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ORIGINAL PAPER

Financing Climate-Smart Agriculture: a case study from the Indo-Gangetic Plains

Roberto Villalba[1] · **Garima Joshi**[1,2] · **Thomas Daum**[2,4] · **Terese E. Venus**[3]

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Abstract

The Indo-Gangetic Plains represents one of South Asia's most productive agricultural regions, yet it is highly vulnerable to climate change and requires the widespread adoption of Climate-Smart Agriculture. Although farmers understand the benefits of such technologies, financial constraints often undermine adoption. Using a case study from Haryana, we assess the opportunities and challenges aligned with the different pathways available for farmers to adopt and finance two capital-intensive technologies: laser land levelers and happy seeders. Our analysis uses unique data from Karnal, where stakeholders have partnered in Climate-Smart-Villages, and combines a household survey from 120 farmers, interviews, and focus group discussions with banks and cooperatives. Our results indicate adoption rates of 77% for laser land levelers and 52% for happy seeders, with only 7% and 21% of farmers owning the technologies, respectively. Hiring is highly preferred over purchase, mainly due to the flourishing of Custom-Hiring Centers, which are vital in driving large-scale implementation. We find that farmers prefer funding from family, savings, and moneylenders (indirect pathways) rather than from commercial banks (direct pathways) to get immediate access to credit and avoid bureaucratic procedures. Our study offers broader insights into the state of agricultural finance in India and adaptation to climate change and reveals that institutional innovations can enhance the financing of CSA technologies for smallholder farmers. Our findings have important implications for decision-makers seeking to streamline credit access for CSA machinery rental. Future research should focus on the efficacy of different finance channels and their causal impact on pathways for technology adoption.

Keywords Climate-Smart Agriculture · Agricultural finance · Credit · Happy Seeder · Laser Land Leveler · India

1 Introduction

Climate-Smart Agriculture (CSA) encompasses a variety of agricultural technologies and practices designed to deal with climate change and address the triple goal of promoting sustainable food production, enhancing resilience, and reducing greenhouse gas emissions (Jatoi et al. 2022; Lipper et al. 2018). CSA technologies are particularly important

Extended author information available on the last page of the article in the Indo-Gangetic Plains, one of India's most productive regions, which will be heavily affected by climate change (Birthal et al. 2014; Sapkota et al. 2015). Previous studies project that by 2100, without any actions, climate change will generate significant fluctuations in temperature and rainfall in this region, dropping rice yield by 15% and wheat yield by 22% (Birthal et al. 2014). The adoption of CSA practices has the potential to offset some of these effects, allowing farmers to increase water productivity by 66% and reduce production costs by 23% (Sapkota et al. 2015).

Farmers in the region are already experiencing some environmental effects of climate change, including the depletion of water tables, soil health deterioration, air pollution from in situ burning, and the loss of crucial plant nutrients (Phogat et al. 2020). For example, due to intensive rice production in Haryana, the government has encouraged farmers to replace water-guzzling rice varieties with maize and pulses to reduce the stress on natural resources (CGIAR, CCAFS, CIMMYT 2014). Moreover, more than 70% of soils in India are affected by soil acidity or soil alkalinity, and about 29% of the total geographical area is under land degradation (Das et al. 2022). Further, in 2018, crop burning from rice, wheat, maize, and sugarcane accounted for 90% of the country's 10 mm of particulate matter in the air (Sahu et al. 2021).

Among India's most promising CSA technologies are the Laser Land Leveler and the Happy Seeder. Both types of machinery belong to a new group of technologies promoted by national and international organizations to contribute to smallholder farmers' adaptation and climate change mitigation (Aryal et al. 2018, 2020b; Taneja et al. 2019). The Happy Seeder is a zero-tillage drilling equipment intended for maize and wheat. It has proven to effectively increase farm profitability by 20% compared to conventional seeders, reduce emissions by 78% compared to residue-burning, and consistently reduce the environmental footprint of farming (Kaushal and Prashar 2021; Shyamsundar et al. 2019). The Laser Land Leveler is a water-smart CSA technology with improved precision that increases water and land productivity. It is mainly used for rice production, generating yield increases of up to 342 kg per hectare and reducing greenhouse gas emissions by 163,600 MT of CO2 (Aryal et al. 2018; Gill 2014).

Despite the climate change adaptation benefits attributed to CSA technologies, CSA adoption in the Indo-Gangetic Plains is varied and relatively limited (Palanisami et al. 2015). Previous research has found that farmers are more likely to adopt CSA technologies if the financial benefits outweigh the initial investment (Branca et al. 2021; Khatri-Chhetri et al. 2017, 2019; Taneja et al. 2019). However, as many of these technologies are capital-intensive and require high upfront equipment, finance is a significant barrier to adopting CSA technologies (FAO 2010). Farmers realize benefits cumulatively and weighted in the short and long run but must pay current period costs. Moreover, widespread implementation of CSA requires not only technological support but also accounting for the socio-demographic, institutional, and resource-endowment challenges faced by farmers (Li et al. 2024), which are particularly higher for smallholder and marginal farmers (Azadi et al. 2021; Ruben et al. 2019; Vishnoi and Goel 2024). This segment of producers plays a crucial role in Indian agriculture, representing more than 80% of the workforce and more than half of the total agricultural produce (Ministry of Agriculture and Farmers Welfare 2022). While adequate access to financial services is critical to increasing crop efficiency, technology adoption, and market opportunities (Christen and Anderson 2013; Mattern and Ramirez 2017), smallholders struggle to access useful and affordable financial products that meet their needs (e.g., transactions, savings, credits, and insurance) (Adegbite and Machethe 2020; Azadi et al. 2021; Vishnoi and Goel 2024). As a result, this limits their ability to acquire formal financial mechanisms and adopt capital-intensive technologies.

Moreover, smallholders not only have limited access to credit but also suffer scale limitations, higher transaction costs, and higher price risks (Villalba et al. 2023), which pose additional barriers to financing CSA technology adoption.

Nevertheless, even if credit is needed, not all farmers need or desire to own farm machinery. In 2010, large farmers owned 38% of all tractors in India, while small farmers owned only 1% (Bhattarai et al. 2018). Rental markets are increasingly making tractors accessible to smallholders, and even though 85% of all landholdings are smaller than 2 ha, up to 90% of farmland is prepared by tractors (Bhattarai et al. 2017, 2018). The farm machinery rental market is estimated at US$ 5 billion yearly (Singh 2017), and the map of business models for mechanization provision is constantly evolving. Private business models aim to reduce transaction costs to access effective mechanization for smallholders, even using digital tools (Daum et al. 2021), while Farmer Producer Organizations (FPO), private contractors, and government-subsidized Custom Hiring Centers (CHC) have also emerged to address the needs of smallholders (Bhattarai et al. 2017).

