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Assessing determinants, challenges and perceptions to adopting water-saving technologies among agricultural households in semi-arid states of India

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A R T I C L E I N F O

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A B S T R A C T

This study investigates the adoption of water-saving irrigation technologies, specifically drip and sprinklers, within India's semi-arid states. Utilizing a probit model and data sourced from the India Human Development Survey-II, the research scrutinizes a sample size of 2891 households while engaging in focus group discussions. The findings highlight several key factors significantly impacting technology adoption, including education, caste, employment status, household income, orchard ownership, landholding size, irrigation source, access to irrigation, the Kisan Credit Card scheme, and utilization of electric and diesel pumps. Moreover, the study uncovers state-specific variations driven by factors such as water resources, crop patterns, and government policies, ultimately shaping the adoption landscape of specific irrigation technologies. Focus group discussions conducted in Andhra Pradesh reveal prominent challenges faced, including limited subsidies, high costs associated with adoption, and crop-specific irrigation requirements. In light of these findings, the study emphasizes the necessity for a comprehensive approach to achieve water conservation and enhance livelihoods. This approach advocates for the integration of joint farming practices, water-sharing methods, supportive financial policies encompassing subsidies and accessible credit facilities, and the implementation of sustainable government social schemes. Such integrated efforts are deemed imperative for fostering resilient societies amidst evolving agricultural and environmental landscapes.

1. Introduction

Water scarcity is a global issue that severely affects arid and semi-arid regions and countries worldwide. Global climate models (GCM) have projected significant changes in rainfall patterns and air temperature, negatively affecting crop production and water resources (Li et al., 2022). This situation particularly endangers rural livelihoods reliant on rainfed agriculture and overall food security in many developing nations (Singh et al., 2018; Gosling and Arnell, 2016). In India, where agriculture plays a vital role in improving rural livelihoods, reports indicate that 50% of the total workforce is engaged in the agricultural sector (CIA, 2017). Semi-arid regions (SARs) in India face dynamic climatic and non-climatic risks, rendering farmers and communities vulnerable. Climate change poses a potential threat to water resources and the agriculture sector, with 75% of cropped areas located in semi-arid regions of the country. States in semi-arid climates experience severe impacts, especially during monsoon rainfall deficits, which directly impede water access for crop irrigation, resulting in below-average crop yields. This is notably observed in drought-prone areas such as Southern and Eastern Maharashtra (Western India),

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Northern Karnataka (South-Western India), Andhra Pradesh (South-eastern coast of India), Odisha (Eastern coast of India), Telangana (Southeastern coast of India), and Rajasthan (Western India) (Dhawan, 2017). Therefore, understanding the implications of semi-arid environments is crucial for formulating effective development strategies and technologies (Morante-Carballo et al., 2022).

Improving water efficiency in agriculture requires innovative, long-term resilience solutions to conserve water, mitigate water crises, and ensure sustainable resource utilization (Rahimi-Feyzabad et al., 2020; Rouzaneh et al., 2021). Water conservation is a major focus in India, with micro-irrigation (MI) emerging as a key strategy. This modern approach to watering plants involves applying small amounts of water directly to the soil surface through emitters placed along water delivery lines, optimizing water usage. The adoption of MI has increased significantly, with 10.66 million hectares of land under micro-irrigation from 2005 to 06 to 2020–21, largely due to the effective implementation of the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) scheme. Launched in 2015, PMKSY aims to enhance farm water access, improve on-farm water use efficiency, promote sustainable water conservation practices, and expand cultivable areas with assured irrigation. Its "Per Drop More Crop" initiative focuses on micro-irrigation for enhanced water use efficiency and provides financial support for various irrigation systems, including drip, micro, and sprinkler irrigation. By adopting drip and sprinkler irrigation technologies, Indian farmers can optimize water usage, reduce wastage, and enhance agricultural productivity. MI technology can boost crop productivity by 20 to 90% for various crops (INCID, 1994, 1998; Narayanamoorthy, 2009). Despite its potential, MI technology has not fully met expectations in most semi-arid states. Previous studies indicate that while the area under drip irrigation significantly increased between 1991 and 92 and 2000–01 across all semi-arid states in India, the proportion of drip-irrigated land relative to the gross irrigated area remained low at only 0.48% in 2000–01 (Narayanamoorthy, 2009; Saleth, 2009; Chand et al., 2020). Although the expansion of drip irrigation could have been faster in earlier years, substantial development has occurred since the 1990s, driven by various government initiatives, with Maharashtra leading, followed by Andhra Pradesh, Karnataka, and Tamil Nadu. Fig. 1 shows a significant increase in the adoption of drip and sprinkler irrigation technologies across various Indian states from 2014 to 15 to 2020–21, primarily driven by proactive government support and incentives. Telangana, Uttar Pradesh, and Tamil Nadu have seen substantial progress due to targeted promotion of micro-irrigation. Karnataka, Rajasthan, Maharashtra, Andhra Pradesh, and Gujarat have also shown notable increases, though at a slower pace.

In contrast, Haryana and Punjab have witnessed slower adoption rates, with Punjab even experiencing a decline in usage. Drip irrigation is the preferred choice in Tamil Nadu, Maharashtra, Andhra Pradesh, Punjab, and Telangana, while sprinkler irrigation is more prevalent in Karnataka, Rajasthan, Uttar Pradesh, and Haryana (refer to Fig. 2). This trend underscores the pivotal role of focused policies and incentives in the adoption of irrigation technologies, highlighting their essentiality for successful implementation and widespread use.

The potential for micro-irrigation technologies, such as drip and sprinkler irrigation, in the semi-arid states of India is around 62 million hectares (Table 1). Sprinkler irrigation is suitable for approximately 44 million hectares of crops like cereals, pulses, oilseeds, and fodder, while drip irrigation is ideal for about 17 million hectares of commercial crops, fruits, vegetables, and pulses (Palanisami et al., 2011; Chand et al., 2020). However, the actual adoption falls short, covering <20% of the potential area, with significant variation among states. Andhra Pradesh leads in drip irrigation, utilizing 72.8% of its potential area, followed by Karnataka (72.0%), Maharashtra (57.4%), Tamil Nadu (37.7%), and Haryana (15.2%). For sprinkler irrigation, Karnataka performs best with 88.1% coverage, followed by Andhra Pradesh (42.2%), Maharashtra (31.0%), Tamil Nadu (19.9%), and Haryana (18.7%). In contrast, Uttar Pradesh and Punjab have not met expected adoption levels. These technologies are less beneficial for crops like paddy, commonly grown in these regions, and wheat, where sprinkler technology does not significantly motivate adoption (Kumar et al., 2009). Limited subsidies for micro-irrigation, primarily aimed at small and marginal farmers, also hamper adoption. Due to their smaller plot sizes, these farmers often cannot afford the technologies even at subsidized rates (Suresh and Samuel, 2020).

