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Micro-Irrigation and Solar Power: Unlocking India's Agricultural Potential

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Abstract

Water is vital for agriculture, but in India its availability is declining due to rising demand and climate variability. To address this, improving water productivity has become a priority. Integrating solar power with micro irrigation systems offers a sustainable way to enhance efficiency while reducing dependence on conventional energy. In this study, the potential area for micro-irrigation in India was estimated using two indices. The estimated potential area under micro-irrigation was approximately 88 Mha based on Index 1, which considered the proportion of the area irrigated by groundwater, tanks, other sources, and 30% of canal-irrigated land. Using Index 2, which included the proportion of the area irrigated by groundwater, tanks, other sources, and 50% of canal-irrigated land, the potential area was estimated to be approximately 93 Mha. MI adoption has grown at a Compound Annual Growth Rate of 9.75, reaching 16.73 Mha in 2023-24, with sprinkler irrigation covering 9.04 Mha (54.1%) and drip irrigation 7.68 Mha (45.9%). However, only 15.85% of the estimated MI ultimate potential (105.60 Mha) has been realized, with six states- Rajasthan, Maharashtra, Karnataka, Andhra Pradesh, Gujarat, and Tamil Nadu- accounting for 78% of MI adoption. Despite increasing solar pump installations (501,673 in 2022-23), their correlation with MI remains weak. Policies must address administrative inefficiencies, enhance incentives, and promote integrated solar-powered MI adoption to maximize sustainability and groundwater conservation.

Keywords: Solar power, Micro-irrigation potential, Groundwater, Irrigation index

Introduction

Water is a fundamental resource for sustaining life, economic development, and social well-being. However, despite the vast hydrosphere, 97.5 % of total water is saline, and only 2.5 % is freshwater. Out of this, 68.7 % is stored in glaciers and permanent snow cover, 29.9 % is present as groundwater, and only 0.3 % is available in lakes and rivers (IWMI, 2020). With a growing population, per capita water availability in India has declined significantly, from 5178 m^3/year in 1951 to 1481 m^3/year in 2021, falling below the water-stressed threshold of 1700 m^3/year. The country's gross water requirement was projected to rise from 813 BCM (Billion Cubic Meters) in 2010 to 1447 BCM by 2050 (CWC, 2010), increasing stress on available water resources. Many related studies have highlighted concerns regarding the sustainability and equitable distribution of irrigation development across regions (Srivastava *et al.,* 2014; Narayanamoorthy, 2011; Selvarajan and Roy, 2004). Groundwater over-extraction is a growing concern in northwestern states like Punjab, Haryana and Rajasthan, while underutilization of surface water resources is prevalent in eastern India (Srivastava *et al.,* 2014). Over the years, significant investments in irrigation infrastructure have led to an increase in gross irrigated area from 22.56 Mha in 1950-51 to 120.38 Mha in 2021-22 (DES, 2023). However, despite these efforts, nearly 44% of India's cultivated area remains rainfed and dependent on rainfall. Over the decades, the share of surface water (Canal) in net irrigated area has declined from 39.77 % in 1970-71 to 22.82% in 2022-23, while groundwater reliance has increased from 28.66 % to 62.74% during the same period (DES, 2023). This overdependence on groundwater has led to ecological and socio-economic challenges, emphasizing the need for water-use efficiency (WUE) technologies in Indian agriculture. (Shah, 2007; Janakaranjan and Moneach, 2006; Kumar *et al.,* 2013)

Numerous demand-side management and supply-side augmentation strategies have frequently been proposed for the comprehensive management of water resources in the face of growing water demand, inter-sectoral competition, decreasing per capita availability, and depleting water resources (Rosegrant, 1997; Briscoe and Malik, 2006; Kumar, 2003). Improving WUE in irrigation is given top priority in this context. The objective of this study was to estimate the state-wise potential area for micro-irrigation in India. The government wants to raise WUE from its current level by at least 20 % as part of the National Water Mission. A concerted effort is underway to encourage the use of sprinkler and drip irrigation technologies in order to save water and improve WUE in agriculture.

