Theme: Sustainable Agricultural Innovations for One Health and Environmental Resilience

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Economic and Energy Efficiency of Rainfed Chilli under Different Irrigation Systems in Tamil Nadu

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ABSTRACT

Background: Chilli is one of the major rainfed crops cultivated in Tamil Nadu. The source of irrigation influences crop productivity, cultivation cost, profitability and energy use. Therefore, the present study was undertaken to evaluate the economics and energy efficiency of rainfed chilli cultivation under different irrigation systems in Tamil Nadu.

Methods: The study was conducted in Ramanathapuram district during the year from 2024-2025 to 2025-2026. A total of 120 farmers cultivating Mundu chilli were selected from Mudukulathur and Paramakudi blocks. Based on the source of irrigation, farmers were classified into borewell owned, borewell rental and village tank irrigation systems. Primary data on input use, costs and returns were collected through personal interviews and analysed using cost concepts and standard energy equivalent coefficients.

Result: Borewell owned irrigation recorded the highest cultivation cost and gross income among the irrigation systems. Borewell rental irrigation recorded the highest net farm income and benefit-cost ratio, while village tank irrigation recorded comparatively lower returns. Human labour, nitrogen fertilizers and electricity were the major contributors to total energy input. Borewell owned irrigation recorded the highest energy input and energy output. Energy use efficiency and energy productivity were below one, while net energy return was negative under all three irrigation systems. Specific energy did not vary significantly among the irrigation systems. Overall, the irrigation source significantly influenced the economic and energy performance of rainfed chilli cultivation. The effective utilization of chilli crop residues can enhance both energy efficiency and profitability of the production systems.

Key words: Economic efficiency, Energy efficiency, Irrigation systems, Mundu chilli, Rainfed agriculture.

INTRODUCTION

Rainfed areas are agricultural regions that are primarily dependent on rainfall for agriculture and allied activities (NRAA, 2022). In India, 49 per cent of the cultivated area falls under dryland farming and contributes significantly to agricultural production (Kalhapure, 2022). In Tamil Nadu, about 40-50 per cent of the cultivated area is under rainfed conditions (Vasumathi *et al*., 2022). These areas are often affected by soil erosion, salinity, waterlogging, nutrient deficiency and low organic matter, leading to low productivity. Among the districts of Tamil Nadu, Ramanathapuram has the highest rainfed cropped area (2.27 lakh ha) (Kumaraperumal *et al*., 2019). The major rainfed crops cultivated in the district are rice, chilli, oilseeds and cotton. Chilli is the second major rainfed crop after rice, covering 13,811 hectares annually (Season and Crop Report, 2024-2025). Mundu chilli is the predominant variety cultivated under rainfed conditions in Ramanathapuram and has been conferred with a Geographical Indication (GI) tag (Spices Board, 2023).

As chilli cultivation in the district is predominantly rainfed, efficient use of available resources is essential for improving productivity and sustainability. Agriculture acts as both an energy consumer and an energy producer (Sharifi, 2018). Economic efficiency refers to achieving a given level of output at minimum cost (Balaji, 2023). Previous studies have demonstrated the usefulness of energy analysis in evaluating resource-use efficiency in agriculture (Sharifi, 2018; Ningoji *et al*., 2023). Likewise, the commission for agricultural costs and prices (CACP) cost concepts are widely used to assess the cost of cultivation and profitability of agricultural crops. However, increasing use of machinery, fertilizers and other agricultural inputs has raised energy consumption in agriculture (Ningoji *et al*., 2023), while excessive use of

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these inputs may cause environmental and health problems (Sharifi, 2018). Although previous studies have evaluated either the economics of crop cultivation or energy use in agriculture, studies integrating CACP-based cost concepts with energy analysis for rainfed Mundu chilli cultivation under different irrigation systems in Ramanathapuram district are limited. Therefore, an integrated assessment is required to identify economically viable and energy-efficient irrigation practices for sustainable chilli cultivation. Hence, the present study was undertaken to evaluate the cost, returns and energy efficiency of rainfed chilli cultivation under different irrigation systems.

Literature review

Rainfed agriculture

National rainfed area authority (2022) described rainfed areas as regions where agriculture and allied activities mainly rely on rainfall due to the unreliable availability of groundwater.

