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Energy Use Efficiency and Economics of Chickpea Production: A Comparison of Integrated Crop Management and Farmers' Practices in Rajasthan

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ABSTRACT

Background: Energy analysis of agroecosystems and cropping systems is an important tool to assess environmental and soil-related challenges and their relation to sustainability. Chickpea cultivation, being energy-intensive, requires systematic evaluation in terms of energy budgeting, efficiency and productivity under different management practices.

Methods: The present study aimed to compare the economics of chickpea cultivation in terms of energy budgeting, energy efficiency and energy productivity. Data were collected through face-to-face questionnaires with farmers and crop cutting experiments were conducted each year from 2018-19 to 2022-23 by Krishi Vigyan Kendra, Sawaimadhopur. Two management practices were compared: farmers' practice and integrated crop management (ICM).

Result: The total energy requirement under ICM plots (5219.18, 5219.18, 5515.14, 5515.14 and 5221.14 MJ ha^{-1} from 2018-19 to 2022-23) was approximately 12.73%, 12.73%, 7.72%, 7.72% and 12.74% lower, respectively, than that of farmers' practice (5977.32 MJ ha^{-1}). The energy use efficiency of ICM plots was higher each year (15.78, 16.73, 15.32, 15.62 and 16.53) compared to farmers' practice (11.04, 11.99, 11.14, 12.26 and 12.30). Similarly, energy productivity in ICM plots (0.42, 0.42, 0.39, 0.39 and 0.42) was consistently greater than in farmers' practice plots (0.27, 0.30, 0.30, 0.31 and 0.31).

Key words: CFLD, Chickpea, Economics, Energy, Yield.

INTRODUCTION

Pulses, often called the "poor man's meat," are vital to India's cropping system and nutritional security. Among them, chickpea is the most important pulse crop, contributing significantly to the nation's production and income. Rajasthan is one of the leading chickpea-producing states, with Sawai Madhopur district playing a key role in regional output. However, productivity remains limited due to suboptimal management and inefficient resource use.

Cluster front line demonstrations (CFLDs) have proven effective in promoting improved technologies through farmers' participation and field-level learning. Efficient energy use in crop production is also crucial for sustainability and environmental protection. Therefore, the present study evaluated chickpea production under Integrated Crop Management (ICM) and farmers' traditional practices to assess differences in energy efficiency, productivity, profitability and benefit-cost ratio in Sawai Madhopur district of Rajasthan.

MATERIALS AND METHODS

The study was conducted across five blocks-Sawai Madhopur, Chauth Ka Barwara, Gangapur City, Khandar and Baunli-of Sawai Madhopur district under the National Food Security Mission-Pulses from *Rabi* 2018-19 *to Rabi* 2022-23 by Krishi Vigyan Kendra, Sawai Madhopur. Cluster front line demonstrations (CFLDs) were implemented on 295 farmers' fields covering 120 ha through participatory approaches. Farmers were selected through group meetings and skill training on Integrated Crop Management (ICM) practices was provided. Prior to implementation, scientists conducted PRA surveys, baseline data collection and soil sampling to assess fertility status.

The demonstrated technologies included improved varieties GNG-1958 (bold-seeded, 22.3 g seed index, 80 kg ha^{-1}) and GNG-2144 (small-seeded, 14.6 g seed

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index, 60 kg ha^{-1}). Seeds were treated with Carboxin 37.5% + Thiram 37.5% DS (1 g kg^{-1}), chlorpyrifos 20 EC (5 ml) and Rhizobium + PSB culture (5 g kg^{-1}). Soil treatment with *Trichoderma viride* (2.5 kg ha^{-1}) mixed in FYM/Vermicompost (50 kg ha^{-1}) was applied to manage wilt and soil-borne fungi. Recommended fertilizers (N:P:Zn @ 20:40:5 kg ha^{-1}) were applied at sowing. One irrigation was given at 45-50 DAS after nipping. Pod borer management included 50 bird perches ha^{-1} and Emamectin benzoate 5% SG @ 200 g ha^{-1} at ETL level. Demonstration fields were regularly monitored by KVK scientists to collect data and farmer feedback. Yield and yield parameters were recorded through crop cutting experiments at maturity.