Material and Methods

The data for identification of suitable crops for micro-irrigation systems was based on the classification provided by the National Committee on Plasticulture Applications in Horticulture (NCPAH). Additionally, data on the area covered under MI across various states, crop wise was sourced from the PMKSY website, along with information from the Directorate of Economics and Statistics and MNRE report. Using these datasets, crops that are suitable for both drip and sprinkler irrigation systems were identified (Table 1).

Estimation of potential area

The gross irrigated area under various crops was compiled for major states for 2022-23. In the short term, the gross irrigated area was seen as the ultimate potential under MI, as it has a reliable source of irrigation. Over time, once irrigation facilities are expanded, unirrigated lands can be included in potential calculations (distant potential). However, Farmers who have access to adequate groundwater or canal water may not implement MI immediately, so it cannot be assumed that MI will cover all irrigated areas in India. To accurately estimate the potential area under MI, it is essential to have crop-wise data on the area irrigated by different irrigation sources. Accordingly, two indices were developed for each state using different combinations of irrigated areas and irrigation sources, based on these indices, the potential area estimated under two scenarios (Kishore *et al.*, 2022).

- *Irrigation Index I:* Proportion of the area irrigated through groundwater, other source, tanks, and 30% of canal irrigated land. (Scenario 1)
- *Irrigation Index II:* Proportion of the area irrigated through groundwater, other source, tanks, and 50% of canal irrigated land. (Scenario 2)

Outreach of micro-irrigation

The location coefficient was computed to account for the concentration of micro-irrigation areas across states. This aids in analysing the development trend and regional differential of micro irrigation. The location coefficient was determined as follows:

$$L = \frac{M_j / M}{G_j / G}$$

Where, M_j, area under micro irrigation in the j^{th} state; M, area under micro irrigation at the national level; G_j, area under minor-irrigation in

Table 1. Classification of Suitable Crops under Sprinkler and Drip Irrigation

Micro Irrigation	Crops
Drip	Paddy*, Condiments & Spices, pigeon pea, Sugarcane, Fruits, Sunflower, Tobacco, Coconut, Cotton
Sprinkler	Paddy*, Wheat, Vegetables, Sesamum, Rapeseed & Mustard, Maize, Pearl millet, Sorghum, Ragi, Other cereals & millets, Fodder crops, Gram, Other pulses, Soybean, Groundnut, Linseed, Other oilseeds

Source: NCPAH (2014), (Kishore *et al.,* 2022), (Chand *et al.,* 2020)

**Note:* Area under paddy has been equally divided between drip and sprinkler irrigation based on studies and PMKSY data.

the jth state; G, area under minor-irrigation at the national level (Kishore *et al.,* 2022).

Results and Discussions

Status of micro-irrigation in India

Micro-irrigation, including drip and sprinkler systems, has revolutionized agriculture by significantly enhancing water use efficiency (WUE). Acknowledging its transformative potential, the Government of India launched centrally-sponsored schemes in 2006, 2010, 2014, and 2015 to promote its adoption. These initiatives, particularly the Per Drop More Crop component introduced in 2015, focus on optimizing on-farm water use to boost agricultural productivity and sustainability (NITI Aayog, 2017). These policy initiatives have led to a rapid expansion of MI, with adoption growing at a CAGR of 9.75 %, from 2.24 Mha in 2005-06 to 16.73 Mha in 2023-24 (Fig. 1). Of the total MI-covered area, 54.1 % (9.04 Mha) was under sprinkler irrigation, while 45.9 % (7.68 Mha) was under drip irrigation. Despite these advances, only 15.85 % of the estimated MI ultimate potential (105.60 Mha) has been achieved, with six states-Rajasthan, Maharashtra, Karnataka, Andhra Pradesh, Gujarat, and Tamil Nadu- contributing 83.50 percent of the total MI-covered area.