FAO (2026) stated that rainfed agriculture consists of agricultural production practices that depend entirely on natural rainfall.

Cost and returns

Doll and Orazem (1978) emphasized that farm cost measurement should include both explicit and implicit costs to accurately estimate the opportunity cost of production resources.

Debertin (2012) stated that cost of production can be measured in relation to the output produced and consists of both fixed and variable costs incurred during the production process.

Mandal and Basak (2026) defined cost of cultivation as the total expenditure incurred in crop production, comprising actual input costs and imputed costs. It is estimated using the CACP cost concepts from Cost A_1 to C_3, which include paid-out expenses, owned resources, family labour, and managerial charges.

Sharma (2019) and Arpitha *et al.* (2025) defined net returns as the profit obtained after deducting the total operating cost from the gross returns, while gross returns as the total income obtained from the sale of produce before deducting any costs.

Patel and Chandrakar (2022) stated that returns are the economic gains from an investment and are measured as gross and net returns.

Energy efficiency

Hatirli *et al*. (2006) explained that energy use efficiency represents the ratio of crop production output to the total energy input, comprising direct and indirect energy inputs, with crop yield expressed in energy-equivalent terms.

According to Sebestyénné (2013) and Jan *et al*., (2023) energy efficiency refers to maintaining the same level of economic activities or services while consuming less energy.

Tutak and Brodny (2022) described energy use efficiency as the ratio of energy output to energy input in a system or process.

MATERIALS AND METHODS

The study was conducted during 2024-25 and 2025-26 in Ramanathapuram district, Tamil Nadu, which has the largest rainfed cropped area (2.27 lakh ha) in the state and about 13,811 ha under rainfed chilli cultivation (Season and Crop Report, 2024-2025). Mundu chilli was the predominant variety grown in the district. Based on information from the Assistant Directorate of Horticulture, Mudukulathur and Paramakudi blocks were purposively selected, with Thaliyarendal and Puseri villages from Mudukulathur and Kalaiyur and Vengittan Kurichy villages from Paramakudi. A total of 120 chilli farmers (60 from each block) were selected through simple random sampling. Primary data on input use, costs and returns were collected through personal interviews, while energy equivalent coefficients were obtained from secondary sources.

Tools of analysis

Cost concepts

The chilli cost of cultivation was estimated using the commission on agricultural cost and prices (CACP) approach (Shaker *et al*., 2021; Economics, Statistics and Evaluation Division, 2021). These cost concepts provide a standardized method by accounting for variable, fixed and imputed costs. Table 1 presents the cost items included in the study.

The CACP cost concepts were estimated as:

Cost A_1= Actual paid-out cost.

Cost A_2= Cost A_1 + Rent paid for leased in-land.

Cost B_1= Cost A_1 + Interest on value of owned fixed capital assets (excluding land).

Cost B_2= Cost B_1 + Rental value of owned land and rent paid for leased-in land.

Cost C_1= Cost B_1 + Imputed value of family labour.

Cost C_2= Cost B_2 + Imputed value of family labour.

Cost C_2*= Cost C_2 + Additional value of human labour at the statutory minimum wage rate.

Cost C_3= Cost C_2* + 10 per cent of cost C_2* to account for farmer's managerial input.

Farm income measures

Farm income measures were used to evaluate the profitability of chilli cultivation under different irrigation systems (Shaker *et al*., 2021; Indhushree, 2016) as follows:

Net farm income (NFI)= Gross income-Cost C_3.

Family labour income (FLI)= Gross income-Cost B_2.

Farm business income (FBI)= Gross income-Cost A_1.

Farm investment income (FII)=

Farm business income-imputed value of family labour.

$$\text{Benefit-cost ratio} = \frac{\text{Gross income}}{\text{Gross expenses}}$$

Energy analysis

Each input used in mundu chilli cultivation was converted into energy units using the respective energy equivalent coefficients (Gokdogan *et al*., 2017), as provided in Table 2.

Energy indicators were estimated to evaluate the efficiency of energy utilization in chilli cultivation. Energy use efficiency indicates the effectiveness of converting input energy into output energy. Energy productivity represents the crop yield obtained per unit of energy input, while specific energy indicates the amount of energy required to produce one kilogram of chilli. Net energy return represents the difference between energy output and energy input. These indicators were calculated as follows (Ningoji *et al*., 2023).