Thus, CSA technologies, such as the Happy Seeder and Laser Land Leveler, show great potential to ensure that agricultural systems in the Indo-Gangetic Plains adapt to the new realities of climate change. However, their widespread implementation depends on adoption by many smallholder farmers who face significant challenges in financing such technologies, even if they foresee their benefits (Branca et al. 2021; Mizik 2021). Shedding light on inclusive financing mechanisms that foster access and adapt to smallholders' needs is crucial for policymakers to design programs that ensure CSA adoption.

Against this backdrop, this study aims to identify the opportunities and challenges aligned with the different pathways available for farmers to adopt and finance CSA technologies in the study area. To this end, we first map farmers' adoption mechanisms of both technologies; then, we explore the drivers associated with each mechanism and link those with financial preferences. Finally, we explore the role of different stakeholders in designing and enhancing CSA finance and its implementation. Drawing on the findings from Haryana, the study offers three key contributions to current discussions on CSA adoption: first, it provides a framework to map and classify financing pathways for CSA technologies; second, it explores the factors that motivate farmers to own or hire CSA technologies, and third, it offers insights into institutional innovations that could enhance the financing of CSA technologies for smallholder farmers.

The rest of the paper is structured as follows. Section 2 provides a literature background about Climate-Smart Agriculture in India and current financing mechanisms to promote its adoption. In Section 3, we describe the study area, data collection, and data analysis. Section 4 presents our key findings regarding farmers' adoption and financing mechanisms to implement CSA technologies. In Section 5, we discuss our results, and in Section 6, we present our conclusion and policy recommendations.

2 Theoretical background

2.1 Climate-Smart Agriculture in India

The concept of Climate-Smart Agriculture has been actively promoted in India through related policies and interventions by the government and by international and national research institutions (Dinesh et al. 2017). Among them is the National Mission for Sustainable Agriculture, one of the eight Missions outlined under the National Action Plan on Climate Change (NAPCC), which supports adopting CSA practices and technologies in India. Similarly, the government launched the National Innovations on Climate Resilient Agriculture (NICRA) to conduct strategic research on adaptation and mitigation and increase awareness through field demonstration plots and training programs (Dinesh et al. 2017).

Various technologies and practices have been prioritized in India to enhance the adoption of Climate-Smart Agriculture. Table 1 summarizes the major CSA technologies and practices, their potential for achieving CSA's triple goal, and their estimated costs for adoption based on previous studies. Many technologies and practices have positively impacted farm profitability, climate resilience, and emissions. Notably, the Happy Seeder and Laser Land Leveler come with many benefits but are the most capital-intensive technologies.

The Happy Seeder is an advanced seeder machine and zero-tillage drilling equipment that can plant wheat seeds directly into the rice crop residue (Jat et al. 2019). It is a tractor-mounted implement that combines a zero-tillage seeder with a straw management unit (Keil et al. 2021). In addition to no-residue burning, the use of a Happy Seeder can yield several benefits, such as a reduction in labor requirements of 80%, a decrease in irrigation needs between 20 and 25%, and a cut in herbicide use by 50% (Keil et al. 2021). The retention of rice residue on soil acts as mulch and adds to soil organic matter, improving the soil's seedbed quality and water retention ability (CGIAR, CCAFS, CIMMYT 2014). The cost of Happy Seeder is reported at INR 150,000 (US$ 1,800) (Kaushal and Prashar 2021).

The Laser Land Leveler is a tractor-towed, water-smart CSA technology with improved precision that focuses on improving water and land productivity. By leveling the field, it ensures even-handed reach and distribution of water (NAFCC 2016). The estimated volume of irrigation water that can be saved in Haryana using a Laser Land Leveler is 933 million cubic meters per year (CGIAR, CCAFS, CIMMYT 2014). Further, the technology holds the potential to mitigate and adapt to climate change by reducing irrigation requirements and fuel consumption. It is estimated that it can contribute towards reducing the annual GHG emissions by 163,600 MT of CO2 equivalent (Gill 2014). However, the technology is costly, with a market price of INR 355,299 (US$ 4,285) (Aryal et al. 2018).

2.2 Financing of CSA technologies

Financing is crucial to support farmers in adopting CSA technologies. However, developing adequate financing mechanisms requires technological innovations and socioeconomic and institutional changes (Ruben et al. 2019). A wide range of financial instruments exist, such as in-kind investments, profit reinvestments, productive safety nets, debt and equity finance, grants, and subsidies, which can be availed to meet the diverse agricultural needs at the farm level (Branca et al. 2011). The World Bank (2017) recognizes the importance of long-term investments in CSA and the need to couple them with short-term risk management interventions. Further, FAO (2010) suggests that CSA can be financed through the public and private sectors and public-private partnerships.

Previous studies suggest three pathways are key for financing CSA in rural areas (Ruben et al. 2019). First, *direct pathways* refer to enhancing direct investments in CSA technologies. For example, short-term loans can be helpful to finance CSA practices, such as fertility management and crop diversification, as these financing mechanisms are mainly disbursed for seasonal agricultural production (Islam 2020). Medium- and long-term loans can be appropriate for more expensive technologies, given high prices and long periods of depreciation (Daum and Birner 2017), and they could be matched with CSA technologies

Table 1 Major Climate-Smart Agriculture technologies and practices in India, impacts and estimated costs

CSA technology	Intended crop use	CSA Impacts			Estimated market price
		Increase in farm profitability	Resilience to climate	Reduction of emissions	
Happy Seeder	Maize, wheat	Increase by 10% compared to zero-till seeders Increase by 20% compared to conventional seeders (Shyamsundar et al. 2019)	Reduces the environmental footprint of farms (Shyamsundar et al. 2019)	Reduction of 78% per hectare compared to burning options (Ordóñez, 2017)	INR 150,000 (USD 1,800) (Kaushal and Prashar 2021)
Laser Land Leveler	Rice, vegetables	Increase in rice and wheat yields by 342 kg/ha and 323 kg/ha, respectively (Aryal et al. 2018)	Increase in rice and wheat yields by 342 kg/ha and 323 kg/ha, respectively (Aryal et al. 2018)	Reduces annual GHG emissions by 163,600 MT of CO_2 (Gill 2014)	INR 355,299 (USD 4,285) (Aryal et al. 2018)
Direct seeded rice	Rice, maize	Increase by 5–10% yield compared to transplanted rice (Marasini et al. 2016) Increase profit by INR 4,600 (70 USD) per hectare (CGIAR, CCAFS, CIMMYT 2014)	Enhances soil physical attributes and decreases water consumption of the crop (CGIAR, CCAFS, CIMMYT 2014; Marasini et al. 2016)	Reduces methane emissions relative to the conventional puddling method (Marasini et al. 2016)	INR 20,000 to INR 40,000 (USD 270 to USD 540) (Kumar et al. 2022)
Zero tillage	Maize, wheat	Increase in net revenue by 8,000 INR (USD 97.5) per hectare (Aryal et al. 2015)	Buffers the terminal heat effects in wheat production (Aryal et al. 2015)	Reduces GHG emissions by 1.5 Mg CO_2-eq per hectare Aryal et al. 2015)	INR 60,000 to INR 150,000 (USD 810 to USD 2030) (ICAR, 2018)
Alternate wetting and drying in rice	Rice	No significant (Pinto et al. 2020), but it reduces the input of irrigation water by 38% (Aryal et al. 2020)	Allows farmers to improve irrigation decisions (CGIAR, CCAFS, CIMMYT 2014)	Reduces methane emissions by 48% (CGIAR, CCAFS, CIMMYT 2014; Pinto et al. 2020)	Not applicable
Crop diversification	Any	Increased crop portfolio (CGIAR, CCAFS, CIMMYT 2014)	Diversifies climate risk (CGIAR, CCAFS, CIMMYT 2014)	Improves nitrogen fixing if leguminous crops are incorporated into the rotation (CGIAR, CCAFS, CIMMYT 2014)	Not applicable