Drip and sprinkler irrigation, along with other efficient methods like rain-gun, micro-sprinklers, and subsoil drip systems, are crucial for enhancing water efficiency in agriculture. Drip irrigation offers substantial benefits, including water savings, increased water-use efficiency, reduced tillage, higher-quality products, improved yields, and better fertilizer-use efficiency (Magar et al., 1988; Qureshi et al., 2001; Kumar and Palanisami, 2010; Narayanamoorthy, 1997, 2003, 2005, 2006; Namara et al., 2005; Dhawan, 2000, 2002; Verma et al., 2004; Singh and Gandhi, 2024). Well-designed and managed drip systems can double water-use efficiency, making them favorable for farmers reliant on groundwater, leading to enhanced water productivity, savings, and increased net returns per unit volume of groundwater (Sivanappan, 1994; Chandrakanth et al., 2013). Sprinkler irrigation also significantly enhances crop yields and water-use efficiency by creating a favorable microclimate for crop growth (Yang et al., 2000; Suresh and Samuel,

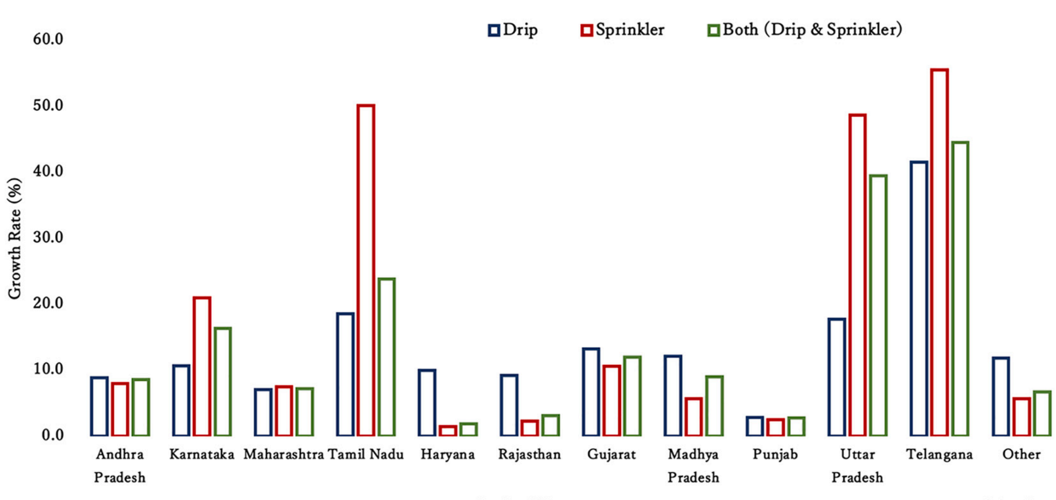

Fig. 1. State-wise annual growth rate of the area covered under Micro-Irrigation Technologies (Drip and Sprinkler) in India, 2014–15 to 2020–21.
Source: Agricultural Statistics at a Glance from 2015 to 2021.

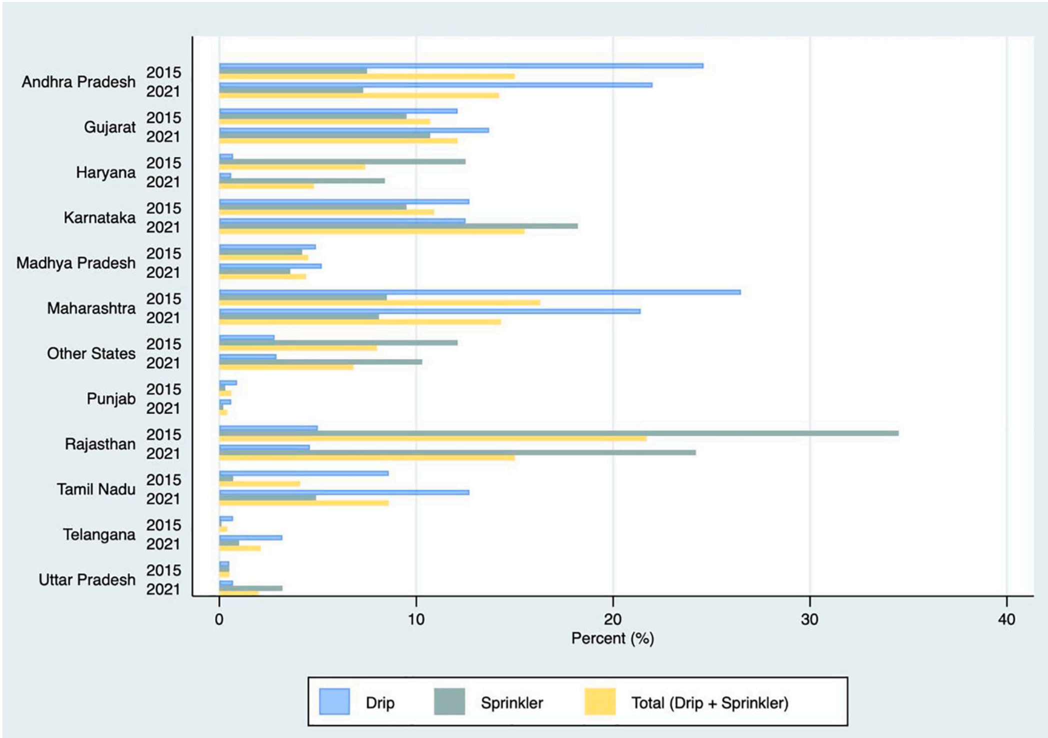

Fig. 2. State-wise distribution of the area covered under MI Technologies in India, 2014–15, and 2020–21.

Table 1
Potential and Actual Area under MI in Semi-arid States in 2020 (Area in 000′ ha).

State	Drip			Sprinkler			Total		
	Potential	Actual	percent	Potential	Actual	percent	Potential	Actual	percent
1. Andhra Pradesh (AP)	1390	1388	99.9	1230	519	42.2	2620	1907	72.8
2. Karnataka (KT)	1270	723	56.9	1190	1049	88.1	2460	1772	72.0
3. Maharashtra (MH)	1460	1315	90.1	1810	562	31.0	3270	1876	57.4
4. Tamil Nadu (TN)	1440	687	47.7	1270	253	19.9	2710	939	34.7
5. Haryana (HR)	970	36	3.7	3170	592	18.7	4140	628	15.2
6. Rajasthan (RJ)	1220	264	21.7	7240	1685	23.3	8460	1949	23.0
7. Gujarat (GJ)	2280	801	35.1	2840	729	25.7	5120	1530	29.9
8. Madhya Pradesh (MP)	930	322	34.6	6560	249	3.8	7490	571	7.6
9. Punjab (PB)	1600	36	2.3	4670	14	0.3	6270	50	0.8
10. Uttar Pradesh (UP)	4300	32	0.8	13,350	179	1.3	17,650	211	1.2
11. Telangana (TG)	1120	196	17.5	1160	71	6.1	2280	267	11.7
Other States (OS)	3150	163	5.2	6540	676	10.3	9690	839	8.7
Semi-arid States	**17,980**	**5800**	**32.3**	**44,490**	**5901**	**13.3**	**62,470**	**11,701**	**18.7**
All India	**21,130**	**5963**	**28.2**	**51,030**	**6577**	**12.9**	**72,160**	**12,540**	**17.4**

Source: Chand et al. (2020); Agricultural Statistics at a Glance, 2020.