Table 1: Components of Costs used for estimating the cost of cultivation of mundu chilli.

Cost Item	Description	Measurement units
Hired human labour	Wages paid to hired labourers for agricultural operations	(Rs./acre)
Hired bullock labour	Charges paid for hiring bullocks for field operations	
Owned bullock labour	Imputed cost of using owned bullocks for field operations	
Owned machine labour	Imputed cost of using owned farm machinery and equipment	
Hired machine labour	Charges paid for hiring tractors or other farm machinery	
Hired machinery charges	Expenses incurred for hiring agricultural implements and machinery	
Seed	Cost of purchased or farm-produced seed used for cultivation	
Insecticides and pesticides	Expenditure incurred on plant protection chemicals	
Manure	Cost of organic manures applied	
Fertilizers	Expenditure incurred on chemical fertilizers applied	
Irrigation charges	Cost incurred for irrigation water, pumping, electricity or diesel	
Depreciation of implements and farm buildings	Annual depreciation value of farm implements, machinery and farm buildings	
Land revenue cesses and other taxes	Statutory land revenue, cesses and taxes paid	
Interest on working capital	Interest charged on operating expenses during the crop period	
Miscellaneous expenses	Other cultivation expenses not included under specific cost items	
Rental value of owned land	Imputed rental value of owned agricultural land	
Rent paid for leased in-land	Actual rent paid for leased agricultural land	
Imputed value of family labour	Estimated value of unpaid family labour engaged in cultivation	
Managerial input of the farmer	Imputed value of the farmer's managerial services (10% of Cost C_2*)	
Statutory minimum wage rate	Government-prescribed minimum wage used for	Rs./day (or Rs./labour day)

Table 2: Energy equivalent coefficients of inputs and outputs in mundu chilli cultivation.

Energy source	Energy equivalent	Units	References
Human labour	1.96	MJ/hr	(Ningoji *et al*., 2023)
Nitrogen	60.6	MJ/kg	
Phosphorous	11.1	MJ/kg	
Potassium	6.7	MJ/kg	
Manure	0.3	MJ/kg	
Electricity	11.93	MJ/kwh	
Diesel	56.31	MJ/ltr	
Irrigation water	0.63	MJ/m^3	
Seed	14.7	MJ/kg	(Kargwal *et al*., 2022)
Castor cake	14.40	MJ/kg	(Regar *et al*., 2025)
Panchagavya	3.6	MJ/kg	(Ram and Verma, 2017)
Gypsum	10	MJ/kg	(Krupnik *et al*., 2022)
Output	3.13	MJ/kg	(Ambrose *et al*., 2024)

Note: The output energy equivalent for dry chilli production was determined based on energy equivalent for fresh chilli (0.8 MJ/kg) and change in moisture content under solar drying (Ambrose *et al*., 2024).

Net energy return (MJ ha^{-1}) = Energy output - Energy input

$$\text{Energy use of efficiency} = \frac{\text{Energy output (MJ ha}^{-1})}{\text{Energy input (MJ ha}^{-1})}$$

$$\text{Energy productivity (kg MJ}^{-1}) = \frac{\text{Yield (kg ha}^{-1})}{\text{Energy input (MJ ha}^{-1})}$$

$$\text{Specific energy (MJ kg}^{-1}) = \frac{\text{Energy input (MJ ha}^{-1})}{\text{Yield (kg ha}^{-1})}$$

Statistical analysis

The Kruskal-Wallis test was used to compare the economic and energy indicators among different irrigation systems.

RESULTS AND DISCUSSION

Supplementary irrigation during critical crop stages was provided through borewell owned, borewell rental and village tank irrigation systems. Farmers under borewell rental irrigation accessed groundwater through rented borewells. The economic and energy performance of these irrigation systems is presented below.

Cost and return analysis

Human labour constituted the major operational cost under all irrigation systems (Fig 1). Fertilizer expenditure was almost similar across systems, whereas manure cost was comparatively higher under village tank irrigation. Irrigation charges varied with the source of irrigation, while crop insurance, interest on working capital and miscellaneous expenses remained nearly uniform. Among fixed costs (Fig 2), interest on owned fixed capital formed the major share, followed by depreciation on implements. The rental value of owned land was higher under borewell owned irrigation, whereas rent for leased-in land was incurred only under borewell rental and village tank irrigation.