Irrigation indices

Two irrigation indices that assign varying proportions of canal irrigated area were constructed in order to account for the various irrigation sources in each state. Canal irrigated area varied, but groundwater, other sources, and tank irrigated area stayed the same in both indices. States with a larger percentage of their land under irrigation have higher index values. (Annexure 1).

Estimation of potential micro-irrigation in India

Potential areas for micro-irrigation in India were estimated using constructed indices and categorized under sprinkler and drip irrigation systems according to crop suitability. The total irrigated area has been referred to as the ultimate potential area for the short-term adoption of micro-irrigation. With index I and index II, the estimated potential area for micro-irrigation was approximately 88 and 93 Mha, respectively (Table 2). In Scenario 1, the estimated potential area for sprinkler irrigation was 57.61 Mha, or two-thirds of the total, with drip irrigation contributing the remaining portion. Uttar Pradesh has the largest potential area (20%) of the total potential estimated under scenario 1, followed by Madhya Pradesh (16%) and Rajasthan (9%). In Scenario 2, when 20% more canal-irrigated area was included in the irrigation index, the absolute

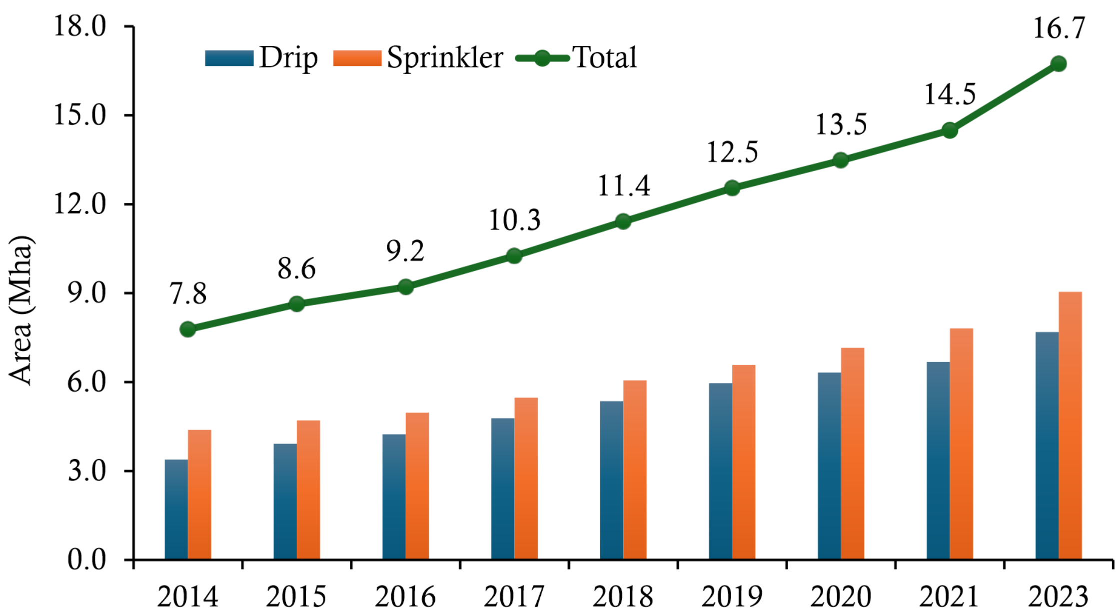

Fig. 1 Micro irrigation area trend in India (*Source:* DES, Agricultural Statistics- At a Glance, 2023)

Table 2. Micro-irrigation potential area across states (Mha)

