

# Resource-Use Efficiency and Economic Impacts of Micro-Irrigation Adoption among Smallholders in Eastern India

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## ABSTRACT

The necessity of water scarcity, increased demands for irrigation energy and increased production costs make it important to have strategies which improve the efficiency of water and energy use, as well as to increase farm profitability. In this study, the impact of micro-irrigation adoption on resource-use and economy was evaluated in the smallholder crop field of two districts of south Odisha, India – Gajapati and Rayagada and Koraput districts. The survey was conducted by multistages stratified sampling approach on 300 farmers including 150 farmers who adopted micro-irrigation and 150 conventional-irrigation farmers. The descriptive statistics, mean comparison test, and  $\chi^2$  analysis were used to evaluate the socio-economic and institutional characteristics, irrigation and input application, crop productivity, and production costs and returns. Propensity score matching (PSM) was then used to address the observable selection bias and to estimate the average treatment effect on the treated (ATT). The micro-irrigation farmers consumed 37.4% less irrigation water, 42.2% less irrigation labour and 33.7% less energy as compared to the conventional-irrigation farmers and produced 22.1% more marketable yield. The physical water productivity rose with 3.86 kg m<sup>-3</sup>. The novelty of micro-irrigation was that the net return was 72,220 ha<sup>-1</sup> more than conventional irrigation. The benefit-cost ratio was also improved from 1.92 to 2.38 and the economic water productivity was improved from ₹ 29.01 to ₹ 68.30 m<sup>-3</sup>. Following matching, the adoption of irrigation was correlated with 34.8% less use of irrigation water, 18.4% more yield, 39.5% more net return and 114.0% more economic water productivity. The results show that the use of micro-irrigation can enhance the physical resource efficiency and economic performance in smallholder production systems. Improved extension, access to institutional credit and specific investments, together with good water governance, can help to support irrigation transitions in southern Odisha that are economically viable and resource efficient.

**Keywords:** Economic water productivity, Farm profitability, Propensity score matching, Resource-use efficiency, Smallholder farming, Technology adoption, Water-energy nexus

Water scarcity has become a significant constraint in sustainable agricultural production and water is becoming scarcer for agriculture, domestic water supply, industry and ecosystems. The agriculture sector is the biggest water consumer with around 72% of the global water withdrawals and around 1.2 billion people living in agriculture with strong

water constraints (Zaman *et al.* 2017; McVicker, 2024). The impacts of climate variability, expected rise in

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evapotranspiration and food demand are likely to create a high demand for available water resources, which necessitates enhancing agricultural water productivity for food security and climate resilience (Maitra *et al.* 2020; Cheptoek *et al.* 2021; Santosh *et al.* 2024). In such cases, the technologies that yield higher economic return on water, energy and other inputs are becoming more relevant (Krishna *et al.* 2024).

The challenge is especially significant in India where irrigation accounts for significant part of agricultural productivity and potential exists for better water-use efficiency. The proportionate increase in the area of irrigation water is from 49.3% of gross cropped area in 2015–16 to 55% in 2020–21, but the efficient irrigation technologies have not increased proportionately. It is estimated that around 16.8 million ha is presently being covered under micro-irrigation, which is only around 25% of the net irrigated area in India and there is a significant variation in the adoption rate across different states in India (Dangar *et al.* 2021; Maheswari *et al.* 2023; Rezaei-Chiyaneh *et al.* 2023). Hence, micro-irrigation has played a significant role in the water-management approach, through the “Per Drop More Crop” programme, which involves efficient on-farm water use in India (Gouda *et al.* 2024).

Micro-irrigation may help to minimize conveyance and application losses and can permit high frequency and controlled irrigation (Maitra and Zaman, 2017; Santosh and Maitra, 2022; Sairam *et al.* 2023). In addition to water saving, reductions in pumping could also help to save energy costs, and better water and nutrient management could increase yield and labour productivity and farm income (Santosh *et al.* 2023; Maitra *et al.* 2026). Technological efficiency, however, doesn’t always lead to overall water savings. Recent multi-State evidence from India has shown that micro-irrigation, while reducing the number of hours farmers spent pumping water per unit area, often led to an increase in the area of irrigation after adoption and a move towards higher value crops, presenting a potential rebound or Jevons effect (Singh *et al.* 2024). Therefore, the assessment of micro-irrigation must not provide a physical water saving perspective only, as this will miss out on behavioural and economic responses.