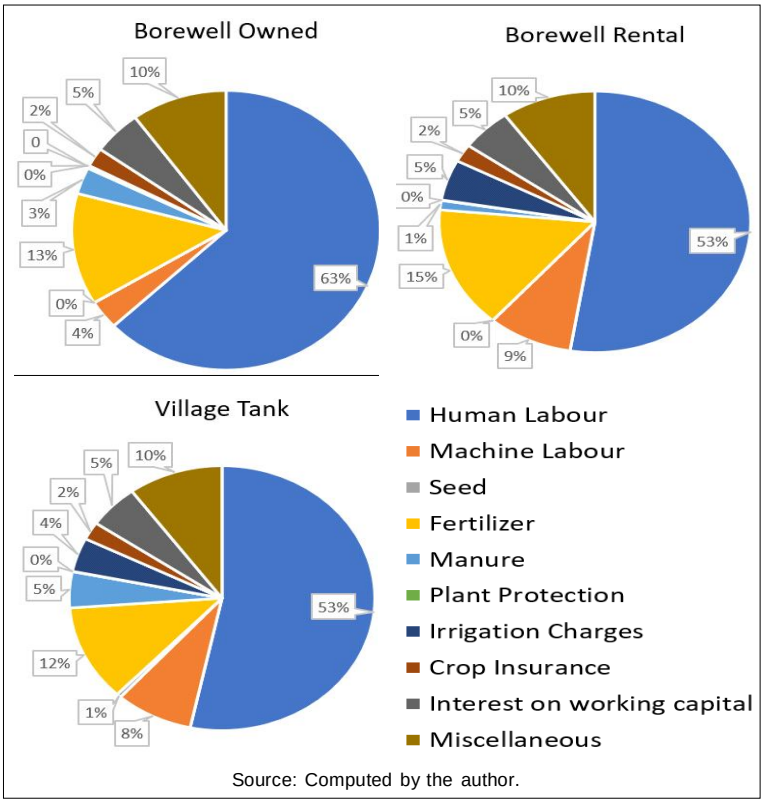
Overall, borewell owned irrigation recorded the highest variable cost (Rs.55,014.78 $acre^{-1}$), fixed cost (Rs.73,014.76 $acre^{-1}$) and total cultivation cost (Rs.128,029.50 $acre^{-1}$), followed by borewell rental (Rs.54,709.63, Rs.31,758.14 and Rs.86,467.76 $acre^{-1}$) and village tank irrigation (Rs.54,975.00, Rs.15,942.00 and Rs.70,917.00 $acre^{-1}$), respectively (Fig 3).

Table 3 presents the Gross income was highest under borewell owned irrigation (Rs.204,417 $acre^{-1}$), followed by borewell rental (Rs.167,273 $acre^{-1}$) and village tank irrigation (Rs.145,128 $acre^{-1}$) (Table 2). In contrast, net income and benefit-cost ratio were highest under borewell rental irrigation (Rs.80,831 $acre^{-1}$; 2.6), followed by village tank (Rs.74,213 $acre^{-1}$; 2.2) and borewell owned irrigation (Rs.76,388 $acre^{-1}$; 1.7).

Cost concepts

The CACP cost concepts of mundu chilli cultivation under different irrigation systems are presented in Fig 4.

Borewell owned irrigation recorded the highest values for all cost concepts (Fig 4). Cost A_1 and B_2 were



Source: Computed by the author.