State/UT	Ultimate Potential			Scenario* 1st			Scenario# 2nd		
	SP	Drip	Total	SP	Drip	Total	SP	Drip	Total
Andhra Pradesh	1.33	2.27	3.60	0.91	1.56	2.47	1.03	1.76	2.80
Arunachal Pradesh	0.04	0.03	0.06	0.04	0.03	0.06	0.04	0.03	0.06
Assam	0.35	0.25	0.60	0.26	0.19	0.45	0.29	0.21	0.49
Bihar	4.09	1.37	5.47	3.22	1.08	4.30	3.47	1.16	4.63
Chhattisgarh	1.11	0.85	1.97	0.76	0.58	1.33	0.86	0.66	1.51
Goa	0.01	0.02	0.03	0.01	0.01	0.02	0.01	0.02	0.02
Gujarat	2.77	4.52	7.30	2.19	3.58	5.77	2.36	3.85	6.20
Haryana	3.78	1.62	5.40	2.77	1.19	3.96	3.06	1.31	4.37
Himachal Pradesh	0.15	0.04	0.20	0.15	0.04	0.19	0.15	0.04	0.19
J & K	0.31	0.16	0.47	0.13	0.07	0.19	0.18	0.09	0.27
Jharkhand	0.16	0.05	0.22	0.16	0.05	0.22	0.16	0.05	0.22
Karnataka	2.30	1.96	4.26	1.96	1.67	3.63	2.05	1.75	3.81
Kerala	0.09	0.31	0.40	0.08	0.27	0.35	0.08	0.28	0.36
Madhya Pradesh	13.83	2.19	16.03	12.18	1.93	14.11	12.65	2.00	14.66
Maharashtra	1.61	2.68	4.28	1.23	2.05	3.29	1.23	2.23	3.46
Meghalaya	0.06	0.06	0.12	0.02	0.02	0.04	0.02	0.03	0.05
Nagaland	0.06	0.06	0.12	0.06	0.06	0.12	0.06	0.06	0.12
Odisha	0.78	0.73	1.51	0.38	0.36	0.74	0.50	0.47	0.96
Punjab	5.42	2.00	7.41	4.84	1.79	6.63	5.01	1.85	6.86
Rajasthan	7.96	2.42	10.39	6.37	1.94	8.30	6.82	2.07	8.89
Tamil Nadu	1.69	1.78	3.47	1.39	1.46	2.85	1.47	1.55	3.02
Telangana	2.71	3.17	5.89	2.16	2.53	4.69	2.32	2.71	5.03
Tripura	0.06	0.05	0.12	0.06	0.05	0.11	0.06	0.05	0.11
Uttar Pradesh	13.28	6.42	19.70	11.89	5.75	17.63	12.28	5.94	18.22
Uttarakhand	0.26	0.19	0.45	0.22	0.16	0.39	0.23	0.17	0.41
West Bengal	4.18	1.78	5.96	4.18	1.78	5.96	4.18	1.78	5.96
India	68.53	37.08	105.60	57.61	30.18	87.80	60.57	32.12	92.70

* - Calculated based on index I, # - Calculated based on index II.

potential area was 5.28% higher than the potential estimate obtained in Scenario 1. The potential area for sprinkler irrigation estimated by Task force on Micro Irrigation (TFMI, 2004) was the same (42.5 Mha) as that estimated by Indian National Committee on Irrigation and Drainage (INCID, 1998), and the micro irrigation potential areas estimated by Narayanamoorthy (2006), Raman (2010), and Chand *et al.* (2020) are 72.02, 42.24, and 72.17 Mha, respectively. However, because of the increase in irrigated area over time, the current estimate shows a value that was nearly 18–51 % higher than the previous estimates. Despite using different approaches, our estimate under Scenario 1 was nearly the same. Raman (2010)'s potential estimate was underestimated because it only took into account crop areas that were subsidized by the National Mission on Micro-Irrigation to install micro-irrigation systems. A similar approach was used by Kishore *et al.* (2022), Chand *et al.* (2020) who used two irrigation indices based on varying proportions of groundwater, tanks, and canal-irrigated land to estimate possible micro-irrigation areas.