Energy budgeting was analyzed as the ratio of output to input energy (Alam *et al*., 2005) using equivalents as given in (Table 1) for human labour, machinery, fuel, fertilizers, pesticides and seed (MJ ha^{-1}). Total dry matter (grain + straw) was considered output. Input energy was computed by multiplying each input quantity with its energy equivalent and total energy use was summed. Output energy was calculated from grain and straw yields. Based on these, net energy, energy use efficiency and energy productivity were estimated (Koocheki *et al*., 2011).

Net energy (MJ ha^{-1}) =

Energy output (MJ ha^{-1}) - Energy input (MJ ha^{-1})

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

$$\text{Energy productivity} = \frac{\text{Crops output (Kg ha}^{-1})}{\text{Energy input (MJ ha}^{-1})}$$

Indirect energy included energy embodied in seeds, chemical fertilizers (NPK), herbicides, pesticides, fungicides and machinery while direct energy covered human labor, diesel, electricity and water use in chickpea production. Non renewable energy includes diesel, electricity, chemical pesticides, chemical fertilizers and machinery and renewable energy consist of human labour, seeds and water.

Economical analysis

The economic inputs under the production of chickpea contains variable costs. The economic output of chickpea production includes grain and straw yield. All prices of input and out were market price. Gross return, net return, BC ratio were calculated as per the following equations (Bockari-Gevao *et al*., 2005; Banaeian *et al*., 2011).

Gross return (Rs ha^{-1}) =

Grain and straw yield (Kg ha^{-1}) × grain and straw price (Rs)

Net return (Rs ha^{-1}) =

Gross return (Rs ha^{-1}) - Total cost of cultivation (Rs ha^{-1})

$$\text{B:C ratio} = \frac{\text{Gross return (Rs ha}^{-1})}{\text{Total cost of cultivation (Rs ha}^{-1})}$$

All these technologies and experimental protocols which performed in a scientific manner was approved under guideline of Indian Council of Agriculture Research and package of practices and technology adopted were scientifically recommended by Agriculture University, Kota, Rajasthan, India.

RESULTS AND DISCUSSION

Cost of cultivation and output of chickpea

The cost of cultivation and output for Integrated Crop Management (ICM) and farmers' practice plots are presented in Table 2 and 3 for 2018-2022. The cost of cultivation in ICM plots was ₹27,460, ₹31,562.76, ₹33,329.61, ₹33,329.61 and ₹31,272.61 ha^{-1} during 2018-19 to 2022-23, respectively. Among the cost components, labour and machinery contributed the largest share, followed by input costs (seed, fertilizers and irrigation). Over the years, a gradual increase in total cultivation cost was observed due to higher labour wages and rising input prices. The inclusion

Table 1: Energy equivalent of inputs and outputs in production of chickpea.

Particulars	Unit	Energy equivalent (MJ unit^{-1})	Ref.
A. Inputs			
1. Human labour	MJ h^{-1}	1.96	Choudhary *et al*., 2017
2. Machinery	MJ h^{-1}	62.70	Pandiaraj *et al*., 2017
3. Diesel fuel	MJ l^{-1}	56.31	Choudhary *et al*., 2017
4. Nitrogen	MJ kg^{-1}	60.6	Oren and Ozturk, 2006
5. Phosphorus	MJ kg^{-1}	11.1	Oren and Ozturk, 2006
6. Micronutrient (Zn)	MJ kg^{-1}	8.40	Argiro *et al*., 2006
7. Water for Irrigation	MJ m^{-3}	1.02	Pandiaraj *et al*., 2017
8. Seed (Chickpea)	MJ kg^{-1}	14.7	Elhami *et al*., 2016
9. Bio-inoculants	MJ kg^{-1}	14.5	Mihov and Tringovska, 2010
10. Insecticide	MJ kg^{-1}	184.63	Paramesh *et al*., 2019
11. Fungicide	MJ kg^{-1}	97.00	Paramesh *et al*., 2019
B. Output			
1. Seed (Chickpea)	MJ kg^{-1}	14.7	Elhami *et al*., 2016
2. By product (Straw)	MJ kg^{-1}	12.50	Koocheki *et al*., 2011

