterogeneity for total land sustainably harvested and EMV adoption, each normalized by baseline planned area to facilitate interpretation. Coefficients on *Seed Subsidy Only* (β_1) and *Seed Subsidy and Training* (β_2) give effects for the below-median subgroup (covariate = 0). Interaction terms (β_3, β_4) show how effects differ for the above-median subgroup (covariate = 1) and the total effects for the above-median subgroup are $\beta_1 + \beta_3$ and $\beta_2 + \beta_4$.

For sustainable harvesting (column 1), both treatments raise the outcome among below-median cultivators by 65 and 73 percentage points, respectively. Because normalization uses baseline planned (rather than realized) cultivation, adding the control mean can yield totals exceeding one. The planned-cultivation interactions are negative and statistically significant (-41 pp and -38 pp), indicating attenuation for above-median cultivators. Implied above-median effects are 0.24 (= 0.65 - 0.41) for *Seed Only* and 0.35 (= 0.73 - 0.38) for *Seed and Training*, both statistically significant. By contrast, interactions are positive and significant along CRM awareness (column 2): effects are larger for the above-median awareness group by 36 percentage points for *Seed Only* and 43 percentage points for *Seed and Training* group, respectively.

For EMV adoption (column 3), both treatments significantly increase adoption among below-median groups by 48 and 57 percentage points, respectively. Along planned cultivation, interactions are small and statistically insignificant. Similarly, along baseline awareness, interactions are indistinguishable from zero, implying similar adoption gains across awareness strata. Across outcomes, effects do not differ meaningfully between the Seed-Only and Seed+Training arms within strata. Across outcomes, I do not detect meaningful differences between the Seed-Only and the Seed+Training arms within strata.

Table 8: Treatment Effects by Baseline Planned Cultivation Area and Awareness of Residue Management

Outcomes	Total Land Sustainably Harvested (Normalized by Baseline Planned Area)		EMV Seed Adoption (Normalized by Baseline Planned Area)	
	(1) Above-median Baseline Planned Cultivation	(2) Above-median Baseline CRM Awareness	(3) Above-median Baseline Planned Cultivation	(4) Above-median Baseline CRM Awareness
Seed Subsidy Only (β_1)	0.65***	0.23**	0.48***	0.38***
	(0.15)	(0.10)	(0.15)	(0.14)
Seed Subsidy & Training (β_2)	0.73***	0.25***	0.57**	0.51**
	(0.15)	(0.092)	(0.23)	(0.21)
Seed Subsidy Only $\times$ Covariate (β_3)	-0.41**	0.36**	-0.12	0.017
	(0.17)	(0.15)	(0.15)	(0.16)
Seed Subsidy & Training $\times$ Covariate (β_4)	-0.38**	0.43***	-0.19	-0.15
	(0.17)	(0.16)	(0.23)	(0.21)
Covariate (β_5)	-0.28***	0.091	-0.29*	-0.054
	(0.087)	(0.36)	(0.16)	(0.14)
N	978	978	978	978
Control Mean	0.403	0.403	0.489	0.489
p-value: $\beta_1 = \beta_2$	0.688	0.846	0.623	0.419
p-value: $\beta_1 + \beta_3 = \beta_2 + \beta_4$	0.237	0.569	0.521	0.532
p-value: $\beta_1 + \beta_3 = 0$	<0.001	<0.001	<0.001	<0.001
p-value: $\beta_2 + \beta_4 = 0$	<0.001	<0.001	<0.001	<0.001
p-value: $\beta_3 = \beta_4$	0.917	0.731	0.721	0.322

Std. errors in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

6 Program Costs and Benefits

This section evaluates the cost-effectiveness of the two intervention arms. I present two complementary exercises. The first compares program costs to the social and mortality damages avoided through reduced crop residue burning, and considers implications under a potential statewide scale-up. The second benchmarks the interventions against Payments for Ecosystem Services (PES) programs that reward verified non-burning behavior.

6.1 Direct Costs and Benefits

I begin by quantifying program costs and the external benefits associated with the observed reductions in burning. Because several benefits such as health, productivity or local pollution improvements are not directly measured in my data, these estimates should be interpreted as conservative lower bounds.