such as the Happy Seeder or Laser Land Leveler. *Indirect pathways* refer to financially incentivizing farm households, generating favorable expenditure effects for adopting CSA technologies. The financial instruments under this category are savings, income from off-farm employment, insurance transfers, and remittances (Ruben et al. 2019). This pathway can be the most efficient option for resource-poor farmers as direct pathways are subject to market failures such as the absence of collateral, moral hazard, and risk covariance (Binswanger and Rosenzweig 1986). Custom hiring services, for example, reduce farmers' need for farm machinery purchase and ownership as they are no longer essential for adoption (Aryal et al. 2019; Daum et al. 2021). Further, previous experience shows that many farmers in countries from the Global South tend to finance mechanization with personal savings and loans from friends and relatives who work outside agriculture (Daum and Birner 2017). Lastly, *behavioral pathways* aim to strengthen the resilience of revenue streams generated by CSA technologies, for example, by using insurance or any other risk-mitigating measures. Given the relationship between risk perceptions and CSA investments, this pathway emphasizes that CSA adoption can increase if farmers have access to insurance services or mobile-based input advisory or delivery services (Ruben et al. 2019).

The financial support and services in the region strongly guide the implementation of CSA interventions in a specific area. Therefore, it is crucial to establish site-specific financial resources to ensure farmers adopt desired CSA technologies (Khatri-Chhetri et al. 2017). Sustainable financial interventions must focus on the farmers and the ecosystem around them and provide all relevant actors with incentives to deliver financial services (Villalba et al. 2023). Further, for upscaling CSA practices, local stakeholders must be involved in designing, delivering, and financing interventions (Khatri-Chhetri et al. 2019; Nazirul et al. 2019; Neufeldt et al. 2015). Thus, financing of CSA can differ between countries and might need to be custom-made as per the socioeconomic conditions of the farming communities. In India, various financial alternatives specifically designed to cater to the credit needs for applying CSA practices and technologies have been developed in recent years.

In Table 2, we present a compilation of the different interventions for smallholder farmers by sector (public, private, public-private) and pathway (direct, indirect, behavioral) for adopting CSA technologies in India. In the context of capital-intensive CSA technologies, one also needs to distinguish between financing the availability of the technology (e.g., helping a Customer Hire Center to buy a Happy Seeder) and financing the accessibility of the technology (e.g., allowing a farmer to hire the respective Happy Seeder). These financial programs and interventions require complementarity, coherence, and synergies between instruments and practices to ensure adequate financing for CSA models, particularly for smallholders. Further, programs should also factor in different combinations of CSA adoption and move beyond a single technology focus (Asante et al. 2024).

3 Methods

To explore the financing mechanisms used by farmers and other stakeholders to finance CSA technologies, we used a mixed-method approach that combined unique data collected from interviews, focus groups, and a farmers' survey. We used qualitative and quantitative methods to analyze the data and identify the underlying pathways for financing the adoption of the Happy Seeder and the Laser Land Leveler in Haryana.

Table 2 Examples of different interventions for financing smallholder farmers in India

		Public sector	Private sector	Public-private partnership
Direct pathway	**Description**	Short term credit	Matching grants or loans to farmers or farmer-producer organizations (Asian Development Bank, 2021)	Formal loan with commodities used as collateral (TERI, 2019)
	Example	Kisan Credit Cards (KCC) by public sector banks	MAGNET project: Asian development bank granted a $100 million loan.	Warehouse receipt financing through banks, warehouses, commodity buyers/ exporters, etc.
Indirect pathway	**Description**	Incentivize farmers to switch to water-saving crops (Crop Diversification, 2020)	Savings and investment instruments (Kisan Vikas Patra Features and Benefits, 2023)	Financial services to smallholders, such as savings, credit, and insurance
	Example	Crop diversification scheme by the government of Haryana	Kisan Vikas Patra (Famer growth scheme) by Axis Bank5	Sustainable Agricultural Finance and Innovation (SAFI)
Behavioral pathway	**Description**	Insurance to incentivize farmers to invest in CSA practices (Ministry of Agriculture and Farmers Welfare, 2016)	Pre-approved loans and daily access to weather forecasts market prices (FPOnEXT | Agri Stakeholders Network to Uplift Smallholders, 2022)	Weather advisory, crop monitoring, and early warning systems for pest and disease outbreaks (Ministry of Agriculture, 2019)
	Example	Pradhan Mantri Fasal Bima Yojana (PMFBY), a crop insurance scheme introduced in 2016	FPOnEXT by Sammunati Financial Intermediation and Services	Crop yield prediction model using AI (Government of India and IBM).

3.1 Case study area

Our case study focuses on the financing of CSA technologies in the district of Karnal in Haryana. The district lies in the Indo-Gangetic Plains and faces high agricultural vulnerability to climate variability and environmental challenges. In recent years, farmers in the region have experienced depletion of water tables, reductions in water use efficiency, and soil health deterioration due to the decline in micronutrient levels in the soil (CGIAR, CCAFS, CIMMYT 2014; Khatri-Chhetri et al. 2016; Phogat et al. 2020). Additionally, the region struggles to address residue burning, as growers in the area engage in the paddy residue burning in situ. This generates severe negative externalities such as air pollution, loss of crucial plant nutrients, and destruction of soil organic matter, and adds to GHG emissions associated with agricultural production (CGIAR, CCAFS, CIMMYT 2014; Phogat et al. 2020).

Agricultural production in Karnal focuses on rice and wheat and is dominated by small and marginal farmers, who represent 68% of all farming households (Ministry of Agriculture and Farmers Welfare 2022). To address the challenges faced by changing climatic events and natural resources, Karnal has been selected as a Climate-Smart hub in the Indo-Gangetic Plains, hosting national agricultural research programs, government run-pilot programs, and 27 Climate-Smart Villages (CSV) spread across four blocks. In this district, the CSV model was implemented in a joint partnership between CCAFS-CIMMYT, under the support of the National Initiative on Climate Resilient Agriculture (NICRA) and involved other key institutions such as the Central Soil Salinity Research Institute (CSSRI), the National Dairy Research Institute (NDRI), Directorate of Wheat Research (DWR), and the Regional Station of CCS Haryana Agricultural University (CGIAR, CCAFS, CIMMYT 2014).