Realization of micro-irrigation coverage area

Scenario 1: Karnataka state has the highest potential area coverage with sprinkler irrigation - 98 % among Indian states, followed by Andhra Pradesh, Maharashtra, and Chhattisgarh. At the national level, Rajasthan, which contributes the largest area (nearly 23%) of sprinkler irrigation, has utilized 25 % of its estimated potential. Andhra Pradesh, which accounts for nearly one-quarter of total drip irrigation area in the country, has covered approximately 98 % of its estimated potential area. As compared to other states, Andhra Pradesh farmers use drip irrigation extensively, even for the cultivation of fruits, vegetables, and maize (PMKSY 2024). In comparison to other states, Andhra Pradesh achieved the highest percentage of the estimated potential area, approximately 85 %. This might be the result of the government's combined efforts through the Andhra Pradesh Micro-Irrigation Project (APMIP), a special purpose vehicle established in 2003. At the country level, scenario 1 has achieved 19.06 % of estimated potential area through micro-irrigation (Table 3).

Scenario 2: The addition of a larger proportion of canal-irrigated area increased the total estimated potential from 87.80 to 92.70 Mha (Table 3). Therefore, as more area falls under the potential estimate for each state, the estimate of scenario 2 may indicate lower penetration. Overall, Andhra Pradesh has had the highest penetration of micro-irrigation, followed by Karnataka and Maharashtra. Based on this estimate, micro-irrigation covers 18.05 % of India's estimated area. The proportion of micro-irrigation area to previously estimated potential area ranged between 11-46 % for sprinkler irrigation and 29-61 % for drip irrigation (TFMI 2004, INCID 1998, Narayanamoorthy 2006, Chand *et al.,* 2020, Raman 2010, Kishore *et al.,* 2022). With clearly defined procedures, this study offers a limited range of 14.94–15.70 % for sprinklers and 23.94–25.48 % for drip irrigation.

Outreach of micro-irrigation across states

The higher value of coefficient depicts higher concentration of MI (Suresh *et al.,* 2018; Ramasamy *et al.,* 2005). Due to groundwater scarcity, the concentration of micro-irrigation has grown quickly over time, according to the location coefficient for Karnataka and Andhra Pradesh. Karnataka, Maharashtra, and Andhra Pradesh have received the most funding under PMKSY-PDMC and a dedicated implementing agency, such as APMIP, since 2003. Other states, including

Table 3. Penetration of micro-irrigation compared to estimated potential

State/UT	Actual area* covered			% to Scenario 1st			% to Scenario 2nd		
	SP	Drip	Total	SP	Drip	Total	SP	Drip	Total
Andhra Pradesh	0.56	1.53	2.09	61.28	98.43	84.70	54.22	87.09	74.94
Assam	0.03	0.01	0.05	12.50	6.72	10.09	11.44	6.15	9.23
Bihar	0.11	0.03	0.13	3.34	2.34	3.08	3.10	2.17	2.86
Chhattisgarh	0.36	0.04	0.41	48.18	7.11	30.37	42.48	6.27	26.77
Gujarat	0.89	1.06	1.95	40.51	29.61	33.75	37.66	27.53	31.38
Haryana	0.70	0.05	0.75	25.31	4.42	19.05	22.93	4.01	17.25
Himachal Pradesh	0.01	0.01	0.01	4.40	18.92	7.67	4.40	18.79	7.66
Jharkhand	0.02	0.04	0.06	12.61	83.64	28.18	12.56	83.32	28.07
Karnataka	1.94	0.92	2.85	98.91	54.79	78.58	94.26	52.22	74.90
Kerala	0.01	0.03	0.04	13.28	9.41	10.28	12.70	9.00	9.83
Madhya Pradesh	0.37	0.39	0.76	3.00	20.38	5.38	2.89	19.62	5.18
Maharashtra	0.72	1.57	2.30	58.68	76.65	69.90	58.68	70.53	66.31
Nagaland	0.01	0.02	0.03	17.52	32.78	25.09	17.52	32.78	25.09
Odisha	0.19	0.04	0.23	50.08	10.07	30.74	38.70	7.78	23.76
Punjab	0.02	0.04	0.06	0.41	2.25	0.91	0.40	2.17	0.88
Rajasthan	2.03	0.48	2.51	31.86	24.78	30.21	29.73	23.13	28.19
Tamil Nadu	0.46	1.00	1.46	33.00	68.38	51.15	31.05	64.35	48.13
Telangana	0.10	0.26	0.36	4.61	10.27	7.66	4.30	9.57	7.14
Uttar Pradesh	0.31	0.12	0.43	2.65	2.00	2.44	2.56	1.94	2.36
Uttarakhand	0.02	0.02	0.03	7.44	11.03	8.95	7.12	10.55	8.57
West Bengal	0.15	0.01	0.16	3.49	0.61	2.63	3.49	0.61	2.63
India	9.05	7.69	16.73	15.70	25.48	19.06	14.94	23.94	18.05