Program costs depend on total expenditures per farmer (subsidies and training) and the corresponding reductions in burned acreage. I estimate the cost per unburned acre by dividing the total cost incurred per farmer by the total reduction in burned area.[5] As shown in Table 8, the total expenditure per farmer was significantly higher in the *Seed Subsidy and Training* arm ($p < 0.001$), reflecting both higher EMV adoption and additional training costs. Despite higher costs, the relative cost-effectiveness of the two arms is not directly comparable because the training arm also achieved larger reductions in burning. Assuming that partial burning on an acre is equivalent to half acre of full burning, dividing total costs by the estimated reductions in burned acreage yields an implied cost per unburned acre of ₹1104 ($12.76) for *Seed Subsidy Only* and ₹1257 ($14.53) for *Seed Subsidy and Training*. These estimates are statistically indistinguishable from each other ($p = 0.746$).

To evaluate whether the social benefits of the interventions outweigh their costs, I next quantify the external damages avoided through reduced burning. The main social benefits arise from lower greenhouse gas emissions and improved air quality. Burning crop residue releases both global pollutants, such as greenhouse gases, and local pollutants that harm health and productivity. Prior work has linked poor air quality to adverse health outcomes (Huang et al., 2022; Raza et al., 2022), lower agricultural yields (Miao et al., 2017), and reduced worker productivity (Adhvaryu et al., 2022; Wyon, 2004). Because these damages hinge on local exposure and population vulnerability (Abubakari et al., 2024), I adopt a

[5] The per-acre costs were approximately $2.60 for the seed subsidy and $1.10 for training. A monitoring cost of $0.60 per acre, which is study-specific, is excluded following Jack et al. (2025).

conservative approach and quantify only the external costs using greenhouse-gas emissions, following Abubakari et al. (2024).

To translate reductions in burning into avoided emissions, I draw on prior estimates of emissions per acre burned. Using a residue volume of 3.28 tons per acre (Kemanth et al., 2024) and an emission factor of 1,460 kg of CO_2 per ton burned (Jenkins and Bhatnagar, 1991), fully burning one acre releases approximately 4.79 tons of CO_2. Applying a social cost of carbon of \$86 per ton of CO_2 (Ricke et al., 2018), the corresponding climate damage amounts to about \$412 per fully burned acre.

I find that both treatment arms prove highly cost-effective in reducing residue burning. Dividing the climate damages averted per acre of reduced burning with the cost of achieving that reduction, I estimate that each dollar of program spending generates social benefits of roughly \$32.28 for the *Seed Subsidy Only* treatment and \$28.35 for the *Seed Subsidy and Training* treatment. These results indicate that both interventions deliver substantial welfare gains, with the subsidy-only approach performing slightly better in benefit–cost terms.

Another important question is whether the health benefits from reduced burning also exceed program costs. Jack et al. (2025) estimate that mortality damages from crop residue burning amount to approximately ₹513,000 (\$6,400) per acre. Comparing these mortality damages with the per-acre cost of preventing burning implies that the avoided health losses are roughly 400–460 times larger than the cost of reducing burning through seed subsidies with training and without training, respectively. These magnitudes underscore the large health benefits to reducing residue burning.

Finally, I assess the likely cost-effectiveness of a statewide scale-up. Such a scenario is likely to further enhance cost-effectiveness for two reasons. First, program costs would fall as public implementation eliminates research randomization costs, delivers training in groups, and exploits economies of scale and mass communication channels (e.g., radio, television, print) to disseminate training material. Second, benefits are likely to remain comparable to those estimated in this study. The 2024 baseline burning rate reported by sandhu (2025) is 62% —closely matching the control mean in my experiment (63.7%; see Table 8), suggesting strong external validity and that the treatment effects are likely to persist under large-scale roll-out.

To put these cost-effectiveness estimates into perspective, it is useful to consider the implications of scaling up the interventions across Punjab. Lan et al. (2022) estimate that crop residue burning caused approximately 86,000 premature deaths across India in 2018, with Punjab accounting for about 43 percent of the pollution exposure during the postmonsoon months that coincide with rice harvesting and burning. In the same year, Kumar et al. (2019) report that roughly 4.67 million acres of cropland were burned in Punjab between October and November.

A simple back-of-the-envelope extrapolation, combining these figures with my estimated program costs and impacts, suggests that eliminating residue burning statewide would cost between \$60 million-\$68 million per year, equivalent to less than 1 percent of Punjab's GDP. The associated benefits would be substantial: an estimated reduction of around 37,000 premature deaths annually from improved air quality, and approximately 22 million tons of avoided CO_2 emissions.[6] These magnitudes underscore the enormous potential welfare gains from investing in programs that reduce crop residue burning in Punjab.