The issue takes significance especially in southern part of Odisha where small and marginal farms, diverse terrain, fluctuating irrigation availability and growing horticultural output generate opportunities and constraints to achieve efficient irrigation investments. Although significant national research efforts have been undertaken into micro-irrigation, research is geographically skewed and focused on relatively high adoption states and regions (Mohanty *et al.* 2016; Santosh *et al.* 2025). The previous estimates too showed significant spatial variation in the extent of micro-irrigation penetration in India, which indicates the importance of assessing the micro-irrigation penetration per location instead of generalizing the results (Santosh *et al.* 2026). More important, limited empirical evidence simultaneously combines physical water use, energy and labour needs, productivity of crops, farm profitability, economic water productivity and selection effects of adoption to the Eastern Ghats region of Odisha. The economic effects of the technology may be overestimated or underestimated due to systematic differences between adopters and non-adopters in education, landholding, income, source of credit, access to extension services and institutional support.

Within this context, the present study examines the resource-use and economic consequences of micro-irrigation adoption of smallholder farmers in Gajapati, Rayagada and Koraput districts in the South of Odisha. This study specifically aims: To characterize the socioeconomic, farm and institutional attributes of both micro-irrigation adopters and non-adopters; Quantify differences in irrigation water use, energy consumption, labour requirement, fertilizer application, yield and physical water productivity; and Assess the effects of micro-irrigation on production costs, gross and net returns, benefit–cost ratio and economic water productivity. The study further attempts to quantify the effects of micro-irrigation adoption on key resource-use, productivity and profitability indicators while considering the observable differences between the adopters and non-adopters, using propensity score matching. The study incorporates agricultural-engineering measures of water and energy use efficiency, alongside farm-level economic and treatment-effect analyses to evaluate the extent to

which improving physical resource-use efficiency can yield measurable economic benefits at the farm level. The results will serve as empirical evidence to advance technology targeting, water investment decisions, and policies to boost water use efficiency and smallholder profitability in water-scarce production settings like southern Odisha, and other such contexts in eastern India.

## MATERIALS AND METHODS

The study has been carried out in Gajapati and Rayagada and Koraput districts of the Eastern Ghats production environment in southern Odisha, India, where agriculture and horticulture plays an important role in living and irrigation conditions are highly variable. The predominant topography in Gajapati is steep hill and there is significant horticulture potential, whereas in Rayagada, out of 234,736 ha net sown area only 54,664 ha is irrigated and hence efficient irrigation is very relevant. A multistage stratified sampling was used. Within each district blocks and villages with significant cultivation of irrigated vegetables/horticultural crops were selected and thereafter the farm households were selected randomly. A number of 300 farmers including 150 farmers who adopt micro-irrigation and 150 farmers who practise conventional irrigation were sampled and a pre-tested structured questionnaire was used for data collection. A farmer who had drip/ sprinkler irrigation for the selected crop for the reference production season was considered as adopter. Household characteristics, landholding, institutional access, irrigation, input utilization, production, costs, returns were the farm level information collected.

The socio-economic characterization was obtained for age, education, farming experience, operational holding, vegetable area, distance from the irrigation source, extension contacts, farm income, institutional credit, irrigation subsidy and farmer organizations membership. Data for continuous variables were presented as means  $\pm$  SD and two group comparisons were performed by independent-sample t-tests (equal to one-factor ANOVA). Pearson's  $\chi^2$  test was used to compare categorical variables. Resource-use indicators comprised seasonal irrigation water, frequency of irrigation, pumping time, energy use, labour used in irrigation, nitrogen application,

marketable yield and physical water productivity. The volume of water used for irrigation during the season was estimated from the length of time the pump was in operation and the amount of water pumping. Marketable yield per irrigation water use was used to estimate water productivity.

The economic analysis covered the cost of planting material, fertilizers and manure, plant protection, labour, irrigation energy, other variable costs and annualized investment and maintenance cost of the micro-irrigation system. The gross return was determined using marketable output and realized farm-gate price while net return was determined by subtracting total cultivation cost from gross return. The benefit-cost ratio was determined from gross return/overall cultivation cost while economic water productivity was determined as net return/irrigation water used in cubic metres. The significant difference between groups was tested at the level of  $p < 0.05$ .