2020). Both technologies outperform traditional methods in terms of water-use efficiency, energy conservation, and yield enhancement, proving technically feasible and environmentally sustainable (Dhawan, 2000; Kumar and Palanisami, 2010).

Multiple studies have demonstrated the substantial cost savings associated with Micro Irrigation (MI), including up to 25% reduction in fertilizer use, decreased labor expenses, and improved crop yields for cotton, castor, groundnut, and potato by 5% to 80%, all while maintaining soil health (Bhaskar et al., 2005; Narayanamoorthy, 2006; Verma et al., 2004; Wrachienb et al., 2014; Reddy et al., 2017). Additional research by Kumar et al. (2016) and Namara et al. (2005) has underscored the water-saving potential of drip irrigation, with optimal field water use efficiency observed at a 65% irrigation level and increased marginal productivity of water with MI technologies. Despite these advantages, the adoption of MI technologies has been limited in water-scarce semi-arid regions of India due to farmers' capacity constraints, the capital-intensive nature of the technology, and a lack of awareness of its potential benefits (Misquitta and Birkenholtz, 2021; Nair and Thomas, 2023). However, the government's subsidy scheme for MI aims to encourage wider adoption by farmers. In 2020, the actual area under micro-irrigation covered only 18.7% of semi-arid states and 17.4% across India, raising uncertainty about its future farm-level adoption rate and performance in semi-arid areas. Economic benefits can be realized by farmers through the adoption of MI technologies. Extensive research has identified various factors influencing the adoption of MI technologies, including personal and farm characteristics, economic resources, natural conditions, social networks, and physical assets (Singh and Gandhi, 2024; Wang et al., 2024; Apio et al., 2023; Angom and Viswanathan, 2023; NCAP, 2019; Zhang et al., 2019). Understanding these determinants, perceptions, and challenges is crucial to enhance farmers' adaptive capacity and scale up irrigation systems. Therefore, promoting the widespread adoption of MI technologies is essential, particularly in semi-arid regions of India.

Considering these concerns, this paper focuses on two pivotal issues: (1) what factors influence the adoption of MI technologies in semi-arid states in India? (2) what are the difficulties and causes of not adopting MI technologies? While prior studies have examined factors and processes related to the adoption of drip and sprinkler irrigation across various Indian states (Narayanamoorthy, 2009; Nair and Thomas, 2023), this study specifically focuses on the top ten semi-arid states in India, which heavily depend on agricultural practices. The novelty of this study lies in its thorough analysis of MI technology adoption, offering a deeper comprehension of the intricacies surrounding MI adoption, including the roles of human capital, economic factors, and regional disparities in these semi-arid states. This approach contributes to the literature by presenting actionable policy recommendations to facilitate MI technology adoption, thus bolstering agricultural productivity, water conservation, and sustainability in developing nations like India. The study aims to identify the primary determinants influencing farmers' decisions regarding the adoption of irrigation technologies in these semi-arid states in India. Additionally, the study delves into farmers' viewpoints, barriers, and experiences related to the adoption or non-adoption of MI technologies. This will be accomplished through a series of Focused Group Discussions (FGDs) carried out in the semi-arid region of Andhra Pradesh, situated in southern India.

The remaining paper is structured as follows: the next section will outline the empirical model and data used in the study, while Section 3 will explore the empirical results. Section 4 will examine farmers' perceptions and challenges in adopting MI technologies, using the state of Andhra Pradesh as a case study. Finally, Section 5 will cover conclusions, limitations, and future research directions, followed by Section 6 on policy implications.

2. Material and methods

2.1. Study area of semi-arid states in India

According to the Central Water Commission (CWC) report, the majority of drought-prone districts are distributed across 14 states in India. However, the region's most susceptible to drought are concentrated in semi-arid states such as Rajasthan, Karnataka, Andhra Pradesh, Maharashtra, and Tamil Nadu. These states experience uneven and erratic rainfall, leading to frequent water scarcity and resulting in dry farmlands that significantly impact agricultural production. An area of 123.4 million hectares, equivalent to 37.6%, is spread across 175 districts in the country's geographical locations (Todmal, 2019; Pankaj et al., 2020). Therefore, improving the sustainability of agriculture in semi-arid regions requires substantial measures aimed at building long-term resilience. One such solution is the adoption of micro-irrigation technologies, which can effectively reduce water losses (Mohan et al., 2022). This paper focuses on all ten semi-arid states, including Gujarat, Madhya Pradesh, Punjab, Uttar Pradesh, and Haryana, in addition to the five states mentioned earlier. The semi-arid states under consideration in our study comprise approximately 30% of the country's total geographical area, which is 3.28 million square km (Table 2). Maharashtra, Karnataka, and Andhra Pradesh constitute a significant portion, accounting for about 14% of the total area.

2.2. Data collection and sampling procedure

The study utilized both secondary farming household datasets and primary focal group interviews. However, the majority of the farming household data was sourced from a nationally representative survey conducted in 2011–12 as part of the India Human Development Report (IHDP-II) by the University of Maryland, USA, and the National Council of Applied Economic Research (NCAER), New Delhi (Desai et al., 2018). This survey provided comprehensive information on various aspects such as socio-economic status, household structure, employment, income, landholding size, farming practices, government subsidies, cultural capital, and details about the head of the household. The selected farming households included in the study were exclusively from villages where at least one of the micro-irrigation technologies, either drip or sprinkler, or both, were identified as being adopted. The non-adopter or control group comprised farming households from the same villages that did not practice these micro-irrigation technologies, as outlined in Table 3. Only those farming households that reported their land holdings and engagement in farm activities were considered for inclusion in the study.

Table 2
Area covered under semi-arid Indian states.

State	Area covered by the semi-arid zone the in State (Km^2)
Rajasthan	121,020 (3.68)
Gujarat	90,520 (2.75)
Punjab & Haryana	58,650 (1.78)
Maharashtra	189,580 (5.77)
Karnataka	139,360 (4.24)
Andhra Pradesh	138,670 (4.22)
Tamil Nadu	95,250 (2.90)
Uttar Pradesh	64,230 (1.95)
Madhya Pradesh	59,470 (1.81)

Source: Bhawan, Jal Vigyan. "Status Report on Hydrology of Arid Zones of India".
Note: The figures in parentheses represent the percentage of semi-arid area under the total geographic area.