As Climate-Smart Agriculture technologies must be customized to specific agroecological and socioeconomic conditions to ensure locally viable and extensive solutions (Lipper et al. 2014), we study CSA technology adoption within a Climate-Smart Village setting in Karnal. CSVs are community approaches to sustainable agriculture where farmers, researchers, and policymakers work together to develop local solutions that serve as a model for upscaling Climate-Smart Agriculture (Ghosh 2019). In turn, good practices are utilized by policymakers and practitioners for drawing lessons and synthesizing plans to scale up successful models. The concept of CSV was first piloted in 2011 by CCAFS in the Karnal district of Haryana state and the Vaishali district of Bihar state (Aryal et al. 2020). In Karnal, stakeholders have prioritized and implemented a mix of CSA interventions based on their perceived contributions to food security, climate risk management, adaptation, and mitigation potential (CGIAR, CCAFS, CIMMYT 2014). Among the CSA technologies available in the area, the Happy Seeder and Laser Land Leveler have been prioritized for their high potential for impact and adoption.

3.2 Data collection

The data were collected between July and September 2022 from four blocks in Karnal in collaboration with the International Maize and Wheat Improvement Center (CIMMYT). The four blocks were Gharaunda, Indri, Nissing, and Nilokheri, which are part of the Karnal districts where CSA Villages have been promoted and where farmers have already been exposed to the Happy Seeder and the Laser Land Leveler (Fig. 1). In Karnal, the pilot started with four villages in 2012, and by 2015, it was scaled to 27 villages in Nilokheri, Indri, Gharaunda, and Nissing blocks (Aryal et al. 2020; CGIAR, CCAFS,

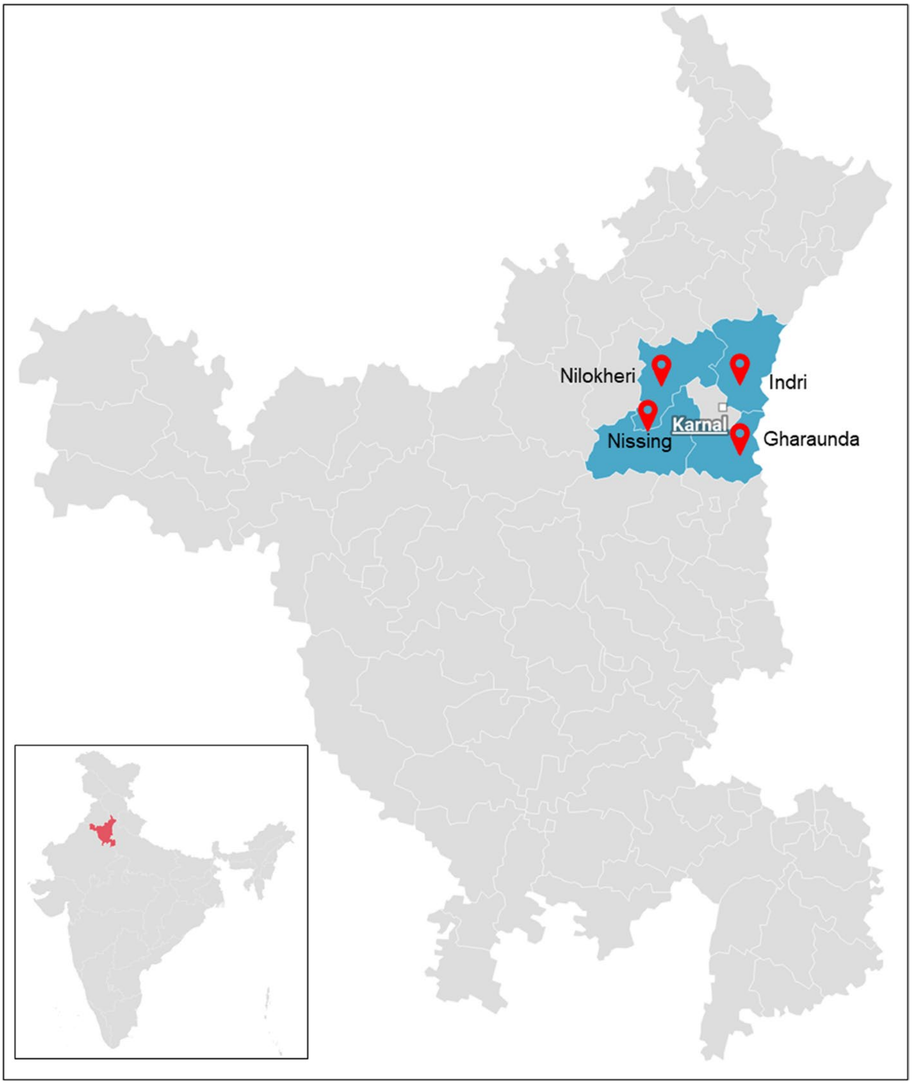

Fig. 1 Study blocks in Karnal district in Haryana, India

CIMMYT 2014). As farmers were familiar with both technologies and some had adopted them, this allowed us to explore the pathways they followed to finance them.

We used a mix of qualitative and quantitative methods to gather data from key stakeholders and farmers in the four blocks in Karnal (Table 3). First, we conducted 13 semi-structured interviews with representatives from the State Agriculture Department, Krishi Vigyan Kendra, Banks, research institutions, and private money lenders. We also used snowball sampling to interview additional stakeholders via referrals from the first group of participants. This allowed us to identify influential stakeholders from Farmer Producer Organizations, Government machinery dealers, and Custom Hiring Centers. The latter

Table 3 Data collection methods and sample size

Methods		Total
Qualitative methods	Interviews with key stakeholders	13
	Focus group discussions	2
Quantitative methods	Survey with farmers	120

refers to machinery owners who offer mechanization services customized to the needs of farmers who cannot afford their machinery. Custom Hiring Centers usually dispose of essential equipment for land preparation, sowing, and harvesting and represent a popular alternative for smallholders to access machinery in India, in particular for high-cost farm machinery, such as combine harvesters, Laser Land Levelers, rotavator, and paddy transplanter (Daum et al. 2021). We also conducted 2 Focus Group Discussions with farmers to discuss the impact of CSA technologies at the community level and understand the drivers and barriers to the financial alternatives employed by them.