Adoption of micro-irrigation was not random, so propensity score matching (PSM) was used to estimate the impact of the adoption. A binary logit model was used to estimate the probability of adoption, which included pre-treatment household, farm and institutional characteristics such as age, education, farming experience, operational holding size, labour in household, irrigation-source characteristics, credit access, extension contact, farmer-organization membership and district effects. Similar observations were made between the groups of adopters and non-adopters within common support and the average treatment effect on the treated (ATT) was calculated for irrigation water, energy consumption, marketable yield, water productivity, gross returns, net returns, B:C ratio and economic water productivity. Observational farm data can be used with PSM, which creates comparison groups based on observed characteristics, but will not eliminate any bias due to those unobserved characteristics. Covariate balance and common support diagnostics were checked prior to interpreting treatment effects, and statistical significance was determined for levels of 1 and 5%.

## RESULTS AND DISCUSSION

The results of the study are presented and discussed in terms of farmers' socioeconomic characteristics, resource-use efficiency, crop productivity, economic performance and the estimated impacts of micro-

irrigation adoption. Table 1 shows the socioeconomic and the farm characteristics of the micro-irrigation users and non-users. Adopters were significantly younger than non-adopters (43.6 years compared to 46.1 years;  $p = 0.042$ ) and had significantly higher number of years of formal education (9.2 years compared to 7.5 years;  $p < 0.001$ ). There was no significant difference between the two groups in the amount of experience they had in farming ( $p = 0.051$ ). The main difference in the size of farms and land use between micro-irrigation and non-micro-irrigation adopters was that the former had larger farm size (1.74 ha) and assigned more land to vegetables (0.83 ha) than the latter (1.42 ha and 0.61 ha, respectively;  $p = 0.001$ , and  $p < 0.001$ ). The extension service engagement also varied significantly with an average of 5.8 extension contacts per year for adopters against 3.4 for non-adopters ( $p < 0.001$ ) and farm income of about ₹ 2.84 lakh household<sup>-1</sup> in the former group against ₹ 2.17 lakh in the latter group ( $p < 0.001$ ). Owning a farm cooperative, participating in a FPO or SHG, and having access to institutional credit were also significantly higher among adopters compared to non-adopters ( $p \leq 0.001$ ). However, there was no significant difference between the groups in terms of distance from the source of irrigation ( $p = 0.076$ ). Overall, the results show the presence of systematic socioeconomic and farm size and institutional differences between the adopters and non-adopters, suggesting that observed heterogeneity must be taken into consideration when estimating the economic impact of micro-irrigation.

The differences between the socio-economic status of micro-irrigation adopters and non-adopter are consistent with the literature that says human capital, farm resource base and institutional support will affect the adoption of technology in Indian agriculture. Higher education can enable farmers to increase their capacity to access technical information, assess the costs and benefits and manage knowledge-based irrigation systems. Similarly, education, availability of information, irrigation facility and credit has been found to be important factors for the adoption of micro-irrigation in India (Mohan *et al.* 2024). Adopters' bigger operational holdings and vegetable cropped areas could provide additional investment viability through the dispersion of fixed costs across a wider land area and increasing the returns of high-value crops (Rastogi *et al.* 2024). The group of adopters had more extension contact, access to institutional credit, and participation in farmer organizations than the rest of the farmers, reinforcing the importance of institutional support, as found in the other regions of India (Kishore and Birthal, 2024). These systematic differences also suggest that there may be selection bias since high farm performance cannot be explained completely by the use of micro-irrigation. Thus, treatment-effect methods like propensity score matching must also be used to adjust for observed differences to estimate the economic effects of adoption.

Micro-irrigation adoption brought significant and statistically significant gain in resource use