The focus group discussions (FGD) were conducted in three different Mandals in the East Godavari district of Andhra Pradesh, India. Each FGD consisted of 4–8 participants, including both men and women. In Rajanagaram, there were four male participants; in Korukonda, there were six male and two female participants; and in Gandepalli, there were five male participants. However, there was a higher participation of men than women in each group, mainly due to their greater involvement in MI technology operations. These areas were selected due to their significant potential and actual area under Micro-Irrigation (MI), accounting for 72.8%, which is among the highest in the semi-arid states as of 2020. FGD is a qualitative approach that links farmers' perceptions, socio-economic status, and cultural context to their decision-making process regarding the adoption of water-saving technologies. Farmers often form opinions and interpretations based on their immediate environment and experiential knowledge (Bennett et al., 2017; Nyumba et al., 2018). The FGD interviews were conducted as part of the Water for Sustainable Development (WSD) project, funded by the Ministry of Environment, Japan. Three FGD interviews were carried out in the East Godavari district of Andhra Pradesh in May–June 2021, guided by an FGD manual designed to cover barriers and facilitating factors influencing the adoption of drip and sprinkler irrigation. The discussions were audio-recorded in local languages and subsequently translated into English, ensuring an accurate representation of participants' opinions and perceptions while avoiding bias due to linguistic differences. The resulting transcripts were analyzed and categorized into different themes using QSR International's NVivo 11 qualitative data analysis software.

2.3. Methods

2.3.1. Empirical model

In order to select an appropriate econometric model for analyzing the factors influencing the adoption of different MI technologies (drip, sprinkler, and drip & irrigation) by farming households required consideration of the discrete-dichotomous nature of the MI technologies adoption variable. A farming household is either categorized as an "adopter" if they have these MI technologies (drip, sprinkler, or both), or as a "non-adopter" if they do not possess any MI technology. Probit and logit models are commonly employed to estimate technology adoption

Table 3
Sampling distribution across the semi-arid states.

State	No. of Treated (adopters) Households			No. of Control (non-adopters) Households	Total No. of Households
	Drip Irrigation (DI)	Sprinkler Irrigation (SI)	Drip & Sprinkler Irrigation (D&SI)		
Punjab	11	7	18	88	106
Haryana	14	11	25	156	181
Rajasthan	13	81	94	492	586
Uttar Pradesh	12	8	20	172	192
Madhya Pradesh	32	19	51	265	316
Gujarat	6	3	9	85	94
Maharashtra	72	57	129	588	717
Andhra Pradesh*	8	6	14	70	84
Karnataka	37	63	100	500	600
Tamil Nadu	7	1	8	7	15
Semi-Arid States	212	256	468	2423	2891

Source: Author's computations from India Human Development Survey-II, 2011–12.
* Telangana is part of the State of Andhra Pradesh before June 2014.

methods (Feder et al., 1985; Namara et al., 2005; Oladeji et al., 2015; Nhemachena et al., 2014; Chuchird et al., 2017). For this study, the Probit model was selected due to its advantages, such as higher sensitivity to outliers and the ability to maintain predicted probabilities within the 0 to 1 range. These characteristics make it effective for estimating the likelihood of items belonging to different categories based on specific characteristics, unlike linear or Logit models, which primarily focus on odds ratios. The benefits of Probit regression have led to its widespread adoption in studies on water conservation practices and technologies (Ngcobo et al., 2023; Apio et al., 2023; Tolassa and Jara, 2022). However, it is essential to note that Probit models may not always be superior to Logit models, as the choice depends on the study's objectives and data nature (Degfe et al., 2023; Zhang et al., 2019; Jha et al., 2019). One limitation of the Probit model is its requirement for normal distributions for all unobserved components, which can be a drawback in cases where other distributions like lognormal would be more appropriate but cannot be accommodated within the Probit framework (Train, 2009).

For this study, a probit model was employed. The mathematical expression for a probit model is typically represented as:

$$Pr(y_i = 1/x_j = \Phi(\beta_0 + \beta_1 x_1 + \ldots + \beta_j x_j) \quad (1)$$

The Probit model estimates the probability $P(y_i = 1/x_j)$, where y_i represents the dependent variable being 1 given the independent variable x_j. Here, Φ is the cumulative distribution function of the standard normal distribution, and β represents the coefficients of each selected factor. The estimation process of the Probit model entails maximizing the likelihood function, which is calculated using observed data.

The study modifies the basic probit model expressed in Eq. (1) as follows

$$Y_i = \beta_o + \sum_{i=1}^{\eta=20} \beta_i X_i + \epsilon \quad (2)$$

Where Y_i is the micro irrigation technology adoption (1 if adopted and 0 otherwise); β_o is the intercept; β_i is the vector of the parameter estimates; X_i is a vector of the explanatory variables, each providing unique insights chosen as possible factors of the adoption of MI technologies. These variables include the age of the head of the household X_1, the level of education X_2, the gender of the respondent X_3, the caste of the respondent X_4, the principal employment activities for the household X_5, the annual income of farmers X_6, the purpose of loan taken X_7, the total cultivated area in hectares X_8, the area under plantation/orchards X_9, the types of water sources X_{10}, Kisan credit card X_{11}, beneficiaries of social schemes from the government X_{12}, involvement in membership activities such as SHG X_{13}, agriculture, milk, or other cooperative groups X_{14}, access to electricity power in hours per day X_{15}, households owning equipment for agriculture such as electric pumps X_{16}, diesel pumps X_{17}, bullock cart X_{18}, tractor/tiller X_{19}, and semi-arid states X_{20}; η is the number of explanatory variables and ϵ is the random disturbance term. These variables provide a comprehensive view of the social, human, economic, natural, and physical capital aiding in the understanding and analysis of various factors influencing the choices of MI technology adoptions.

In addition, the marginal effects of the probit regression model will also be assessed to determine the extent to which the explanatory variables affect the probability of adopting MI technologies in semi-arid areas of India. The following equation can be used to calculate the marginal effects of the probit regression model (Caudill and Jackson, 1989).

$$\partial Y_i/(\partial x_i) = \beta_i \varnothing(\beta_0 + \beta_1 x_1 + \ldots. + \beta_n x_n) \quad (3)$$

In this context, Y_i represents the probability of an event i, specifically the marginal effect defined as the impact of a one-unit change in x on the probability of a household choosing to adopt MI technologies. The symbol $\varnothing$represents the standard univariate normal cumulative density distribution function, while β and x denote the vectors of regressors and model parameters, as illustrated in Eq. 3.

2.3.2. *Description of selected variables*

Table 4 shows the explanatory variables (X1-X20), which include human, economic, natural, and physical capital, social programs and groups, and semi-arid state controls.

3. Results and discussions

Table 5 presents the results of the probit model for the adoption of three micro-irrigation technologies (Model 1: DI, Model 2: SI, Model 3: D&SI) by farming households in the top ten semi-arid states in India. The selected parameters were based on a review of the literature on determinants of micro-irrigation technology adoption (Namara et al., 2005; Jara-Rojas et al., 2012; Sabbagh and Gutierrez, 2022). Most of the variables in the DI, SI, and D&SI models had the expected signs. Human capital variables such as age, level of education, caste, gender, and employment were found to be important factors for the adoption of irrigation technologies. Age can influence the adoption of agricultural technologies positively or negatively (Apio et al., 2023). We expected age to similarly affect the adoption of Micro Irrigation (MI) Technologies. Additionally, while gender is statistically insignificant, it shows a positive coefficient in MI adoption, indicating that male farmers are more likely to adopt MI practices due to the physical labor involved (Asfaw and Neka, 2017). Educated farmers are thought to be more aware of and better able to utilize new technologies (Ndiritu et al., 2014). Education is also a crucial factor in the adoption of modern, cost-effective technologies such as Micro Irrigation (MI). However, despite these expectations, education indicators have shown a significant and

Table 4
Variables used in the probit regression model and their descriptions.