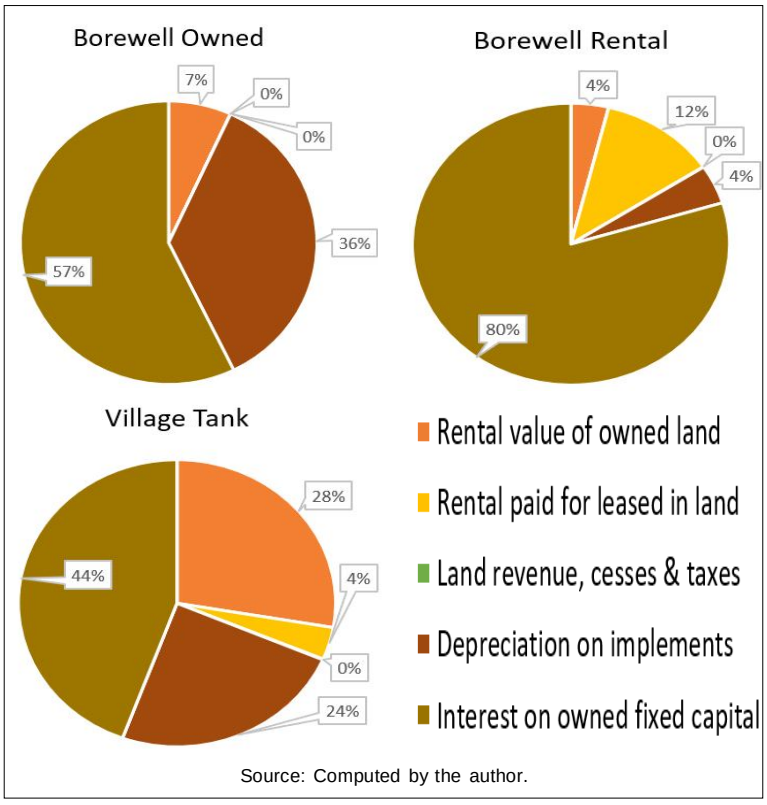
Fig 1: Variable cost components of mundu chilli cultivation under different irrigation systems.

Rs.99,956.83 and Rs.146,732.80 acre^{-1} under borewell owned irrigation Rs.72,628.74 and Rs.80,149.82 acre^{-1} under borewell rental and Rs.67,668.33 and Rs.79,736.24 acre^{-1} under village tank irrigation, respectively. Cost C_3 was highest under borewell owned irrigation (Rs.182,643.90 acre^{-1}), followed by village tank irrigation (Rs.107,182.00 acre^{-1}) and borewell rental irrigation (Rs.105,629.90 acre^{-1}).

Table 4 presents the Kruskal-Wallis test showed highly significant differences among the irrigation systems for all cost concepts. The highest Kruskal-Wallis statistic was recorded for Cost A_2 (56.14), followed by Cost A_1 (55.28), Cost B_1 (51.79), Cost B_2 (51.01), Cost C3 (49.11), Cost C_2* (49.11), Cost C_1 (48.94) and Cost C_2 (48.75).

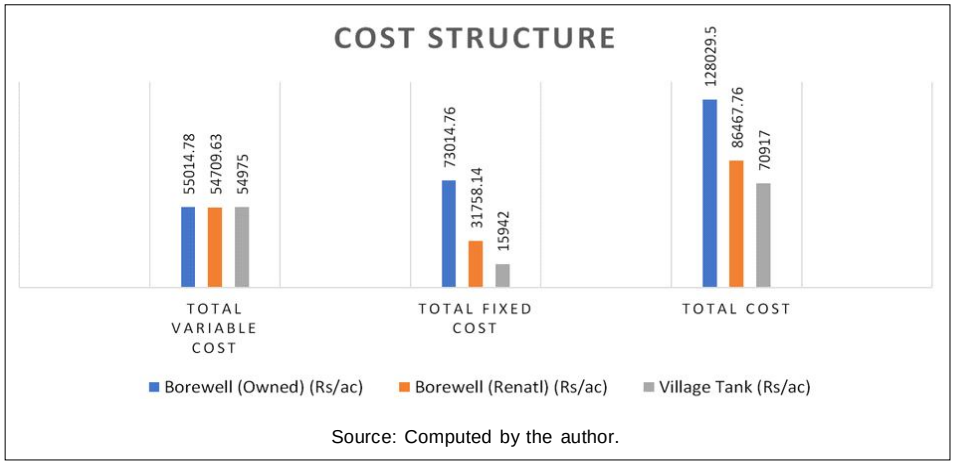
Farm income measures

Fig 5 shows that borewell owned irrigation recorded the highest gross income (Rs.2,04,417.40 acre^{-1}), farm business income (Rs.1,04,460.60 acre^{-1}) and farm investment income (Rs.68,549.52 acre^{-1}). Borewell rental



Source: Computed by the author.

Fig 2: Fixed cost components of mundu chilli cultivation under different irrigation systems.