**Table 1:** Socio-economic and farm characteristics of sampled farmers

| Characteristic                                       | Micro-irrigation adopters ( $n=150$ ) | Non-adopters ( $n=150$ ) | Overall ( $N=300$ ) | Test statistic   | p-value |
|------------------------------------------------------|---------------------------------------|--------------------------|---------------------|------------------|---------|
| Age (years)                                          | 43.6 $\pm$ 10.2                       | 46.1 $\pm$ 11.0          | 44.9 $\pm$ 10.7     | $t = -2.04$      | 0.042   |
| Education (years)                                    | 9.2 $\pm$ 3.6                         | 7.5 $\pm$ 3.8            | 8.4 $\pm$ 3.8       | $t = 3.98$       | <0.001  |
| Farming experience (years)                           | 19.1 $\pm$ 9.8                        | 21.4 $\pm$ 10.5          | 20.3 $\pm$ 10.2     | $t = -1.96$      | 0.051   |
| Operational holding (ha)                             | 1.74 $\pm$ 0.91                       | 1.42 $\pm$ 0.79          | 1.58 $\pm$ 0.87     | $t = 3.25$       | 0.001   |
| Area under vegetables (ha)                           | 0.83 $\pm$ 0.48                       | 0.61 $\pm$ 0.39          | 0.72 $\pm$ 0.45     | $t = 4.35$       | <0.001  |
| Distance from irrigation source (m)                  | 146 $\pm$ 91                          | 128 $\pm$ 84             | 137 $\pm$ 88        | $t = 1.78$       | 0.076   |
| Extension contacts (no. year <sup>-1</sup> )         | 5.8 $\pm$ 3.0                         | 3.4 $\pm$ 2.3            | 4.6 $\pm$ 2.9       | $t = 7.78$       | <0.001  |
| Annual farm income (₹ lakh household <sup>-1</sup> ) | 2.84 $\pm$ 1.31                       | 2.17 $\pm$ 1.12          | 2.51 $\pm$ 1.27     | $t = 4.76$       | <0.001  |
| Access to institutional credit (%)                   | 68.7                                  | 48.0                     | 58.3                | $\chi^2 = 13.18$ | <0.001  |
| Received irrigation subsidy (%)                      | 74.0                                  | 18.7                     | 46.3                | $\chi^2 = 92.7$  | <0.001  |
| Member of FPO/SHG/cooperative (%)                    | 54.7                                  | 36.0                     | 45.3                | $\chi^2 = 10.55$ | 0.001   |

efficiency and crop productivity when compared to conventional irrigation (Table 2). In the micro-irrigation experiment, the mean use of irrigation water averaged 3,286 m<sup>3</sup> ha<sup>-1</sup>, whereas in the conventional irrigation experiment, the mean use of irrigation water averaged 5,247 m<sup>3</sup> ha<sup>-1</sup>, which resulted in a 37.4% reduction ( $F = 490.7$ ;  $p < 0.001$ ). Likewise, the duration of pumping decreased by 34.7%, the energy used for pumping decreased by 33.7% and the labour required for irrigation decreased by 42.2% ( $p < 0.001$ ). The smaller, more controlled applications have led to significantly lower amounts of water used per season despite the higher frequency at which irrigation was applied by the micro-irrigated farms (31.8 events season<sup>-1</sup> compared to 18.6 events season<sup>-1</sup>). The application of nitrogen was also 10.5% less under micro-irrigation ( $p < 0.001$ ) suggesting that there is scope for nitrogen input rationalisation. Marketable yield, on the other hand, showed a significant increase from 21.16 t ha<sup>-1</sup> under conventional irrigation to 25.84 t ha<sup>-1</sup> under micro-irrigation, indicating a 22.1% increase ( $F = 80.3$ ;  $p < 0.001$ ). The reduction in irrigation water and increase in yield led to a decrease in water productivity by 94.1% from 4.10 to 7.96 kg m<sup>-3</sup> ( $F = 557.9$ ;  $p < 0.001$ ). The results of these tests showed that the potential physical resource-use efficiency was significantly higher among the sampled farms in southern Odisha under micro-irrigation.

The decrease in irrigation water and time with micro-irrigation is indicative of water being applied more often and in small quantities closer to the root zone, reducing conveyance and non-beneficial water losses. The same evidence provided from four states in India revealed that, micro-irrigation resulted in around 32 % lesser pumping time per hectare (Singh

*et al.* 2024). The present study resulted in a decrease in energy consumption of 33.7%, which is similar to the energy savings recorded in drip-irrigated farms of Maharashtra with a reduction in pumping needs (Shroff and Miglani, 2024). Nitrogen application reductions might be due to better synchronization in water and nutrient supply by fertigation, which could lead to better nutrient and water productivity (Mohanty *et al.* 2025). Most importantly, the 37.4% reduction in irrigation-water use along with the 22.1% increase in marketable yield greatly enhanced water productivity, corroborating recent findings of water savings and productivity gains for drip-based irrigation systems in India (Sairam *et al.* 2025). These benefits, however, are farm-level efficiencies and do not necessarily equate to water savings at the regional level as expansion in irrigated area or changes in cropping patterns can lead to rebound effects (Nair and Thomas, 2023). Micro-irrigation has improved water use efficiency, energy use efficiency and labour use efficiency overall, however, suitable water-governance practices are essential for harnessing the efficiency at the farm level to scale up water conservation.