Representation	Variable Name	Description	Variable Type/ Criteria
Dependent Variable			
Y	Adoption (Dependent Variable)	Farmer's adoption of micro irrigation technology (Drip, Sprinkler, or both)	Dummy: 1 if adopted, 0 otherwise
Human Capital			
X1	Age	Head of the Household	1 = <35 years old, 2 = 36 to 60 years old, 3 = Above 65 years old
X2	Education	Level of education	1 = No education, 2 = Primary, 3 = Secondary, 4 = Graduate/Post-Graduate
X3	Gender	Respondent's Gender	Dummy: 1 = Male, 2 = Female
X4	Caste	Respondent's Caste	1 = Forward, 2 = OBC, 3 = SC & ST, 4 = EBC or others
X5	Primary Employment Activities	Principal employment activities for the household	1 = Agriculture related, 2 = Non-agriculture related, 3 = Business; 4 = Others
Economic Capital			
X6	Farmers' Income	Farmers' annual household income	Continuous variable
X7	Loan	Purpose of loan taken	Dummy: 1 if loan for agriculture/ agriculture equipment, 0 otherwise
Natural Capital			
X8	Size of Landholding	Total cultivated area in (ha)	1 = Marginal (<1.0 ha), 2 = Small (1.0–2.0 ha), 3 = Semi-Medium (2.0–4.0 ha), 4 = Medium (4.0–10.0 ha); 5 = Large (above 10.0 ha)
X9	Orchard Plantation	Area under plantation/orchards	Dummy: 1 if have plantation, 0 otherwise
X10	Source of water	Types of water sources	1 = Rainfed, 2 = Tube well, 3 = River or Canal, 4 = Other water bodies
Social Network			
X11	KCC	Kisan Credit Card	Dummy:1 to have card, 0 is otherwise
X12	Indira Awas Yojana	Benefited from social schemes from Government	Dummy: 1 if receive, 0 otherwise
X13	SHG	Involvement of membership activities	Dummy: 1 if member, 0 otherwise
X14	Agriculture, Milk, or other Co-operative Group	Involvement of membership activities	Dummy: 1 if member, 0 otherwise
Physical Capital			
X15	Electricity Access Hours	Access of electricity power in hours per day	1 = Below 6 h, 2 = 7–12 h, 3 = 13–18 h, 4 = Above 19 h
X16	Electric pumps	Households owned equipment's for agriculture	Dummy: 1 if owned, 0 otherwise
X17	Diesel pumps	Households owned equipment's for agriculture	Dummy: 1 if owned, 0 otherwise
X18	Bullock cart	Households owned equipment's for agriculture	Dummy: 1 if owned, 0 otherwise
X19	Tractor/tiller	Households owned equipment's for agriculture	Dummy: 1 if owned, 0 otherwise
Control Variable			
X20	State ID	Semi-arid states	Punjab, Haryana, Rajasthan, Uttar Pradesh, Madhya Pradesh, Gujarat, Maharashtra, Andhra Pradesh, Karnataka, Tamil Nadu

unexpected negative impact on the adoption of MI. This unexpected finding may be due to specific levels of education, such as having no education or only primary education, which can result in lower technical efficiency and difficulties in decision-making regarding the prioritization of irrigation technologies (Degfe et al., 2023). The caste variable showed a positive sign in the Model 2 and 3 groups of OBC and the general category, indicating a higher rate of adoption of SI and D&SI compared to the SC & ST group (Chand et al., 2020), which had a negative and significant effect on the probability of low adoption of MI technologies due to higher maintenance costs and hardware issues (Patil et al., 2019).

The analysis of marginal effects reveals the influence of education on the adoption of irrigation technologies. According to the research, farmers with little or no formal education have lower adoption rates of both drip irrigation (3.0–4.0%) and sprinkler irrigation (4.0–4.2%) compared to those with higher levels of education. However, when both irrigation systems are considered together, the adoption rate increases significantly to 5.0–6.0%. This indicates that education levels play a crucial role in promoting the adoption of irrigation technologies. The positive marginal effects observed for graduate education under drip irrigation support the notion that higher education levels contribute to increased adoption rates, as indicated by NCAP (2019). This finding is in line with Gilg and Barr's (2006) research, which highlights the beneficial impact of education on promoting water-saving behavior.

The economic and natural capital parameters of household income, orchard size, landholding size, and source of irrigation were all found to be statistically significant and positively correlated in all three models. In particular, higher farm income plays a vital role and can provide strong motivation for farmers to invest in and adopt MI technologies compared to farmers with minimal income. Larger farm household incomes strongly motivate farmers to invest in and adopt MI technologies compared to those with smaller holdings. However, households actively engaged in non-farm activities, especially if they become the primary income source, may hinder the adoption of modern technology among farmers. Therefore, the impact of non-agricultural income on the adoption of MI technologies shows both positive and negative effects (Namara et al., 2007).

The study also found a positive correlation between landholding size, access to irrigation, and the adoption of irrigation technologies. Farm size, as a measure of wealth, can positively influence the adoption of MI technologies due to greater resources (NCAP, 2019). However, this impact can turn negative if certain technologies are not suitable for

Table 5
The probit model results of the factor influencing the adoption of variable micro irrigation technologies.