Finally, we surveyed wheat and rice producers to collect information about their adoption of CSA technologies and the mechanisms they use to finance them. We selected these two crops as the rice-wheat production system is used by approximately 65% of the farmers in Haryana (Ministry of Agriculture and Farmers Welfare 2022). We designed a standardized questionnaire using the World Bank's software *Survey Solutions* and collected the data using Android-based smartphones. The survey included questions on household demographics, agricultural production, farmers' perceptions of climate change, availability of financial services, and access to CSA technologies and mechanisms to finance them[1]. To analyze the quantitative data, we used Stata MP17. All farmers were located in the Karnal district, in the four different blocks, and the sampling was performed as follows: (1) within each block, we purposefully selected three villages based on the criteria that farmers belonged to one of the CSV and had been exposed to information about CSA technologies; and (2) in each village, a total of 10 farmers were randomly selected based on lists provided by CIMMYT. A total of 30 households were surveyed in each block, generating 120 households surveyed in the case study area.

3.3 Data analysis

The qualitative and quantitative data were analyzed using a case study approach. Case studies typically combine different data sources (e.g., interviews, surveys, and observations) and develop a novel, testable, and valid theory about new topics (Eisenhardt 1989). Moreover, as case study research aims to understand the nature of the research problem instead of quantifying observed characteristics (Glaser and Strauss 1967), we aim to gather a holistic view of the financing of climate-smart agriculture technologies. Within the GAO (1990) description of case study research, our study can be best categorized as illustrative with a single-case study design. It is noteworthy to mention that among the limitations of case studies are the

[1] Key questions on CSA technologies (Happy Seeder and Laser Land Leveler) availability and finance included the following: *(i) Which of the CSA technologies did you implement in the last year?; (ii) How did you access to the CSA technology?; (iii) If you own the CSA technology, how did you finance its purchase?; (iv) From whom did you receive the financial services/loans to purchase the CSA technology?; (v) In case you do not own the CSA technologies, what were your reasons for not purchasing them?*

overwhelming amount of data that can result in empirical evidence that is overly complex (Eisenhardt 1989), susceptibility to case selection (Fletcher and Plakoyiannaki 2011; Seawright and Gerring 2008), and risk of narrow theories that describe very idiosyncratic phenomena and from which it is difficult to raise any level of generality (Ton et al. 2010).

To evaluate the data that emerged during the stakeholder interviews and focus groups, we used different qualitative data analysis methods, which allowed us to explore the case in Haryana in-depth while permitting the emergence of new topics. Single-case designs allow for interpretive approaches using inductive and interactive processes and are optimal for developing a contextualized understanding of an empirical setting (Fletcher and Plakoyiannaki 2011). To ensure methodological rigor, we followed the grounded theory as applied by Gioia et al. (2013). In this methodological approach, data are divided into two rounds of analysis: in the first one, we followed an inductive approach by letting codes emerge as data collection progressed (Miles et al. 2014); and in the second one, we generated thematic statements based on commonality. Moreover, along with the qualitative analysis process, we followed the evaluation standards of qualitative research, which included data collection until a point of saturation (persistent observations), discussions with research peers (peer debriefing), and research participants and experts (member checks). Finally, the different data sources facilitated the triangulate of data, ensuring credibility and confirmability (Bitsch 2005).

4 Results

In this section, we present the farmer's characteristics and access to CSA technologies (4.1) and (4.2); the financing pathways farmers use to finance Happy Seeder and Laser Land Leveler (4.3); the role played by different stakeholders in financing CSA technologies (4.4); and the key drivers and barriers to accessing financing for these technologies in the study area (4.5).

4.1 Household characteristics

Table 4 presents an overview of the characteristics of agricultural households in the sample. Household heads were, on average, 45 years old and were male. The average household had 6.4 members, and 93% belonged to the General caste. In India, the caste system is one important social indicator that can directly influence access to information and technology (Rajam et al. 2021). Moreover, household heads had 10.5 years of education on average, indicating they completed secondary education, and 23% of the population obtained education beyond the secondary level. Membership at a community-based organization (e.g., FPO or cooperative) was reported at 47%.

Regarding the production and economic characteristics, 85% of the households reported having off-farm income. We also captured data about the households' distance to the nearest market and to the closest financial institution, as these represent measures of farmer's accessibility to inputs and knowledge and play a crucial role in the adoption of technologies. The village markets (*Mandi)* were located at a mean distance of 6.75 km. *Mandis* are essential for financial transactions as private moneylenders usually operate in them. The formal financial institutions (mainly banks) were located in a radius of 1.99 km. Further, farmers cultivated 10.15 hectares on average, with 13% being marginal farmers.

Regarding access to finance, farmers in the region access formal credit services from different sources. First, the Kisan Credit Card (KCC), a short-term credit instrument, is

Table 4 Overview of the sample's socioeconomic, production, and financial characteristics

Variable	Mean	SD
Sample size = 120		
Socioeconomic characteristics		
Age of Household head in years (mean)	45.1	12.23
Male Household Heads (%)	1.00	0
Household members (mean)	6.44	2.77
General caste (%)	0.93	0.29
Years of education	10.52	3.73
Membership in community-based organization (%)	0.47	0.50
Production and economic characteristics		
Off-farm income (%)	0.85	0.35
Average distance from nearest village market (in km)	6.75	11.02
Average distance from nearest formal financial institution (in km)	1.99	1.79
Land owned (in Ha)	10.15	11.86
Financial characteristics		
Access to loan from Kisan Credit Card (%)	0.73	0.44
Access to loan from bank (%)	0.88	0.34
Access to loan from cooperative (%)	0.12	0.33
Access to loan from private moneylenders (%)	0.48	0.50
Access to savings account at bank (%)	0.99	0.11
Access to crop insurance (%)	0.22	0.42

Table 5 CSA adoption, ownership and hiring rates in the study area

CSA Technology	% Farmers adopt	% Farmers own	% Farmers hire	Providers of CSA technologies for hiring	
				CHC	Cooperative
Happy Seeder	51.7	21.0	79.0	95.9	4.1
Laser Land Leveler	76.7	6.5	92.5	98.8	1.2

extremely popular among farmers, with 73% reportedly using it. However, since it offers limited credit in terms of monetary value per season, it is often insufficient to meet all the financial needs of farmers. In the study area, 88% of the households reported having short-term loans from commercial banks and 12% from cooperatives. Access to informal credit services, which are used in parallel with formal financial services, was reported at 48% and came mainly from private money lenders. Lastly, access to savings accounts was nearly universal at 99%, while crop insurance was reported at 22%.