The economic performance of micro-irrigation adopters was significantly different from that of the farmers in conventional irrigation (Table 3). The total cost of cultivation was slightly lower under micro-irrigation (₹ 163,160 ha<sup>-1</sup>) than conventional irrigation (₹ 165,180 ha<sup>-1</sup>) but it was not significant statistically ( $F = 0.91$ ;  $p = 0.341$ ). The extra annualised system and maintenance expenses of ₹ 10,850 ha<sup>-1</sup> with micro-irrigation were compensated for predominantly by a reduction in the costs of fertilizer, labour and irrigation energy. Both labour and irrigation-energy costs were reduced by 13.9

**Table 2:** Resource use and productivity under micro-irrigation and conventional irrigation

| Parameter                                                                | Micro-irrigation<br>(n=150) | Conventional<br>irrigation (n=150) | Change due to<br>MI (%) | F-value | p-value |
|--------------------------------------------------------------------------|-----------------------------|------------------------------------|-------------------------|---------|---------|
| Irrigation water (m <sup>3</sup> ha <sup>-1</sup> season <sup>-1</sup> ) | 3,286 ± 624                 | 5,247 ± 886                        | -37.4                   | 490.7   | <0.001  |
| Irrigation events (no. season <sup>-1</sup> )                            | 31.8 ± 6.2                  | 18.6 ± 4.7                         | +71.0                   | 431.5   | <0.001  |
| Pumping duration (h ha <sup>-1</sup> )                                   | 122.4 ± 28.6                | 187.3 ± 42.5                       | -34.7                   | 240.4   | <0.001  |
| Energy consumption (kWh ha <sup>-1</sup> )                               | 468 ± 116                   | 706 ± 171                          | -33.7                   | 199.5   | <0.001  |
| Irrigation labour (person-days ha <sup>-1</sup> )                        | 10.8 ± 3.1                  | 18.7 ± 4.5                         | -42.2                   | 313.3   | <0.001  |
| Fertilizer-N applied (kg ha <sup>-1</sup> )                              | 128.6 ± 22.8                | 143.7 ± 28.4                       | -10.5                   | 25.8    | <0.001  |
| Marketable yield (t ha <sup>-1</sup> )                                   | 25.84 ± 4.71                | 21.16 ± 4.32                       | +22.1                   | 80.3    | <0.001  |
| Water productivity (kg m <sup>-3</sup> )                                 | 7.96 ± 1.72                 | 4.10 ± 1.02                        | +94.1                   | 557.9   | <0.001  |

and 35.9%, respectively, which were statistically significant ( $p < 0.001$ ). Most importantly, the gross return from micro-irrigation was found to be higher at ₹ 387,600 ha<sup>-1</sup> than conventional irrigation was at ₹ 317,400 ha<sup>-1</sup>, with a 22.1% increase ( $F = 76.52$ ;  $p < 0.001$ ). Consequently, net returns increased significantly from ₹ 152,220 to ₹ 224,440 ha<sup>-1</sup>, an improvement of 47.4% ( $F = 91.86$ ;  $p < 0.001$ ), while the benefit-cost ratio increased from 1.92 to 2.38 ( $F = 69.37$ ;  $p < 0.001$ ). The relative improvement was the most significant for the economic productivity of the irrigation water, increasing from ₹ 29.01 to ₹ 68.30 m<sup>-3</sup>, corresponding to a 135.4% improvement ( $F = 216.41$ ;  $p < 0.001$ ). As such the economic benefit of micro-irrigation was largely due to the increased output value and better resource productivity as opposed to a significant decrease in production cost.