6.2 Comparison With Payments for Ecosystem Services (PES)

A natural question is how the effectiveness of my interventions compares with alternative approaches to reducing residue burning. One approach that has gained wider use in the broader context of natural resource conservation is Payments for Ecosystem Services (PES). PES programs reward verified ecological outcomes such as non-burning by aligning farmers' private incentives with social objectives. While PES has not yet been implemented by policymakers to address crop residue burning in India, Jack et al. (2025) evaluate a randomized PES program in Punjab that experimentally tested this approach. They find that partial up-front payments reduced burning by 7.7–11.5 percentage points, whereas purely ex-post payments had no measurable effect. The close proximity in both time and location between their study and mine provides a useful benchmark for comparing the relative efficiency of these interventions.

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[6] Assuming complete burning of the 4.67 million acres in 2018 as the baseline.

remainder paid after verification of non-burning.[7] They find that up-front payments reduced burning by 7.7–11.5 percentage points relative to the control group, whereas purely ex-post payments had no measurable effect. The close proximity in both time and location between their study and mine offers a useful benchmark for comparing the relative efficiency of these interventions.

I find that the interventions I test are both more cost-effective than the up-front PES. To enable comparison, I use a common metric: the cost per additional unburned acre. The estimated cost in my intervention arms (₹1104–₹1257) is substantially lower than the corresponding cost for the up-front PES treatment (₹2695), implying that my programs achieve an unburned acre at 53–60 percent lower cost.

While this paper focuses on a direct comparison, an important question for future research is how these two policy approaches interact when implemented jointly. Because PES (outcome-based) and EMV/training (input-based) interventions address different behavioral and technological constraints, they may complement rather than substitute each other. Understanding these complementarities could inform how limited public funds can be allocated most effectively to achieve large-scale reductions in agricultural burning.

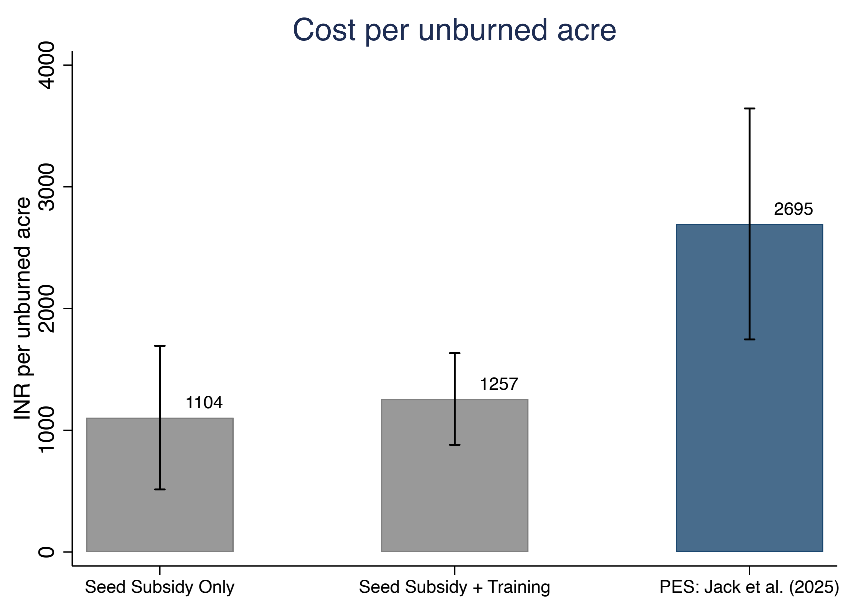

Figure 2: Cost Effectiveness Comparison with Payments for Ecosystem Services

[7] In the up-front PES arm, farmers received part of the payment before harvest—intended to alleviate liquidity and trust constraints—and the remaining conditional payment after verification of non-burning. The up-front payment was not clawed back if burning occurred, as recovery was undesirable or infeasible in this low-income context.

7 Conclusion

This study provides the first causal evidence demonstrating the effectiveness of early-maturity variety (EMV) seeds as a viable policy tool to mitigate crop residue burning in India. Through a randomized controlled trial in Punjab, I find that offering a modest seed subsidy significantly increases the adoption of sustainable harvesting practices. Crucially, the results show that this effect is amplified more than twofold when the subsidy is combined with technical training on alternative residue management methods. This synergistic effect highlights that while financial incentives are a powerful lever, they are most impactful when they are accompanied by targeted interventions that address the underlying informational and knowledge-based constraints faced by farmers.