of seed treatment and nipping operations slightly raised the cost in ICM plots compared to farmers' practice. In contrast, the cost of cultivation in farmers' plots was ₹23,672.5, ₹29,561.05, ₹30,781, ₹30,781 and ₹26,292 ha^{-1}, *i.e*., 16.00%, 6.76%, 8.27%, 8.27% and 18.79% lower than ICM plots, respectively. The lower cost in farmers' practice was mainly due to the absence of systematic seed and soil treatment, reduced fertilizer use and fewer intercultural operations. In fertilizer management, farmers applied only DAP at sowing, in higher quantities, without following recommended doses or using micronutrients. Zinc deficiency was common, yet awareness of micronutrient application was low, causing cost variation. Nipping, which enhances lateral branching and yield (Sanbagavalli *et al*., 2020), was performed only in ICM plots, increasing labour cost. Gram pod borer infestation at pod formation required integrated pest management (IPM). ICM plots demonstrated pheromone traps and Emamectin benzoate 5% SG @ 200 g ha^{-1}, constituting 2.1% of total cost, while farmers used the less effective Dimethoate 30 EC @ 1 L ha^{-1}.

Table 2: Impact of ICM practices on cost of cultivation and output of chickpea.

Particulars	ICM cost (Rs ha^{-1})					Remarks
	2018-19	2019-20	2020-21	2021-22	2022-23	
A. Input						
1. Inputs (Seed and other)	7476	9612	10403	10403	8865	Seed rate 80 kg ha^{-1}, Seed cost @ Rs 75 kg^{-1} Seed: Fungicide: Carboxin 37.5% + Thiram 37.5% DS (Rs 225), Insecticeide: Chloropyrifos 20 EC (Rs 400), Rhizobium + PSB culture (Rs 200) Soil: *Trichoderma viride* 2.5 kg ha^{-1} @ (Rs 375) N:P:Zn @ 20:40:5 kg ha^{-1} {DAP : Rs 2125.92, Urea : 50.69 + Zinc sulphate (mono): Rs 1275) RS 2500 per irrigation (Paleva + one irrigation at 45-50 DAS) Emamectin benzoate 5% SG @ 200 g ha^{-1}
2. Labour and machinary	19984	21950	22926	22926	22418	
						-
Total cost	27460	31562	33329	33329	31272	
B. Output						
1. Main product (Grain)	96650	106080	105105	113072	113595	2210 kg ha^{-1} (@ 48.75 Rs kg^{-1})
2. By product (Straw)	4130	4425	4223	4350	4350	4223 kg ha^{-1} (@ 1.0 Rs kg^{-1})
3. Green leaves (Nipping)	200	300	300	300	300	50 kg ha^{-1} (@ 6.0 Rs kg^{-1})
Total cost	100980	110805	109628	117722	118245	

Impact of integrated crop management practices on total energy input, output, net energy, energy use efficiency and employment generation

Data presented in Table 4 and 5 revealed that the consistent reduction (7.7-12.7%) in total energy input under Integrated Crop Management (ICM) compared to farmers' practice (FP) reflects a more resource-efficient production system. This reduction mainly resulted from optimized fertilizer and fuel use, demonstrating that ICM practices align with the principles of sustainable intensification-producing more with fewer external inputs. A balanced contribution of major energy-consuming inputs such as diesel (31.56%), nitrogen (23.22%) and seed (16.90%) under ICM indicates a rational distribution of energy sources, enhancing input-use efficiency and reducing environmental pressure through lower fossil fuel dependency.