Table 6 Factors associated with CSA technology ownership in the study area (probit model)

Variables	Happy Seeder		Laser Land Leveler	
Age HH head	−0.047**	(0.022)	−0.072***	(0.027)
HH members	0.146**	(0.072)	0.174**	(0.076)
Years of education	−0.005	(0.062)	−0.086	(0.066)
Group membership	−1.514**	(0.593)	−2.383**	(0.942)
Off-farm income	0.900	(0.620)	1.485**	(0.735)
Land owned	0.037***	(0.013)	0.029**	(0.015)
Distance to market	0.000	(0.019)	0.004	(0.020)
Distance to financial institution	0.075	(0.178)	0.146	(0.208)
Kisan Credit Card	−0.916	(1.045)	−1.481	(1.167)
Credit from moneylender	−0.566	(0.498)	−0.426	(0.577)
Credit from cooperative	−0.260	(1.240)	−0.014	(1.091)
Credit from bank	−0.850	(1.217)	−1.482	(1.101)
Constant	2.162	(2.535)	5.058	(3.101)
Number of observations	104		104	
Prob > chi2	0.002		0.001	
Log-likelihood	−32.437		−28.094	

Note: Standard errors are in parentheses. *, **, and *** denote significance levels at 0.10, 0.05, and 0.01, respectively

4.2 Factors associated with the adoption of CSA technologies

In what refers to the adoption pathways used by farmers to access Laser Land Leveler and the Happy Seeder, adoption rates were reported at 77% and 52%, respectively (Table 5). To adopt CSA technologies, farmers tend to opt for ownership or hiring. For Laser Land Leveler, farmers reported an ownership rate of 6.5%, among which 5.5% offer mechanization services to other farmers and 1% use it exclusively at their farms. Machinery hiring was preferred by 92.5% of the farmers, with Custom Hiring Centers being the predominant provider. Regarding the Happy Seeder, 21% of the households owned this machinery, with 16% providing mechanization services to fellow farmers. Similar to the Laser Land Leveler, 79% of households preferred hiring the Happy Seeder, primarily from Custom Hiring Centers (96%) and to a lesser extent from Cooperatives or FPOs (4%).

A probit model was conducted to explore the underlying factors influencing farmers' decisions to own the Happy Seeder and the Laser Land Leveler (Table 6). The results suggest that older household heads have a significantly lower probability of adoption, whereas household size seems to increase the likelihood of ownership substantially. Other sociodemographic variables, such as gender of household head and caste, were omitted in the model as all households that reported machinery ownership had a male head and belonged to the General caste.

We find that group membership in local agricultural institutions, such as cooperatives or Farmer Producer Organizations, reduces the likelihood of ownership of both technologies. In line with previous literature about CSA technologies (Aryal et al. 2019, 2020b; Zhou et al. 2023), this may reflect that households that belong to farmer groups face lower transaction costs and prefer to hire mechanization services. Farm households with off-farm income show a higher probability of owning the Laser Land Leveler; however, this does not stand for the

Happy Seeder. This might reflect that, due to the higher price of the Laser Land Leveler, only households with diversified sources of income can afford to buy this technology. Moreover, farm size and land ownership positively influence the likelihood of purchasing CSA technologies. This suggests that larger farms foresee the use of machinery to reduce manual labor, which allows them to ensure timeliness and agricultural operations and reduce vulnerability to labor shortages. Further, this might also show that farmers who own larger plots have higher collateral that can be used to finance technology adoption. As suggested in previous research, better-endowed households are often more likely to adopt technologies, particularly capital-intensive machinery (Aryal et al. 2019; Daum and Birner 2017).

While households far from markets tend to be less likely to adopt CSA technologies (Aryal et al. 2018, 2019, 2020b), this variable did not influence ownership decisions in our sample. Similarly, distance from financial institutions did not impact household ownership decisions. Notably, we find that access to formal and informal sources of credit did not influence the households' decisions for ownership of CSA technologies. This could suggest that the availability of custom hiring services for CSA technologies reduces the farmers' necessity of ownership, but it increases the demand for immediate cash for hiring these services.

4.3 Financing pathways for CSA adoption

Based on the qualitative interviews and focus groups, we identified three primary alternatives to access CSA technologies: individual purchases, individual hiring, and group purchases. These are presented in light of the three financial pathways used to access CSA technologies.

4.3.1 Direct pathways

As the interviewees reported, individual purchases are challenging due to bureaucratic procedures, lack of collateral, and unsuitable subsidies for individual farmers. Moreover, as shown in Table 7, the price after subsidy for individual purchase is INR 62,500 (USD 750) for the Happy Seeder and INR 420,000 (USD 5,090) for the Laser Land Leveler, which for some farmers can still be too high for acquiring CSA technology. Further, individual purchases can remain problematic because of the potential difficulty of complying with all the steps and transaction costs involved in the subsidy application process. For group purchases, access to finance was classified as moderately challenging. Group members can access higher governmental support than individual purchases and bring their share of money from their existing Kisan Credit Card (KCC) or borrow from personal networks. Nevertheless, as reported by the study participants, this purchase option also entails high transaction costs.

4.3.2 Indirect pathways

We identify several indirect pathways, including family lending, subsidies, and investments in capacity building. As part of the interviews and focus groups, Individual Hiring was considered easier to access finance due to the discounted prices, which makes it more affordable for farmers. Farmers can hire CSA technologies and pay the costs from their savings or existing KCC limits. Moreover, if hiring services are available in the area, they can avoid bureaucratic procedures, including applications to banks and government departments. The reported prices in Table 7 indicate that for individual hiring, farmers can access the Laser Land Leveler for INR 1,062 per hour and the Happy Seeder for INR 1,136 per acre.

Table 7 Alternatives to finance CSA technologies adoption

CSA Technology	Purchase options	Market price before subsidy	Type of governmental support	Price after subsidy	Individual hiring (reported prices)
Happy Seeder	Individual purchase	INR 125,000	50% subsidy	INR 62,500	1,136 INR (per acre)
	Group purchase		80% subsidy	INR 25,000	
Laser Land Leveler	Individual purchase	INR 490,000	Subsidy of up to INR 70,000	INR 420,000	1,062 INR (per hour)
	Group purchase		Subsidy up to INR 210,000	INR 280,000	

4.3.3 Behavioral pathways

Farmers also use more innovative financial products, such as crop insurance and mobile money, which can improve access to finance for CSA technologies. Crop insurance, such as Pradhan Mantri Fasal Bima Yojana (PMFBY), has the potential to provide farmers with a safety net against crop failures, helping them avoid financial losses and improve their financial stability. While the adoption of PMFBY is still evolving, and there is still a need to create much awareness about the coverage criteria and benefits, its introduction has been a significant step towards improving farmers' financial security. Furthermore, mobile banking platforms are also becoming common, making it easier and more convenient for farmers, especially those in remote areas, to access financial services. This has helped to overcome the challenges associated with traditional banking, such as the need to visit a bank branch in person, and has made it easier for farmers to manage their finances. We summarize the existing financial instruments and their benefits and limitations in Table 8.