The policy implications extend beyond Punjab to other regions facing similar dual cropping constraints and air pollution challenges. The intervention's success in addressing both time constraints (through EMV adoption) and knowledge gaps (through training) offers a replicable model for other states in India's Indo-Gangetic Plain. Moreover, the relatively low cost per unit of emission reduction positions this intervention favorably compared to other pollution abatement strategies.

While this study offers a robust foundation for policy, its findings also point to avenues for further inquiry. It would be valuable to investigate the long-term sustainability of the observed behavior change. Finally, as large-scale adoption of EMVs could increase demand for certain complementary inputs, future work should consider how such scaling might affect market prices and supply chains, ensuring that the intervention's benefits are not undermined by unforeseen market shifts.

As India continues to invest in low-cost, scalable solutions to curb agricultural emissions, the EMV-based policy model evaluated here offers a promising pathway. However, broader adoption will require parallel efforts to address concerns around seed availability, market preferences, and farmer trust. These findings underscore the value of integrated, evidence-based approaches that align private incentives with environmental goals in resource-constrained agricultural settings.

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8 Appendix

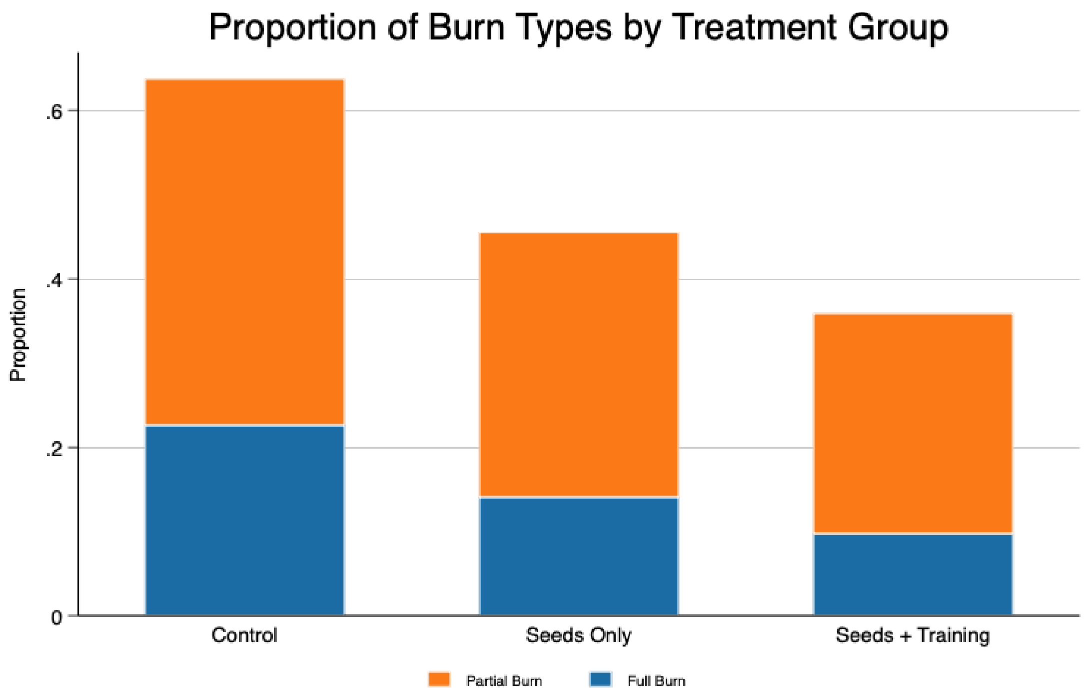


Table 9: Results: Burning Outcomes (Self Reported)

Outcomes	Any Burning Dummy	Partial Burning Dummy	Full Burning Dummy
	(1)	(2)	(3)
Seeds Only	-0.27***	0.048**	-0.31***
	(0.032)	(0.021)	(0.026)
Seeds + Training	-0.32***	0.020	-0.33***
	(0.030)	(0.020)	(0.024)
N	978	978	978
Control Mean	0.430	0.0625	0.357
p-val Seeds Only = Seeds + Training	0.0500	0.225	0.165

Heteroskedasticity-robust standard errors in parenthesis. * p<0.1, ** p<0.05, *** p<0.01