*Area in Mha; *Source:* DES (2023)

Chhattisgarh, Gujarat, and Rajasthan, have seen an increase in the area under micro-irrigation in recent years. In states like Punjab, Haryana, and others with over-exploited groundwater, micro-irrigation coverage is still low and requires special policies to encourage its use.

With the implementation of PMKSY, an additional 8.34 Mha were brought under micro-irrigation. However, there is significant variety across states. The projected potential area for micro-irrigation ranges from 87.80 to 92.70 Mha, with only 18.05-19.06 % covered. States like Andhra Pradesh, Karnataka, Maharashtra, and Tamil Nadu can cover more than half of their projected potential area. On the other hand, one-third of states have less than 10 % of their projected area covered with micro-irrigation.

Adoption of micro irrigation

The share of MI in year 2022-23 indicated both Gross Irrigated Area (GIA) and Gross Cropped Area (GCA) differed widely, with Andhra Pradesh (57.3% in GIA; 28.6% in GCA) and Karnataka (45.5%; 19.3%) showing the highest adoption, while Kerala (6.9%; 1.4%) and Himachal Pradesh (7.2%; 1.7%) reported the lowest penetration (Fig. 2). Sprinkler irrigation expanded rapidly in Rajasthan, Karnataka, Haryana, and Uttar Pradesh, whereas drip irrigation gained greater traction in Maharashtra, Andhra Pradesh, Gujarat, and Punjab (Table 3). Maharashtra witnessed a significant surge in MI adoption between 2016–17 and 2017–18, while Punjab lags in MI coverage due to several administrative inefficiencies, including manual subsidy processes, absence of a dedicated MI department, and lack of Direct Benefit Transfer for MI subsidies (Chand *et al.,* 2020). According to state-wise MI potential estimates, Uttar Pradesh has the highest untapped MI Ultimate potential at 19.70 Mha.

Policies for solar powered micro irrigation

The Government of India has launched several schemes, including PM-KUSUM, to promote efficient utilization of solar energy and maximize crop production per unit area. However, the correlation between micro-irrigation (MI) and solar pump adoption remains weak. Some states with high MI adoption exhibit low solar pump usage, and vice versa. Chhattisgarh has the highest solar pump adoption but one of the lowest MI adoption rates, whereas Karnataka has the highest MI coverage but lags in solar pump deployment as shown in Fig 3 and 4. Solar pump installations have grown substantially, from 11,626 in 2013 to 501,673 in 2022–23, with a CAGR of 54.64% (Figs. 3–4), yet they account for only 2.33% of India's total 21.5 million irrigation pumps (Srivastava *et al.*, 2024).