Factors	Model1: Drip Irrigation (DI)		Model2: Sprinkle Irrigation (SI)		Model3: Drip & Sprinkle Irrigation (D&SI)	
	Coef.	Marginal Effects	Coef.	Marginal Effects	Coef.	Marginal Effects
Human Capital						
Gender (Male)						
Female	0.00 (0.19)	0.00 (0.02)	0.03 (0.16)	0.00 (0.02)	0.01 (0.14)	0.00 (0.02)
Age (< 35 years old)						
36–60 years old	0.12 (0.15)	0.01 (0.01)	0.08 (0.12)	0.01 (0.01)	0.08 (0.11)	0.01 (0.02)
>61 years old	0.19 (0.16)	0.02 (0.02)	0.04 (0.14)	0.00 (0.02)	0.12 (0.12)	0.02 (0.02)
Education (Secondary)						
No education	−0.35* (0.13)	−0.04* (0.01)	−0.32* (0.12)	−0.04* (0.02)	−0.35* (0.11)	−0.06* (0.02)
Primary	−0.28* (0.11)	−0.03* (0.01)	−0.32* (0.1)	−0.04* (0.01)	−0.28* (0.09)	−0.05* (0.02)
Graduate	−0.01 (0.20)	0.00 (0.03)	−0.09 (0.19)	−0.01 (0.03)	−0.07 (0.17)	−0.01 (0.03)
Caste (Forward)						
OBC	−0.06 (0.10)	−0.01 (0.01)	0.07 (0.10)	0.01 (0.01)	0.03 (0.08)	0.01 (0.02)
SC & ST	−0.29*** (0.16)	−0.03** (0.01)	−0.27*** (0.15)	−0.03** (0.02)	−0.32* (0.13)	−0.05* (0.02)
Others	−0.55 (0.38)	−0.05** (0.02)	−0.01 (0.26)	0.00 (0.03)	−0.13 (0.24)	−0.02 (0.04)
Primary Employment (Agriculture)						
Non-Agriculture	−0.46 (0.33)	−0.04*** (0.02)	−0.26 (0.24)	−0.03 (0.02)	−0.25 (0.21)	−0.04 (0.03)
Business	−0.24 (0.15)	−0.02*** (0.01)	−0.18 (0.13)	−0.02 (0.01)	−0.17 (0.12)	−0.03 (0.02)
Others	0.06 (0.18)	0.01 (0.02)	0.07 (0.16)	0.01 (0.02)	0.12 (0.14)	0.02 (0.03)
Economic Capital						
Household Income	0.00* (0.00)	0.00* (0.00)	0.00* (0.00)	0.00* (0.00)	0.00* (0.00)	0.00* (0.00)
Purpose of Loan (Other than Agriculture)						
Agriculture / Agr. Equipment's	0.17*** (0.10)	0.02*** (0.01)	−0.11 (0.10)	−0.01 (0.01)	−0.01 (0.08)	0.00 (0.01)
Natural Capital						
Orchard	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00** (0.00)	0.00** (0.00)
Size of Landholding, ha (Marginal Farmers)						
Small	0.25 (0.31)	0.01 (0.02)	0.02 (0.27)	0.00*** (0.02)	0.11 (0.23)	0.01 (0.02)
Semi-medium	0.32 (0.30)	0.02 (0.02)	−0.11 (0.25)	−0.01 (0.02)	0.12 (0.22)	0.01 (0.02)
Medium	0.76* (0.29)	0.06* (0.02)	0.46** (0.23)	0.05* (0.02)	0.66* (0.20)	0.09* (0.02)
Large	0.79* (0.29)	0.07* (0.02)	0.66* (0.23)	0.08* (0.02)	0.83* (0.21)	0.13* (0.02)
Source of Irrigation (Rainfed)						
Tube well	0.99* (0.14)	0.08* (0.01)	1.02* (0.11)	0.11* (0.01)	1.06* (0.10)	0.16* (0.01)
River or Canal	0.59* (0.22)	0.04** (0.02)	0.95* (0.19)	0.10* (0.03)	0.89* (0.17)	0.12* (0.03)
Other water bodies	0.90* (0.24)	0.07* (0.03)	0.63* (0.23)	0.05** (0.03)	0.76* (0.19)	0.09* (0.03)
Social Programmes and Groups						
Kisan Credit Card	0.33* (0.11)	0.03* (0.01)	0.26* (0.10)	0.03* (0.01)	0.34* (0.09)	0.06* (0.02)
Indira Awas Yojana	0.13 (0.24)	0.01 (0.02)	−0.21 (0.24)	−0.03 (0.03)	−0.07 (0.19)	−0.01 (0.03)
Self Help Group (SHG)	−0.21*** (0.13)	−0.02*** (0.01)	−0.03 (0.11)	0.00 (0.01)	−0.14 (0.10)	−0.02 (0.02)
Agriculture, Milk, or Other Co-operative Group	0.14 (0.14)	0.01 (0.01)	0.11 (0.15)	0.01 (0.02)	0.15 (0.13)	0.03 (0.02)
Physical Capital						
Electricity Access Hours (Below 6 Hours)						
7–12 h	−0.07 (0.11)	−0.01 (0.01)	−0.13 (0.10)	−0.02 (0.01)	−0.15 (0.09)	−0.03 (0.01)
13–18 h	−0.14 (0.13)	−0.01 (0.01)	0.11 (0.12)	0.01 (0.02)	−0.07 (0.10)	−0.01 (0.02)
Above 19 h	−0.16 (0.17)	−0.02 (0.02)	0.22 (0.15)	0.03 (0.02)	0.01 (0.13)	0.00 (0.02)
Electric pumps	0.19* (0.05)	0.02* (0.01)	0.07 (0.06)	0.01 (0.01)	0.17* (0.05)	0.03* (0.01)
Diesel pumps	0.20*** (0.11)	0.02*** (0.01)	0.23** (0.10)	0.03** (0.01)	0.21** (0.09)	0.04** (0.02)
Bullock cart	0.12 (0.1)	0.01 (0.01)	0.18*** (0.10)	0.02*** (0.01)	0.15*** (0.09)	0.02*** (0.01)
Tractor/tiller	0.09 (0.13)	0.01 (0.01)	0.13 (0.12)	0.02 (0.01)	0.09 (0.11)	0.02 (0.02)
Control Variable						
State ID (Punjab)						
Andhra Pradesh	0.49 (0.35)	0.05 (0.04)	0.64*** (0.37)	0.04 (0.03)	0.55*** (0.32)	0.06 (0.04)
Gujarat	0.44 (0.31)	0.04 (0.03)	0.11 (0.38)	0.00 (0.02)	0.47*** (0.28)	0.05 (0.03)
Haryana	0.11 (0.28)	0.01 (0.02)	0.44 (0.3)	0.02 (0.02)	0.28 (0.26)	0.03 (0.02)
Karnataka	0.49*** (0.28)	0.05** (0.03)	1.17* (0.28)	0.11* (0.02)	1.02* (0.25)	0.14* (0.03)
Madhya Pradesh	0.33 (0.28)	0.03 (0.02)	0.56*** (0.29)	0.03** (0.02)	0.69* (0.25)	0.08* (0.03)
Maharashtra	0.59** (0.25)	0.06* (0.02)	0.89* (0.26)	0.07* (0.02)	0.88* (0.22)	0.12* (0.02)
Rajasthan	−0.37 (0.29)	−0.02 (0.02)	1.17* (0.28)	0.11* (0.02)	0.74* (0.24)	0.09* (0.02)
Tamil Nadu	2.21* (0.44)	0.46* (0.11)	1.01*** (0.62)	0.09 (0.08)	2.45* (0.42)	0.53* (0.10)
Uttar Pradesh	0.21 (0.31)	0.02 (0.02)	0.47 (0.32)	0.03 (0.02)	0.53** (0.27)	0.06** (0.03)
Constant	−3.30* (0.43)		−3.44* (0.39)		−3.25* (0.34)	
Log pseudolikelihood	−553.58		−667.29		−878.57	
Wald Chi2	408.71		395.22		603.38	
Prob>Chi2	0.0		0.0		0.0	
Pseudo R-Squared	0.2696		0.2285		0.2556	
Number of Observations	2891		2891		2891	

* Significant at the 0.01 level, **significant at the 0.05 level, and *** significant at the 0.10 level.
Figures in parentheses are robust standard errors.

large, medium, or small farms. The marginal effects showed that medium and large farmers have higher adoption rates of drip irrigation, sprinkler irrigation, and combined irrigation systems, ranging from 4.6% to 13.0%, whereas small and marginal farmers have lower adoption rates, ranging from 1.0% to 2.0%. Thus, the size of landholding and access to irrigation are key factors that influence the adoption of irrigation technologies.