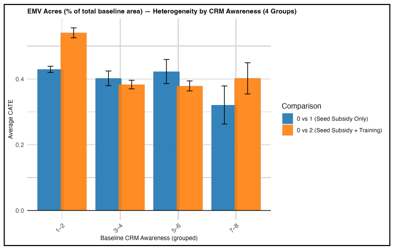


Figure 3: CATE (EMV %) By Baseline Awareness

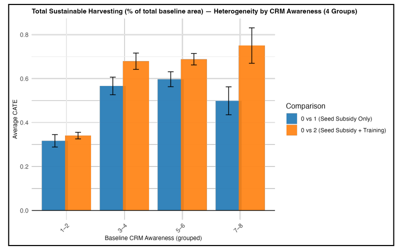


Figure 4: CATE (Sust. Harvest %) By Baseline CRM Awareness

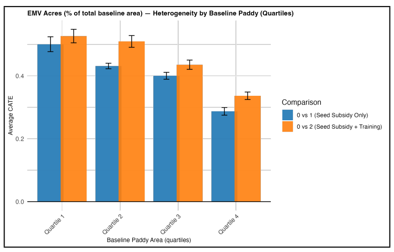


Figure 5: CATE (EMV %) By Baseline Paddy

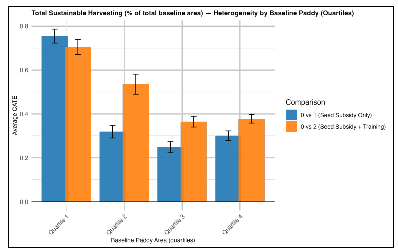


Figure 6: CATE (Sust. Harvest %) By Baseline Paddy

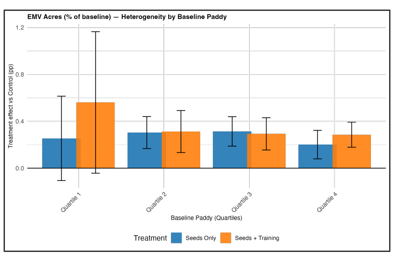


Figure 7: HET (EMV %) By Baseline Paddy

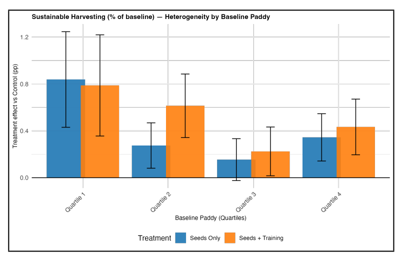


Figure 8: HET (Sust. Harvest %) By Baseline Paddy

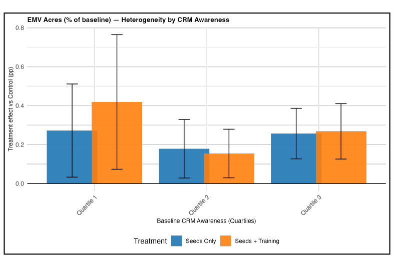


Figure 9: HET (EMV %) By Baseline CRM Awareness

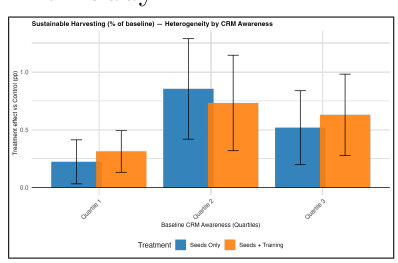


Figure 10: HET (Sust. Harvest %) By Baseline CRM Awareness

Table 10: Main Results (Acreage and Emissions)

Outcomes	CO_2 emissions (tons, 25%)	$2emissions(tons, 50\%)$	$2emissions(tons, 75\%)$
	(1)	(2)	(3)
Seeds Only	-3.77**	-3.86*	-3.95*
	(1.92)	(2.09)	(2.34)
Seeds + Training	-6.07***	-6.71***	-7.34***
	(1.86)	(2.02)	(2.26)
N	978	978	978
Control Mean	14.20	16.95	19.71
p-val Seeds Only = Seeds + Training	0.169	0.113	0.0936