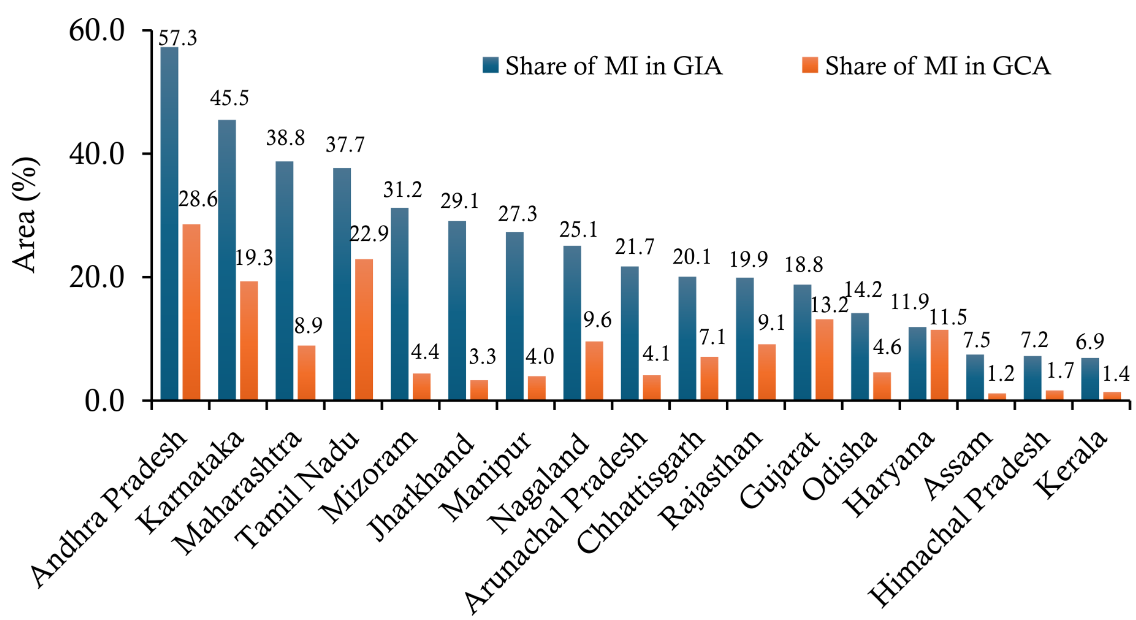

Fig. 2 Penetration of micro irrigation across states in the year 2022-23 (*Source:* DES, Land Use Statistics- At a Glance, 2023) Where, MI is micro irrigated area, GIA is gross irrigated area, GCA is gross cropped area