In addition, the majority of orchid and plantation crops are covered by drip irrigation, and large and medium farmers who have already adopted the technology can use it for other suitable crops. However, small and marginal farmers may find it difficult to shift their cropping patterns, as reported by Kumar (2016), given that 86.0% of farmers are smallholders, according to Agricultural Statistics at a Glance, 2021. Finally, access to irrigation through tube wells, rivers, canals, and other water bodies was found to be statistically highly significant and positively associated with the adoption of micro-irrigation technologies, as expected. The source of irrigation significantly affects MI technology adoption, with regions highly reliant on groundwater (tube wells), such as Punjab and Uttar Pradesh, showing a strong inclination towards adopting MI technologies (Dhawan, 2017). Nonetheless, certain state policies have led to distorted water prices and the overexploitation of water resources, highlighting the urgent need for effective groundwater management. This underscores our expectation of a positive influence from this variable on the adoption of MI technologies.

The marginal effect analysis shows that farmers who used tube wells for irrigation had significantly higher adoption rates of irrigation technologies, ranging from 8.2% to 15.8%. The second-highest adoption rates were observed among farmers who used river or canal water for irrigation, ranging from 3.7% to 12.2%, while farmers who used other water sources had adoption rates ranging from 7.0% to 9.0%. These results can be explained by the fact that farmers in semi-arid regions mainly depend on groundwater resources, which are the primary source of water for tube wells.

The results show that cooperative societies and self-help groups have both positive and negative impacts on the adoption of MI technologies. They provide support to their members, indirectly aiding in technology adoption, but there is a maximum limit of 5 ha per beneficiary for accessing this support (Government of India, 2010). The other social scheme, the Kisan Credit Card, has a positive and statistically significant impact in all three models. Under this scheme, farmers can obtain credit from banks to invest in agricultural equipment, improving crop production and increasing adoption rates of irrigation technologies. The availability of Kisan Credit Cards significantly impacted the adoption of MI technologies among small and marginal farmers, resulting in marginal effects of 3.3% and 3.4% for drip and sprinkler irrigation, respectively. Furthermore, the Kisan Credit Card enabled farmers to acquire allied equipment, such as pump sets, and irrigation filters for their irrigation systems and farming activities.

The study highlights the varying impact of physical capital, particularly access to electricity, on different irrigation methods. Negative coefficients were observed for drip irrigation under specific access hours, while sprinkler irrigation showed positive and significant coefficients with >12 h of access. This underscores the crucial role of uninterrupted electricity in encouraging farmers to adopt irrigation systems. Moreover, Kumar et al., 2022, investigated an indigenous irrigation system developed by local farmers in Gujarat, India. This system utilizes electric-operated tube wells during power interruptions to tackle the issue of intermittent and disrupted power supply in the state. Furthermore, the coefficients for diesel and electric pump sets are positively associated with a higher likelihood of adopting drip and sprinkler irrigation technologies. This could benefit farmers relying on reliable electricity access or using diesel engines. However, the study indicates a higher probability of adopting micro-irrigation systems with diesel engines compared to electric pump sets for sprinkler irrigation, at 3.0% versus 1.0%. This trend is likely due to the prevalent use of diesel engines by farmers in semi-arid regions due to interrupted electric power supply, thereby increasing the adoption of micro-irrigation systems. Similar insights are echoed in earlier studies by Singh and Gandhi, 2024; Wang et al., 2024; Kumar et al., 2022; Suresh and Samuel, 2020; Bahinipati and Viswanathan, 2019; Dhawan, 2017; and Namara et al., 2007.

The adoption and performance of drip, sprinkler, and combined irrigation technologies have shown positive progress in several semi-arid Indian states. Karnataka and Maharashtra have made significant strides, followed by Andhra Pradesh, Tamil Nadu, Rajasthan, and Gujarat. Notably, the Ramthal lift irrigation scheme in Karnataka has effectively implemented drip irrigation, while the Narmada canal scheme in Rajasthan has introduced sprinkler irrigation, expanding the potential area for MI irrigation while conserving water resources (Vohra and Franklin, 2020). A unique indigenous strategy developed by Gujarat farmers allows water storage to support crops during the daytime through gravity flow, irrespective of electricity availability (Kumar et al., 2022). Marginal analysis indicates that drip irrigation is predominantly used in semi-arid states like Maharashtra (6.4%) and Karnataka (5.1%), with a higher adoption rate in Tamil Nadu (45.8%). Conversely, sprinkler irrigation technology is mainly adopted in semi-arid states such as Madhya Pradesh (2.6%) and Maharashtra (6.8%), with a larger distribution observed in Rajasthan and Karnataka, accounting for 11.2% (Government of India, 2004; Narayanamoorthy, 2009; Suresh and Samuel, 2020).

4. Farmers' perceptions and challenges towards adopting MI technologies – a case example of Andhra Pradesh

4.1. Adoption and scaling up (drip, and sprinkler) micro-irrigation technologies

As part of the focus group discussions (FGDs), the interview questions were tailored to uncover the challenges and benefits of adopting MI technologies in three selected administrative mandals in East Godavari district in Andhra Pradesh (Appendix A). The qualitative analysis of the FGDs yielded practical insights, revealing the following main barriers identified by farmers who have adopted and are knowledgeable about drip and sprinkler irrigation. The below photo-A indicates one of the focal discussions in Rajanagram Mandal of East Godavari district, and other photo-B performing drip irrigation for palm tree plantation in Gandepalli Mandal in the same district.

4.1.1. Landholding and subsidies

Most farmers in the selected FGD interview villages in the East Godavari district had leased land. The subsidy scheme for micro-irrigation, particularly drip irrigation, prioritizes land ownership as a key criterion for receiving subsidies. Consequently, farmers who lease land and do not own it are ineligible for government subsidies, which makes them less motivated to adopt capital-intensive micro-irrigation technologies.

> the majority are small farmers cultivating on leased land; we cannot get government support for installing drip irrigation on our farms. Group member, 33, Vangala Pudi village.

Small and marginal land-holding farmers who prefer to adopt low-cost drip technologies must meet the quality standards recommended by the government, or they will not be eligible for subsidies (Verma et al., 2004). Additionally, appropriate sizes for small farms are often not available, making it financially unfeasible and unfavorable for these farmers to adopt water-saving technologies such as drip irrigation (Suresh et al., 2019).

4.1.2. Crop pattern and preferences

The drip irrigation system is well-suited for farmers and promotes the adoption of irrigation technology in plantations such as palm trees. In

Photo-A: Focal Group Discussion, Andhra Pradesh

Photo-B: Palm tree plantation under drip irrigation, Andhra Pradesh

the village of Ramavaram, Jaggampeta, where most farmers grow palm trees, the farmers reported that the technology is easy to use and saves on labour.