4.4 The role of stakeholders in CSA financing and adoption

Based on the interviews and focus group discussions, we identified four key stakeholders in financing and adopting CSA technologies, who play different roles in knowledge dissemination and capacity building, financial service provision, and machinery supply. The roles of the key stakeholders include the following:

4.4.1 Governmental institutions

The government is critical in financing Climate-Smart Agriculture technologies by creating an enabling environment. Government policies and programs that provide subsidies, transfers, or incentives can facilitate farmers' access to CSA technologies. Subsidies, in particular, have been an essential tool for promoting technology adoption. Custom Hiring Centers (CHCs) are one example of successful government interventions that have played a critical role in securing farmers' access to CSA while ensuring financial support. CHCs, typically composed of 8–10 farmers, are independent or part of a farmer-producer organization. The primary goal of CHCs is to provide a range of expensive machinery, including a tractor and operator, to farmers at subsidized rates, facilitating access to hiring services for various agricultural implements such as Happy Seeder and Laser Land Leveler. Subsidizing CHCs proves advantageous as it allows small farmers to rent CSA equipment rather than own it, thus alleviating the financial burden on those lacking the resources to purchase them. Following the purchase and setup, CHCs establish fixed rental charges per implement, extending rental services to other small and marginal farmers in the vicinity.

4.4.2 Farmer Producer Organizations (FPO)

FPOs, groups of smallholder farmers who pool resources and gain access to service, play a critical role. In our case study, one of the FPOs provides diverse services to 4–5 villages, including agriculture advisory, custom hiring services, a processing plant, and an agriculture input shop where farmers can purchase input on credit. Through the CHC, the FPO

Table 8 Existing financial instruments for the adoption of CSA technologies in the study area

Type of instrument	Source	Utility for CSA	Advantages	Limitations
KCC (short-term loans)	Commercial banks	Credit	Lower interest rates	Highly bureaucratic Small loan amount
Short/medium-term loans	Private moneylenders	Credit Sale of produce	Generational trust Quick access	High-interest rate Possible exploitation
Long term loans	Commercial banks	Credit	Lower interest rates	Highly bureaucratic Requires collateral
Lending by family/friends	Private	Credit	Personal relationships Negligible interest	High risk
Insurance	Insurance service providers	Financial coverage	Mitigates risk	High rates Highly bureaucratic
Subsidy	Government	Discounted prices	Incentivizes adoption	Does not always reach small farmers
Invest in capacity building	Government, NGOs	Information transfer	Can lead to behavioral change	Self-selection Transient effects

offers subsidized rental services for Happy Seeder to local member farmers. Further, when collateral is unavailable, the FPO can often leverage its higher bargaining power to reduce the interest rate. Thus, FPOs can serve as a platform for farmers to collaborate and access financing for CSA technologies.

4.4.3 Commercial banks

Commercial banks have emerged as the foremost source of finance for fulfilling the agricultural needs of farmers in the study area. This prevalence can be attributed to the relatively lower interest rates offered by commercial banks compared to private money lenders, the availability of a diverse range of financial services, and the presence of public sector banks close to villages. Further, the Kisan Credit Card (KCC), a short-term revolving credit offered to farmers for agriculture-related purposes, is extremely popular. The interest rate in Haryana under the KCC scheme is 7%, of which the government subsidizes 4%.

4.4.4 Private moneylenders

Private moneylenders or commission agents are also a popular source of credit for farmers. Surprisingly, despite the availability of formal financial institutions, farmers often prefer to take credit from private moneylenders. Moneylenders are usually well-known to the farmers, and the two parties have a sense of trust and familiarity. Moreover, getting credit from a private moneylender is easier and faster than from a formal financial institution, as no paperwork is involved. Additionally, many private moneylenders act as the sellers of agri-inputs and the buyers of agricultural produce, making it convenient for farmers to transact with them. Farmers reported that the principal amount of the loan varies and is determined mainly by their farm and family needs. In the blocks included in the study area, interest rates charged by private moneylenders range from 12% to as high as 70%, the most common being 24%. However, the interest rate may vary depending on the reputation and relationship of the farmer with the intermediary.

4.5 Drivers and barriers to accessing finance for CSA technologies

4.5.1 Drivers for accessing finance for CSA technologies

Respondents claimed that government subsidies enhance access to finance for adopting CSA technologies. Based on discussions with agriculture experts and farmer groups, we found evidence that Karnal’s climate-smart villages result from a partnership between the government, private sector, and civil society. This partnership highlights how integrating resources and expertise can create an enabling environment for adopting sustainable agriculture practices. Local institutions such as Custom Hiring Centers (CHCs) and Farmer Producer Organizations (FPOs) are critical in supporting farmers’ access to CSA technologies and finance. CHCs provided farmers with access to mechanization services, allowing them to adopt CSA practices that require specialized machinery. Therefore, CHCs reduce the upfront costs of adopting CSA practices and make them more accessible to farmers. FPOs allow farmers to access credit, CHC services, technical assistance, training, and capacity building, which helps them to develop realistic business plans and manage their finances effectively. Finally, innovative financial products such as the Kisan Credit

Card, mobile money, and insurance have partially helped overcome traditional banking challenges.

4.5.2 Barriers to accessing finance for CSA technologies

Our investigation revealed several noteworthy challenges in financing Climate-Smart Agriculture technologies in the study area. The results suggest that key challenges arise from five categories: (i) collateral and bureaucratic hurdles: a primary challenge is the lack of suitable collateral for securing loans. This is exacerbated by bureaucratic processes, which often create hurdles for farmers in accessing financing opportunities. (ii) Suboptimal subsidy framework: as reported by the stakeholders, the current subsidy design is still influenced by caste and land ownership, potentially excluding those who genuinely need support. Furthermore, while tractor-mounted equipment is a focal point, the absence of a subsidy for the tractors and fuel creates an imbalance in the support structure. (iii) Informal finance exploitation: despite its high rates, this source of finance often remains more accessible than formal options for many farmers. (iv) Immediate cash needs vs. complex bank processes: the need for immediate cash contrasts starkly with the complex and paperwork-intensive procedures associated with obtaining loans from banks. The protracted processing time can deter farmers from pursuing formal financing; (v) Insufficient financial documentation: the lack of proper financial records and documentation among farmers further complicates matters for formal financial institutions. The absence of tangible data to assess repayment capacity leaves banks with limited information, prompting them to impose stricter terms and collateral prerequisites.

5 Discussion

Linking drivers with barriers in the adoption of CSA technologies among smallholder farmers in the Indo-Gangetic Plains reveals a complex interplay shaping their decision-making processes. While farmers may be driven by the potential benefits of technologies like the Happy Seeder and Laser Land Leveler, several barriers hinder their widespread adoption. Farmers recognize CSA technologies' environmental advantages, yet financial constraints pose a significant barrier to adopt them. In particular, smallholder farmers often lack the necessary funds to invest in CSA technologies. Given the capital-intensive nature of CSA technologies, it is crucial to understand the financial mechanisms for their adoption.

Using a case study of Haryana in the Indo-Gangetic Plains, we analyze current financing mechanisms, challenges, and opportunities for two CSA technologies, which differ in usage patterns and financing requirements. A unique feature of this case study was the setting of climate-smart-villages, which represents a partnership between various stakeholders. We find that in the study region, adoption rates for the Laser Land Leveler were 77% and for the Happy Seeder 52%. Adoption rates in our sample are higher than in previous CSA literature, where adoption was reported at 54.5% for Laser Land Leveler in Haryana (Aryal et al. 2020) and 38% for Happy Seeder in Punjab (Singh et al. 2021).