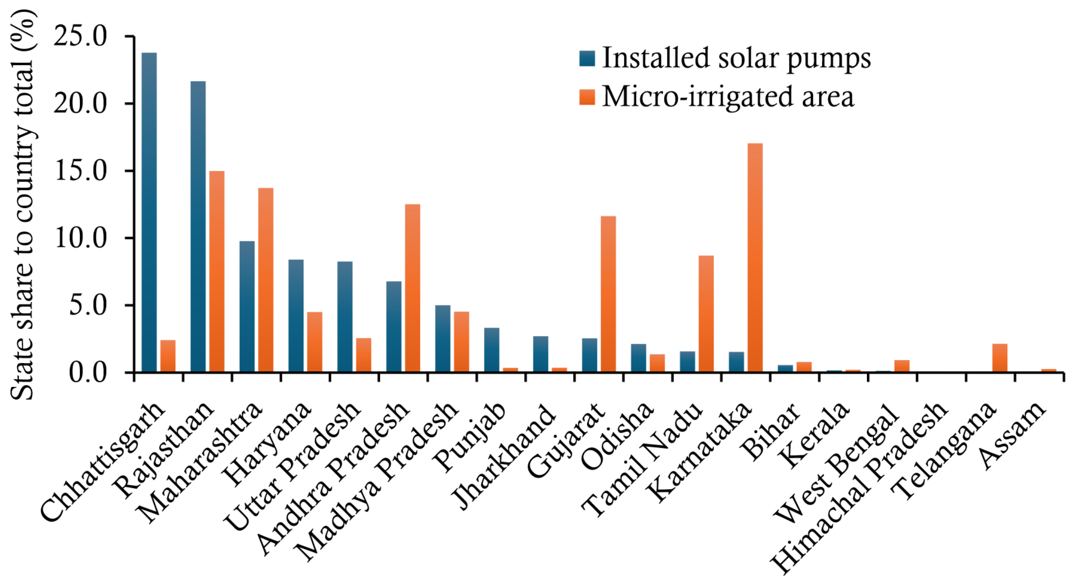

Fig. 3 States' share in micro-irrigated area and installed solar pumps, 2022-23 (*Source:* MNRE, 2023; Land Use Statistics- At a Glance, 2023)

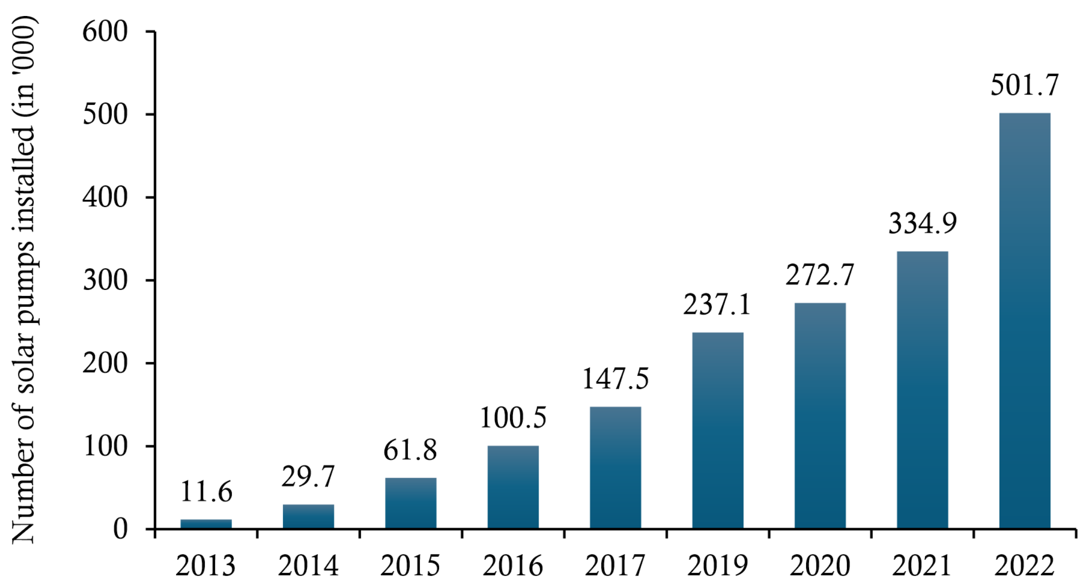

Fig. 4 Trend in solar pumps installation in India (*Source:* MNRE, 2023)

Conclusion

Assessing the potential for micro-irrigation and solar energy availability at the farm level in India is urgently needed to ensure the efficient use of water and energy. This study estimated India's micro-irrigation potential approx. 87.8-92.7 Mha, yet only 16.73 Mha (about 18-19%) has been realized so far using selected indices. The study also highlighted the adoption rate of micro irrigation vary widely across states: such as Uttar Pradesh and Madhya Pradesh have achieved less than 5% of their micro-irrigation potential, whereas Andhra Pradesh and Karnataka have exceeded 75%. The outcomes of this study will be valuable for expanding micro-irrigation areas across states and for integrating available solar power to realize the full potential of agriculture and water conservation at the farm level. The expansion of micro-irrigation through policy support and the growth of solar pumps has laid a strong foundation; however, addressing challenges such as high costs, weak institutional coordination, and uneven outreach remains crucial. Targeted, state-specific policies and the integration of solar-powered micro-irrigation can unlock the full potential of this technology, driving enhanced agricultural productivity and sustainable water conservation.

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