Source: Computed by the author.

Fig 3: Cost structure of mundu chilli cultivation under different irrigation systems.

irrigation registered the highest family labour income (Rs.87,123.15 acre^{-1}) and net farm income (Rs.61,946.35 acre^{-1}). Village tank irrigation recorded the lowest values for all farm income measures.

Table 5 presents the Kruskal-Wallis test revealed significant differences among irrigation systems for all farm income measures (Table 4). Gross income recorded the highest Kruskal-Wallis statistic (51.83), followed by returns over variable cost (46.74), benefit-cost ratio (43.36), net income (19.88), farm business income (15.31), family labour income (13.68) and farm investment income (13.13).

Energy analysis

Table 6 shows that borewell owned irrigation recorded the highest energy consumption from human labour (11,633 MJ acre^{-1}), electricity (10,012 MJ acre^{-1}), irrigation water (2,122 MJ acre^{-1}), panchakavya (41 MJ acre^{-1}), castor cake (387 MJ acre^{-1}) and output energy (6,487 MJ acre^{-1}), whereas borewell rental irrigation had the highest energy use from nitrogen (12,763 MJ acre^{-1}), phosphorus (3,409 MJ acre^{-1}), potassium (483 MJ acre^{-1}) and gypsum (4,272 MJ acre^{-1}), while village tank irrigation recorded the highest energy consumption from diesel (3,050 MJ acre^{-1}) and farmyard manure (299 MJ acre^{-1}).

Total energy input was highest under borewell owned irrigation (45,234 MJ ha^{-1}), followed by borewell rental (36,158 MJ ha^{-1}) and village tank irrigation (32,374 MJ ha^{-1}) (Table 6). Corresponding energy outputs were 6,487, 5,320 and 4,908 MJ ha^{-1}, while net energy remained negative under all systems, ranging from -38,747 to -27,466 MJ ha^{-1}.

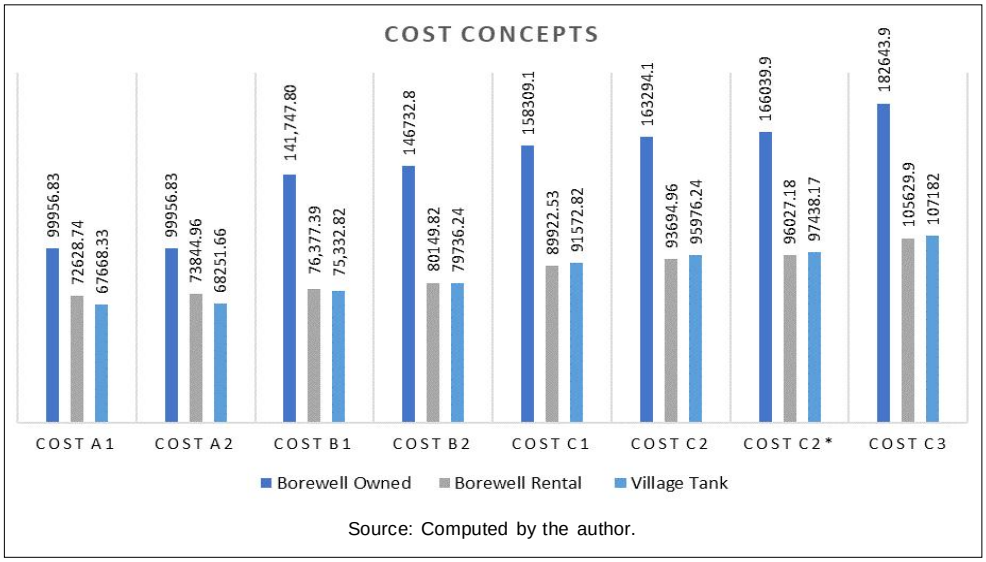


Fig 4: Cost concepts of mundu chilli cultivation under different irrigation systems (Rs/acre).