Better profitability of micro-irrigated farms can be attributed to the combination of higher yields and lower irrigation related inputs (Table 2). Micro irrigation required higher annual investment and maintenance costs, however, the labor, energy and fertilizer costs were more or less compensated for, and overall cultivation costs were similar. In the same way, it was found that drip irrigation led to lower production costs and higher yield and net returns and was economically viable for major commercial crops even without subsidy in Maharashtra (Gorain *et al.* 2020). The B:C ratio also increased from 1.92 to 2.38, which is also consistent with the financial evaluations showing the viability of the drip

irrigation system in terms of B:C ratio, NPV, IRR and payback period (Hiremath *et al.* 2024). In particular, the “net return per cubic metre of irrigation water” increased by 135.4%, showing a significant economic enhancement of limited water resources. Table 1 shows that the socioeconomic and institutional characteristics were different for adopters and non-adopters, which implies that the benefit cost ratio differences are not entirely due to micro-irrigation and thus a treatment-effect approach should be used to take care of selection bias.

Results from the propensity score matching (PSM) estimates showed that the performance benefits of micro-irrigation remained when observable differences between the adopters and non-adopters were controlled (Table 4). The mean treatment effect on the treated (ATT) revealed that the seasonal irrigation water demand decreased by 1771 m<sup>3</sup> ha<sup>-1</sup> (34.8%) and energy consumption by 207 kWh ha<sup>-1</sup> (30.4%) after the adoption of micro-irrigation, which were highly significant ( $p < 0.01$ ). At the same time, the yield of marketable product increased by 3.99 t ha<sup>-1</sup> (18.4%) and water productivity increased by 3.50 kg m<sup>-3</sup> (81.0%). The resource efficiency gains resulted in substantial economic benefits: the additional gross return for adopters was ₹ 59,850 ha<sup>-1</sup> or 18.4% higher, and the net return was ₹ 62,640 ha<sup>-1</sup> or 39.5% higher. The estimated ATT for the B:C ratio was 0.40, which is a 20.4% above matched non-adopters. The highest relative increase was reported in economic water productivity where, the net return per cubic meter

**Table 3:** Cost and return structure of micro-irrigation adopters and non-adopters

| Economic indicator                                                  | Micro-irrigation | Conventional irrigation | Difference (%) | F-value | p-value |
|---------------------------------------------------------------------|------------------|-------------------------|----------------|---------|---------|
| Seed/planting material (₹ ha <sup>-1</sup> )                        | 24,850           | 23,760                  | +4.6           | 3.42    | 0.065   |
| Fertilizer and manure (₹ ha <sup>-1</sup> )                         | 38,420           | 40,870                  | -6.0           | 7.61    | 0.006   |
| Plant protection (₹ ha <sup>-1</sup> )                              | 18,760           | 18,240                  | +2.9           | 1.16    | 0.282   |
| Labour cost (₹ ha <sup>-1</sup> )                                   | 44,680           | 51,920                  | -13.9          | 29.84   | <0.001  |
| Irrigation energy cost (₹ ha <sup>-1</sup> )                        | 7,960            | 12,410                  | -35.9          | 46.73   | <0.001  |
| MI maintenance/annualized system cost (₹ ha <sup>-1</sup> )         | 10,850           | —                       | —              | —       | —       |
| Other variable costs (₹ ha <sup>-1</sup> )                          | 17,640           | 17,980                  | -1.9           | 0.42    | 0.517   |
| Total cost of cultivation (₹ ha <sup>-1</sup> )                     | 163,160          | 165,180                 | -1.2           | 0.91    | 0.341   |
| Gross return (₹ ha <sup>-1</sup> )                                  | 387,600          | 317,400                 | +22.1          | 76.52   | <0.001  |
| Net return (₹ ha <sup>-1</sup> )                                    | 224,440          | 152,220                 | +47.4          | 91.86   | <0.001  |
| B:C ratio                                                           | 2.38             | 1.92                    | +24.0          | 69.37   | <0.001  |
| Net return per m <sup>3</sup> irrigation water (₹ m <sup>-3</sup> ) | 68.30            | 29.01                   | +135.4         | 216.41  | <0.001  |