Std errors in parenthesis. * p<0.1, ** p<0.05, *** p<0.01

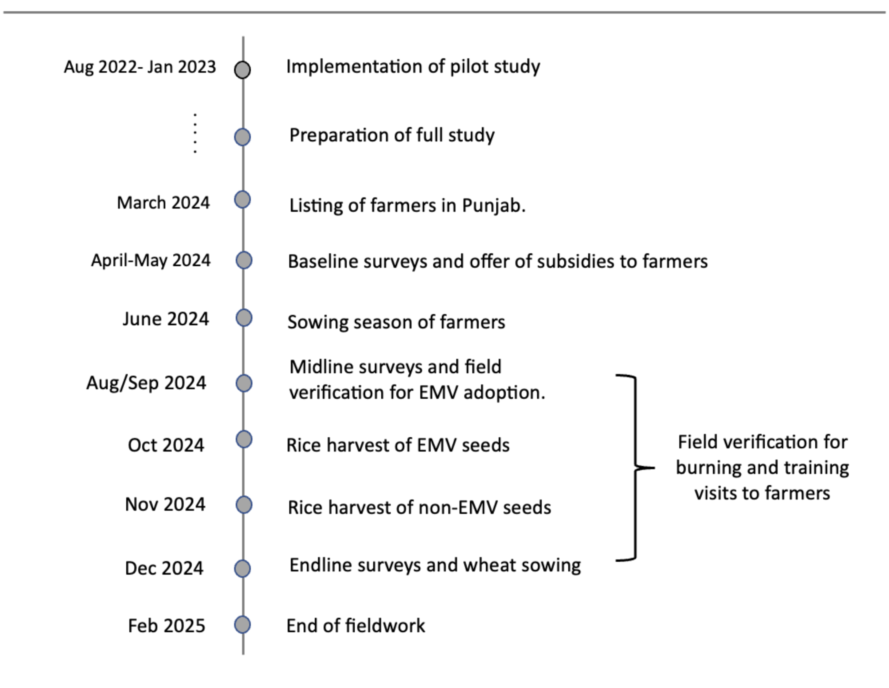
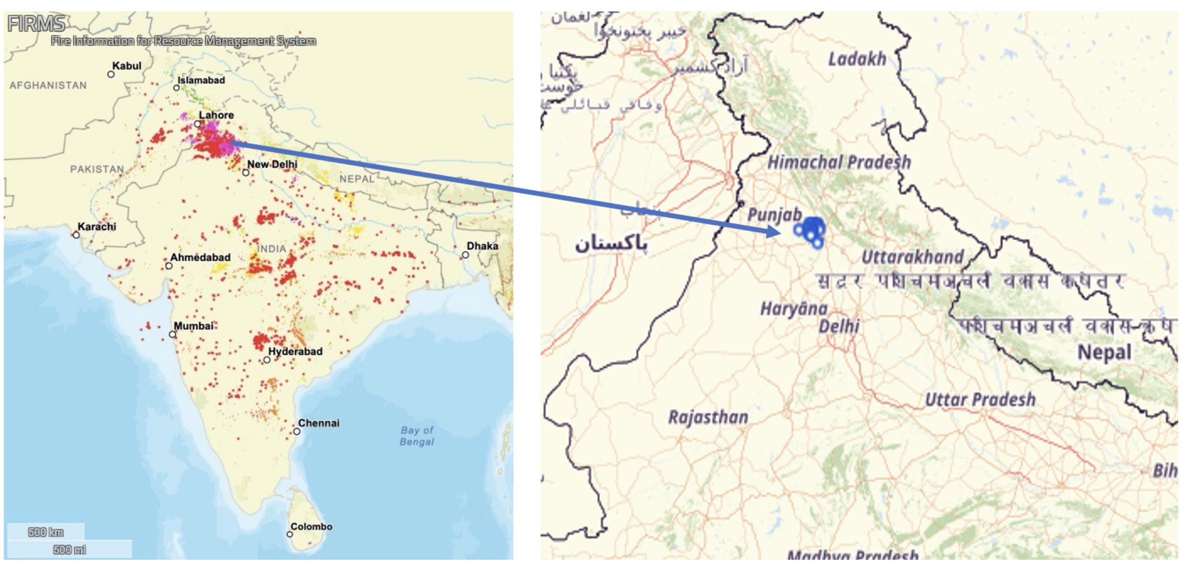


Figure 11: Project Timeline

Table 11: Attrition From Endline Survey

Outcomes	Attrition
	(1)
Seeds Only	-0.0016
	(0.0096)
Seeds + Training	0.016
	(0.012)
N	1000
Control Mean	0.0179
p-val Seeds Only = Seeds + Training	0.152

Std errors in parenthesis. * p<0.1, ** p<0.05, *** p<0.01. The outcome variable is a dummy that takes the value 1 if the respondent attrited from the endline.