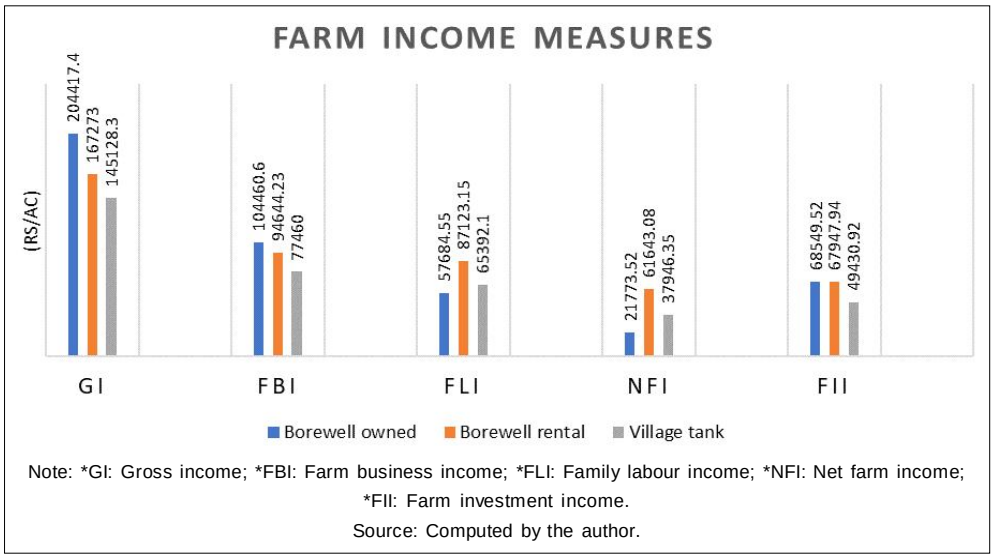


Fig 5: Farm income measures of mundu chilli cultivation under different irrigation systems.

Table 3: Returns from mundu chilli cultivation under different irrigation systems.

Returns (Rs/ac)	Borewell (Owned)	Borewell (Rental)	Village tank
Gross income	204417	167273	145128
Net income	76388	80831	74213
BCR	1.7	2.6	2.2

Source: Computed by the author.

Table 4: Statistical significance of cost concepts under different irrigation systems.

Variable	Statistic
Cost A_1	55.28***
Cost A_2	56.14***
Cost B_1	51.79***
Cost B_2	51.01***
Cost C_1	48.94***
Cost C_2	48.75***
Cost C_2*	49.11***
Cost C_3	49.11***

Note: ***p<0.01; ns >0.10.

Source: Computed by the author.

Table 5: Statistical significance of farm income measures under different irrigation systems.

Variable	Statistic
Gross income	51.83***
Net income	19.88***
Farm business income	15.31***
Family labour income	13.68***
Farm investment income	13.13***
Returns over variable cost	46.74***
BCR	43.36***

Note: *** p<0.01; ns >0.10.

Source: Computed by the author.

Energy use efficiency varied from 0.15 to 0.16, energy productivity from 0.05 to 0.12 kg MJ^{-1} and specific energy from 21 to 23 MJ kg^{-1} (Table 7).

The Kruskal-Wallis test indicated highly significant differences for energy input (47.52), energy output (37.46), net energy (31.67) and energy use efficiency (8.59) (Table 8). However, specific energy (3.69) did not differ significantly among the irrigation systems.

Cost and return analysis

Higher labour cost under borewell owned irrigation resulted from greater yield and harvest volume, which increased labour demand during harvesting and other field operations. Machine labour cost was lower because most farmers owned tractors and implements, whereas borewell rental and village tank farmers relied on hired machinery. Seed expenditure occurred only under village tank irrigation because heavy rainfall during 2025-26 caused waterlogging and necessitated replanting. Although fertilizer use was similar across irrigation systems, village tank farmers applied relatively more manure to improve crop performance under lower soil moisture.

Irrigation cost varied with the water source. Borewell owned farmers incurred no direct irrigation charges because agricultural electricity was supplied free of cost, whereas borewell rental farmers paid irrigation charges to borewell owners and village tank farmers incurred diesel expenses for pumping water. More frequent irrigation under borewell owned farms (6-7 irrigations) than borewell rental (5-6) and village tank irrigation (≈5) contributed to higher yield. However, the substantial investment in borewell infrastructure, depreciation and interest on fixed capital increased cultivation cost, making borewell rental irrigation economically more efficient with higher net income and benefit-cost ratio.