**Table 4:** Estimated impact of micro-irrigation adoption on farm performance

| Outcome variable                                        | Matched adopters | Matched non-adopters | ATT      | Change (%) | SE    | t-value |
|---------------------------------------------------------|------------------|----------------------|----------|------------|-------|---------|
| Irrigation water ( $\text{m}^3 \text{ ha}^{-1}$ )       | 3,315            | 5,086                | -1,771*  | -34.8      | 142.6 | -12.42  |
| Energy use ( $\text{kWh ha}^{-1}$ )                     | 474              | 681                  | -207*    | -30.4      | 29.8  | -6.95   |
| Marketable yield ( $\text{t ha}^{-1}$ )                 | 25.63            | 21.64                | +3.99*   | +18.4      | 0.61  | 6.54    |
| Water productivity ( $\text{kg m}^{-3}$ )               | 7.82             | 4.32                 | +3.50*   | +81.0      | 0.24  | 14.58   |
| Gross return ( $\text{₹ ha}^{-1}$ )                     | 384,450          | 324,600              | +59,850* | +18.4      | 9,740 | 6.14    |
| Net return ( $\text{₹ ha}^{-1}$ )                       | 221,360          | 158,720              | +62,640* | +39.5      | 8,960 | 6.99    |
| B:C ratio                                               | 2.36             | 1.96                 | +0.40*   | +20.4      | 0.061 | 6.56    |
| Net return per $\text{m}^3$ water ( $\text{₹ m}^{-3}$ ) | 66.78            | 31.21                | +35.57*  | +114.0     | 3.41  | 10.43   |

ATT = average treatment effect on the treated. \* indicates  $p < 0.01$ .

of water used has risen by ₹ 35.57  $\text{m}^{-3}$  or 114.0%. Even when matching the adopters with the non-adopters on the observed socioeconomic and farm-level characteristics, the resource-use and economic benefits of micro-irrigation remained statistically significant at the 1% level, indicating that these benefits are still significant.

Advantages of micro-irrigation have been found to be sustained in PSM estimates, despite the significant socioeconomic and resource disparities that were observed between those who adopted and those who did not. The positive ATT for marketable yield is consistent with the PSM evidence in Tamil Nadu, which revealed substantial benefits in yields from the application of micro-irrigation under PMKSY (Mansingh *et al.* 2026). It is also resource conserving, with lower irrigation water and energy demands, but may be tempered by rebound effects, such as additional irrigation water saved with the expansion of irrigated area and/or the increased value of irrigated crops (Šaponjić *et al.* 2025). Especially significant are the net returns (+39.5%) and the economic water productivity (+114.0%) improvements, indicating significant economic benefits to adoption, especially for crops of high value. The ATT estimates, however, apply only for the characteristics observed; therefore, common-support and covariate-balance diagnostics are crucial to draw robust inferences, and the ATT controls should only be applied under the condition of matching assumptions.

## CONCLUSION

The study shows significant improvement in

resource-use efficiency, crop productivity and farm profitability of smallholder farmers in the southern part of Odisha due to adopting micro-irrigation. There were significant differences between the education of adopters and non-adopters, operational holding, extension contact, institutional credit and irrigation subsidies, indicating that institutional and socioeconomic considerations play an important role in technology adoption. The micro-irrigation saved 37.4% of irrigational water during the entire season, pumping duration by 34.7%, energy consumption by 33.7%, and labour requirement for irrigation by 42.2% at the farm level and increased marketable yield by 22.1%. The physical water productivity rose from 4.10 to 7.96  $\text{kg m}^{-3}$ . The resource efficiency gains led to an economic performance increase with an increase in the net return from ₹ 152,220 to ₹ 224,440  $\text{ha}^{-1}$ , while the benefit–cost ratio rose from 1.92 to 2.38, and the economic water productivity increased from ₹ 29.01  $\text{m}^{-3}$  to ₹ 68.30  $\text{m}^{-3}$ .

Importantly, the economic and resource-use benefits remained after controlling for observable differences between adopters and non-adopters with propensity score matching. The matched adopters showed a decrease in irrigation-water use of 34.8%, an increase in marketable yield of 18.4%, and an increase in net return per unit of irrigation water of 114.0%. The results indicate that micro-irrigation may help to boost water-use efficiency and farm profitability in smallholder production systems in southern Odisha. Despite this, the adoption of water-saving technologies is still tied to farmers' information access, financial resources and institutional support, and enhanced water efficiencies at the farm level do

not always lead to conservation at the basin level because expansion of irrigated land is facilitated by water savings. A targeted financial and extension support system should therefore be combined with appropriate water-governance measures in policies. Causal inferences and broader sustainability impacts of micro-irrigation would be further bolstered with future research extending panel data and longer-term system costs/hydrological responses.

## GENERATIVE AI DECLARATION

The author(s) confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript, and no images were manipulated using AI. The authors developed and verified all scientific content, data analysis, interpretation of results, and conclusions. The authors take full responsibility for the accuracy, integrity, and originality of the work presented, and no AI tool was listed as an author.

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