> I have a four-acre farmland where I have planted palm trees; drip irrigation is a boon for me, as it helps me manage the entire farm alone. Group member, 48, Ramavaram Village.

In contrast, in the village of Raghavapuram, farmers expressed a different opinion regarding the technologies and crop choices. They prioritize growing cereals and are unwilling to change to horticulture crops. The main reason behind this reluctance is that agriculture is subsistence-based, and farmers prioritize growing crops that can provide food for their families throughout the year. Even if they prefer to grow other crops, group members reported that wild animals like monkeys often destroy horticulture crops.

> We are small farmers, and we mostly grow rice where we find drip irrigation is not useful at all despite the suitability of soil and climate, on the other side, it is difficult to grow fruits and vegetables in this area because monkeys and other wild animals regularly attack our farms. Group member, 47, Raghavapuram village.

4.1.3. Irrigation practices and policies

The choice of irrigation technology, whether drip, sprinkler or both, depends on the agricultural practices and nature of water sources in the area. For instance, in Srikrishna Patnam village, farmers predominantly grow horticulture crops such as lemon, cashew, and custard apple. They grow these three crops within one plot, with an average landholding size of around 5 acres. The farmers have observed that the handling of drip irrigation practices becomes a burden every time they plough the field before harvesting the crop.

> Before harvesting the fruits, we usually plough the fields to make the ground lose, minimising the crop damage during its harvesting. Drip irrigation does not allow us to plough the field swiftly. Therefore, we prefer surface irrigation. Group member, 45, Srikrishnapatnam village.

The drip irrigation technology is well-suited for farmers who have access to borewells. However, farmers have mentioned that the primary concern is obtaining borewells, as the groundwater level in these areas is below 150–500 ft and the cost of drilling is high. Moreover, the government only provides subsidies for installing drip irrigation systems, not for borewell construction. Therefore, small and marginal farmers in this region are expecting subsidies to cover borewell equipment costs. In 2021, the Andhra Pradesh government launched a free borewell scheme under the flagship Navaratnalu welfare scheme for eligible small and marginal farmers. Farmers using borewells in areas with critical groundwater levels can adopt micro-irrigation technologies to manage decreasing water tables.

> Adopting drip irrigation is not an issue as it is highly subsidised; our main concern is getting water in the field. The water table in the area is shallow, and getting a borewell in the field is costly. We do not get any support from the government for that. Group member,60, Sri Rangapatnam village.

4.1.4. Joint farm cultivation and water-sharing management

Farmers emphasized the significance of joint farming in reducing cultivation costs, human labor, and accessing irrigation facilities that are crucial socio-economic needs for improving micro-irrigation technologies. Some farmers have adopted a water-sharing method to support each other and reduce management costs. Thus, the combined effect of land pooling and water-saving irrigation management systems helps enhance farmers' skills and livelihoods (Mohan et al., 2022).

> Water sharing and combined farm management benefitting us to know more about the new technologies and improving our socio-economic conditions and strengthen human relationships among us. Group member, 41, Srikrishnapatnam village

5. Conclusions, limitations, and future research

The study provides a detailed analysis of the various determinants affecting the uptake of micro-irrigation (MI) technologies in the semi-arid regions of India. Human capital factors such as education, age, caste, gender, and employment status have been identified as pivotal in shaping farmers' decisions to embrace MI technologies. Moreover, economic factors including household income, landholding size, and access to irrigation sources play significant roles in adoption rates. Notably, there is a disparity in adoption rates based on education levels and landholding sizes (Suresh and Samuel, 2020), with higher-educated farmers demonstrating a greater propensity to adopt MI, emphasizing the influence of knowledge and awareness in technology adoption. Similarly, medium- and large-scale farmers exhibit higher adoption rates than smaller counterparts, indicating resource availability and operational scale impact. Regional disparities are also evident, with distinctive patterns of MI technology adoption observed across various states, driven by factors such as water availability, crop types, and government policies (GOI, 2014). For instance, Andhra Pradesh, Karnataka, and Tamil Nadu exhibit a strong correlation with drip irrigation adoption, while Maharashtra, Karnataka, and Rajasthan lean more towards sprinkler irrigation technology (Suresh and Samuel, 2020; Chand et al., 2020; Narayanamoorthy, 2009). It is important to note that the focus group discussions and interviews were exclusively conducted in Andhra Pradesh due to resource constraints. This decision was influenced by Andhra Pradesh's status as a leading state in MI technology adoption, with 72.8% of land covered by potential and actual MI systems, surpassing other states. While this approach allowed for in-depth insights from a high-adoption state, it limits the generalizability of findings to other semi-arid states with potentially different adoption landscapes.

In future research, it is important to broaden focus group discussions and conduct farmer interviews across more semi-arid states in order to better understand the challenges faced by MI technology adopters and non-adopters. Exploring the relationship between water quality, MI technologies, and farmers' income and livelihoods will provide valuable insights into the overall sustainability and viability of these technologies. Additionally, studying the economic impact of MI adoption and raising awareness about subsidies and government policies related to MI technologies are important for sustainable agricultural practices. Research efforts should focus on developing strategies to enhance farmers' understanding and utilization of available support mechanisms. Initiatives such as joint farming and collaborative water-sharing methods should be further explored as viable solutions to address small and marginal farmers' challenges, ultimately contributing to a more resilient and sustainable agricultural landscape.

6. Policy implications

Promoting micro-irrigation (MI) technologies in countries such as India has the potential to enhance agricultural productivity, water conservation, and sustainability significantly. Below are key policy recommendations aimed at facilitating MI technology adoption:

1. Timely subsidies or financial incentives should be provided to smallholder farmers who face challenges in affording upfront costs. Ensuring easy access to credit facilities or low-interest loans tailored for investment in drip irrigation infrastructure can enhance affordability and accessibility for all farmers.
2. Develop essential infrastructure such as water storage facilities, pumping systems, and irrigation filters at subsidized rates, particularly in economically disadvantaged regions (Angom and Viswanathan, 2023). Introducing portable MI irrigation kits that can adapt to various cropping systems is essential to cater to smallholder farmers with diverse land locations and cropping patterns.
3. Effective training programs and workshops should be conducted to educate farmers about technical aspects, and collaboration with the private sector for installation guidance is essential. Implementation of regulatory frameworks addressing electricity quality, equipment standards, and water pricing mechanisms can incentivize efficient water use and promote sustainable farming practices (Kumar et al., 2022).

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CRediT authorship contribution statement

Geetha Mohan: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – review & editing, Writing – original draft. **Lakshmi Narayana Perarapu:** Data curation, Writing – review & editing. **Saroj Kumar Chapagain:** Writing – review & editing. **A. Amarender Reddy:** Writing – review & editing. **Indrek Melts:** Writing – review & editing. **Ranjeeta Mishra:** Data curation, Writing – review & editing. **Ram Avtar:** Writing – review & editing. **Kensuke Fukushi:** Supervision, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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