Our study presents insights into the case of Climate-Smart Villages in Haryana, where farmers, research institutions, financial institutions, and other stakeholders have partnered to enhance the adoption of CSA technologies. While the results shed light on how this case study operates, CSA practices are context and area-specific, and the findings might not be generalizable to all regions of India, particularly those with less governmental support. Each agricultural system has unique challenges; therefore, CSA practices should be tailored to meet each system's needs and constraints (Lipper et al. 2014; Mizik 2021; NAFCC 2016). In addition, the successful adoption of CSA practices requires an enabling policy environment that supports the uptake of CSA practices (McCarthy et al. 2018; Neufeldt et al. 2015; Ruben et al. 2019).

The case study shows several findings that may serve as policy recommendations for decision-makers:

(i) Governments play a critical role in promoting the adoption of CSA practices through developing and implementing policies that support the uptake of CSA practices, such as subsidies, tax incentives, and supportive regulatory frameworks. These programs address some of the critical challenges for farmers as they alleviate some collateral issues by pooling resources and expertise to facilitate access to finance. However, to ensure that all farmers can benefit from such programs, it is essential to adapt them to the financial constraints of farmers, which may again vary according to location (Birthal et al. 2017; Villalba et al. 2023).

(ii) The study shows that innovative financial products, such as the Kisan Credit Card and mobile money, partially address traditional banking challenges. As financially constrained farmers may struggle to access credit or other financing options to finance machinery and CSA technologies due to strict eligibility criteria or paperwork (Aryal et al. 2020, 2020b; Bhattarai et al. 2017; Daum et al. 2021; Daum and Birner 2017), the diversification in financial options helps farmers overcome immediate cash needs and navigate the complexities of formal banking processes. Nevertheless, as these instruments offer limited credit in terms of monetary value per season, they are insufficient to meet all the financial needs of farmers and need to be combined with loans from commercial banks, cooperatives, or moneylenders.

(iii) Custom Hiring Centers (CHCs) are vital in driving large-scale implementation and adoption of CSA practices at the community level. The results indicate that affordability is not always a significant challenge, as farmers are willing to use a mix of financial instruments to access CSA technologies through CHC. By pooling resources and sharing equipment and machinery, farmers can access the necessary CSA technologies without incurring the significant upfront costs of ownership. Notably, if rentals are not standardized, they may be more expensive in the long run, leading to declining adoption levels. It is also noteworthy that ownership provides farmers complete control over the technology and use when required, which may be more cost-effective in the long run but requires a significant upfront investment and may not be feasible for all farmers.

6 Conclusion

Given the capital-intensive nature of CSA technologies, it is essential to understand how finance can pose a barrier to their adoption. Considering this barrier, we analyze current financing mechanisms, challenges, and opportunities for two CSA technologies (Happy Seeder and Laser Land Leveler), which differ in usage patterns and financing requirements. Overall, we find that adoption rates are relatively high (77% and 52%, respectively) and that farmers primarily rent technologies from Custom-Hiring Centers. Our findings suggest opportunities for supporting CSA rental through government subsidies and cooperatives. As most of these CSA technologies are rented rather than owned, a large amount of credit and collateral is not necessary for farmers. However, they require immediate access to smaller amounts of credit to afford hiring CSA technologies. Hence, we recommend that governmental initiatives factor in this aspect.

Our findings highlight the need for more robust knowledge transfer and capacity building. In particular, there is a need to centralize information about banks and their financial products and policy instruments (e.g., subsidies). This can be disseminated through various channels: custom hiring centers, farmer groups, formal banks, research institutions, or jointly through partnerships. This can be achieved through awareness campaigns, training sessions, and creating training material (if possible in the local language) that specifically focuses on educating farmers about the financing options, their eligibility requirements, and in which activities they could be utilized. Training can also improve adaptive capacity and reduce climate risk, and policymakers should promote their expansion in the Indo-Gangetic Plains (Venus et al. 2022). In light of the high usage of mobile phones, stakeholders could jointly create a digital interface that collects the many financial mechanisms available for a specific CSA technology. Such a tool could give farmers a thorough perspective of their funding possibilities and enable them to make informed decisions. They can also consider a match-making option, in which farmers can select the technology they want to own/adopt, along with some customizable options (like want to hire/own, want subsidy or not, public or private sector bank), and receive a recommendation about the financial instruments that could be utilized, along with the description about interest rates, repayment terms, and eligibility conditions.

Finally, given the exploratory nature of our study, we recommend that future research focus on the efficacy of different finance channels and their causal impact on the adoption of technology.

Moreover, while there is strong evidence that CSA implementation enhances productivity (Khatri-Chhetri et al. 2017; Vatsa et al. 2023), new findings suggest that associated changes in land use can substantially alter net climate effects (Lobell and Villoria 2023). Therefore, dealing with these scenarios will require innovation in financing and policy. Further, the trade-offs and synergies associated with CSA practices should be explored at the farm level (Antwi-Agyei et al. 2023) but also at the policy, governance, environment, and energy levels (Singh et al. 2024).

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Data Availability The data supporting this study’s findings are not publicly available to protect the privacy of the stakeholders surveyed and interviewed. Data are, however, available from the authors upon reasonable request.

Declarations

Ethics approval and consent to participate The authors declare that the study was conducted according to the ethical guidelines laid down in the 1964 Helsinki Declaration and its later amendments. The authors certify that every precaution was taken to protect the privacy of research participants and the confidentiality of their personal information and to minimize the impact of the study on their physical, mental, and social integrity. All respondents provided appropriate informed consent to participate in the study and were informed of the right to refuse to participate in the study or to withdraw consent to participate at any time without reprisal.

Conflict of interest The authors declare no competing interests.

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Authors and Affiliations

Roberto Villalba[1] · Garima Joshi[1,2] · Thomas Daum[2,4] · Terese E. Venus[3]

✉ Roberto Villalba
roberto.villalba@tum.de

Garima Joshi
garimajoshi.niam13@gmail.com

Thomas Daum
thomas.daum@uni-hohenheim.de

Terese E. Venus
terese.venus@uni-passau.de

1 Chair of Agricultural Production and Resource Economics, Technical University of Munich, Alte Akademie 14, 85354 Freising, Germany

2 Hans-Ruthenberg-Institute of Agricultural Science in the Tropics, University of Hohenheim, Wollgrasweg 43, 70599 Stuttgart, Germany

3 Bioeconomy Economics, School of Business, Economics and Information Systems, University of Passau, Dr.-Hans-Kapfinger-Str. 30, 94032 Passau, Germany

4 School of Global Studies, University of Gothenburg, Konstepidemins väg 2, 41314 Gothenburg, Sweden