Heat Map of Crop Residue Burning, November 2022.
Source: FIRMS database, NASA

Study Locations For This Project

Figure 12: Study Area

Table 12: Area Under Cultivation and Burning Outcomes (Randomization Inference)

	Total Acres Under Paddy	Partial Burning (Acres)	Full Burning (Acres)	Total Burning (Acres)	Total Land Sustainably Harvested (Acres)
Seeds Only	2.46***	-0.10	-1.01**	-1.11	3.57***
	(0.001)	(0.825)	(0.037)	(0.123)	(0.000)
Seeds + Training	2.50***	-0.70	-1.49***	-2.10***	4.60***
	(0.000)	(0.152)	(0.005)	(0.001)	(0.000)
Observations	9.07	3.03	3.14	6.16	2.90
Control Mean	0.966	0.254	0.378	0.191	0.118
RI p-value: Seeds Only = Seeds + Training	978	978	978	978	978

Notes: Coefficients from OLS with village fixed effects. Randomization inference p-values (1,000 replications, stratified by village) in parentheses. * p<0.1, ** p<0.05, *** p<0.01 based on RI p-values.

Table 13: Burning Outcomes As Percentage of Total Area Under Cultivation

Outcomes	Partial Burning (%)	Full Burning (%)	Total Burning (%)	Total Land Sustainably Harvested (%)
	(1)	(2)	(3)	(4)
Seeds Only	-0.11***	-0.078***	-0.19***	0.19***
	(0.033)	(0.027)	(0.037)	(0.037)
Seeds + Training	-0.15***	-0.12***	-0.26***	0.26***
	(0.034)	(0.026)	(0.037)	(0.037)
N	978	978	978	978
Control Mean	0.413	0.224	0.637	0.363
p-val Seeds Only = Seeds + Training	0.176	0.137	0.0570	0.0570

Heteroskedasticity-robust standard errors in parenthesis. * p<0.1, ** p<0.05, *** p<0.01

No Burn

Partial Burn

Full Burn

Figure 13: Burning Margins

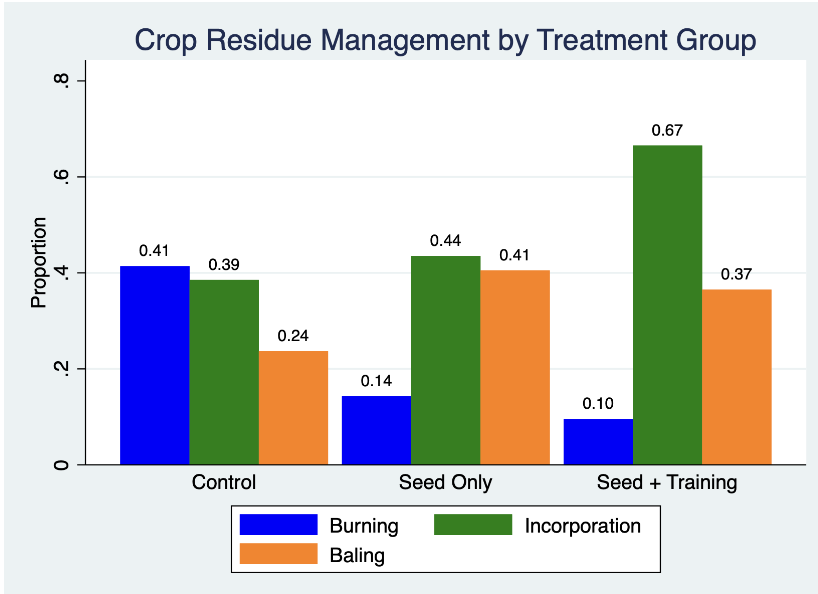


Figure 14

Table 14: Total Cost Incurred Per Farmer for Subsidies and Training

Outcomes	Total Cost Per Farmer (INR)
	(1)
Seeds Only	1167.3***
	(46.7)
Seeds + Training	2311.8***
	(78.3)
N	978
Control Mean	0
p-val Seeds Only = Seeds + Training	0

Heteroskedasticity-robust standard errors in parenthesis. * p<0.1, ** p<0.05, *** p<0.01