Cost concepts

The gradual increase from cost A_1 to cost C_3 reflects the addition of fixed costs, rental value of land, family labour and managerial charges under the CACP framework. Similar cost A_1 and A_2 values indicate comparable operational expenses, whereas the wider variation from Cost B_1 onwards reflects differences in fixed investment, particularly under borewell owned irrigation. The significant Kruskal-Wallis results further confirmed that irrigation source significantly influenced cultivation cost under different CACP cost concepts.

Farm income measures

Higher gross income under borewell owned irrigation resulted from assured irrigation, timely water application, higher yield and superior fruit quality. In contrast, borewell rental farmers depended on irrigation availability from borewell owners, while fluctuating tank water availability under village tank irrigation affected fruit size, colour and market quality, often producing discoloured (“sodai”) pods. Nevertheless, under favourable rainfall conditions, village tank irrigation produced yields comparable to groundwater irrigation. Groundwater-irrigated chilli also received slightly higher market prices (` 240-250 $kg^{-1}$) than village tank chilli (` 220-235 kg^{-1}). Despite higher gross income, the greater cultivation cost reduced profitability under borewell ownership, whereas borewell rental irrigation achieved better economic returns by balancing production cost and income.

Energy analysis

Human labour, nitrogen fertilizer and electricity were the major contributors to total energy input, consistent with the

Table 6: Energy sources in mundu chilli cultivation under different irrigation systems.

Energy source (MJ/acre)	Borewell owned	Borewell rental	Village tank
Human labour	11633	4391	6395
Diesel	2497	2075	3050
Seed	79	77	73
Fertilizer (N)	11194	12763	11038
Fertilizer (P)	2968	3409	3117
Fertilizer (K)	432	483	489
Gypsum	3544	4272	1956
Panchakavya	41	7	5
FYM	209	78	299
Castor cake	387	48	59
Irrigation water	2122	1711	1573
Electricity	10012	6728	4214
Output	6487	5320	4908

Source: Computed by the author.

Table 7: Energy indicators of mundu chilli cultivation under different irrigation systems.

Indicators	Borewell owned	Borewell rental	Village tank
Energy input (MJ ha^{-1})	45234	36158	32374
Energy output (MJ ha^{-1})	6487	5320	4908
Net energy return (MJ ha^{-1})	-38747	-30838	-27466
Energy use efficiency	0.15	0.15	0.16
Energy productivity (kg MJ^{-1})	0.05	0.12	0.12
Specific energy (MJ kg^{-1})	23	22	21

Source: Computed by the author.

Table 8: Statistical significance of energy indicators under different irrigation systems.

Variable	Statistic
Energy input	47.52***
Energy output	37.46***
Energy use efficiency	8.59***
Specific energy	3.69 (ns)
Net energy	31.67***

Note: *** p<0.01; ns >0.10.

Source: Computed by the author.

findings of (Heidari and Omid 2011; Ali *et al*., 2022). Borewell owned irrigation recorded the highest energy input because of greater labour, electricity and irrigation use. Energy use efficiency and energy productivity remained below one, while net energy return was negative because only dry chilli output was considered, excluding crop residues. Chilli residues have potential for composting, vermicomposting, mulching, biochar and biogas production (Kumar *et al*., 2025). Their utilization could improve output energy, nutrient recycling, energy efficiency and farm profitability. Future studies should quantify residue biomass to obtain a more comprehensive assessment of the energy sustainability of rainfed chilli production.

CONCULSION

The study concludes that the source of irrigation significantly influences the economic and energy performance of mundu chilli cultivation in the rainfed conditions of Ramanathapuram district. Among the irrigation systems, borewell rental irrigation was found to be economically more efficient, whereas borewell owned irrigation achieved higher productivity and gross returns due to better water availability. Human labour, nitrogen fertilizer and electricity were the major contributors to total energy input, while the low energy use efficiency and negative net energy return under all irrigation systems indicate the need for improving energy management practices. Effective utilization of chilli crop residues, which are presently discarded by most farmers, offers an opportunity to enhance resource-use efficiency, sustainability and farm profitability. The findings of this study provide useful insights for farmers and policymakers in promoting economically viable and energy-efficient irrigation practices for rainfed chilli cultivation.

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Disclaimers

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Conflict of interest

Participation in the study was voluntary and informed consent was obtained from all respondents. Confidently of the collected information was maintained. The authors declare no conflict of interest.

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