Higher total and net energy outputs under ICM across all five years (2018-2023) signify greater energy conversion efficiency and ecological sustainability. Total and net energy outputs were markedly higher in ICM plots throughout 2018-19 to 2022-23, confirming greater overall energy gains and sustainability compared to FP. Energy use efficiency values were also superior under ICM (15.72-16.43) than FP (11.20-12.19), indicating better conversion of inputs into productive outputs. Similarly, energy productivity in ICM (0.39-0.41) exceeded FP (0.27-0.31), showing higher energy returns per unit of input. According to Kumbhar *et al*. (2025) the energy parameters under nutrient management and a sowing spacing of 30 × 10 cm recorded higher energy use efficiency and energy productivity compared to the farmers' practice of sowing behind the plough. These results are in close agreement with previous findings and confirm that the adoption of integrated crop management (ICM) practices enhances overall energy indices. From a sustainability perspective, ICM contributes simultaneously to economic, environmental and social goals. Environmentally, lower fossil

energy input and improved nutrient balance reduce carbon emissions and enhance soil health. Economically, higher energy output and net returns improve farm profitability.

Employment generation was greater in ICM (35 man days ha^{-1}) than FP (26 mandays ha^{-1}) due to additional labour requirements for operations such as nipping and seed treatment. The energy consumption pattern in FP followed the order: diesel > nitrogen > seed > machinery > phosphorus > irrigation water > insecticide > human labour > fungicide > micronutrients. In contrast, ICM achieved better optimization of resources with minimal wastage and higher output energy. The improved energy efficiency, productivity and net energy balance under ICM indicate better resource utilization and sustainability.

Overall, the findings demonstrate that ICM practices improved energy efficiency, energy productivity and net energy balance while creating more rural employment opportunities. Similar trends have been reported by Jakhar *et al.* (2025); Singh *et al*. (2023); Babu *et al*. (2023); Gupta *et al*. (2023); Patel *et al*. (2023); Mishra *et al*. (2022); Rai *et al.* (2022) and Kumar *et al*. (2021, 2022); Singh *et al*. (2020); Yadav *et al*. (2023).

Comparison of integrated crop management practices and farmers practices for total energy, net energy, energy use efficiency and energy productivity over five years using paired t-test (α = 5%)

A comparative study using SPSS software (Table 6) analyzed energy metrics from 2018 to 2022, revealing significant differences between Integrated Crop Management (ICM) and Farmers' practices (FP). Total energy for ICM increased from 82,067.16 MJ ha^{-1} (2018) to 85,789.44 MJ ha^{-1} (2022), while FP rose from 66,987.12 to 72,915.40 MJ ha^{-1}, with all years showing significant *t*-values (2018: 76.903; 2019: 6.117; 2020: 23.990; 2021: 9.924; 2022: 41.895). The difference trend is depicted in Fig 1.

Net energy followed a similar pattern, increasing in ICM from 76,847.98 to 80,568.27 MJ ha^{-1} and in FP from 61,009.80 to 66,938.40 MJ ha^{-1}, with significant *t*-values (2018: 80.770; 2019: 6.475; 2020: 24.685; 2021: 10.275; 2022: 44.354). Fig 2 illustrates this rising trend for ICM plots.

Energy use efficiency in ICM was higher (15.72-16.43) than FP (11.21-12.20), showing significant variation (2018: 128.910; 2019: 10.440; 2020: 32.800; 2021: 15.299; 2022: 80.569). Likewise, energy productivity was greater in ICM (0.40-0.42) than FP (0.27-0.31) with significant *t*-values (2018: 59.383; 2019: 22.337; 2020: 21.173; 2021: 6.124; 2022: 46.944), as shown in Fig 3.

Overall, the study confirms the superior efficiency of ICM over conventional methods in optimizing energy use. These findings align with those of Yadav *et al*. (2024); Singh *et al*. (2023); Kumar *et al.* (2022); Pawar *et al*. (2021); Meena *et al*. (2022); Bamboriya *et al.* (2023) and Nath *et al.* (2020).

Practical recommendations

The present findings suggest that Integrated Crop Management (ICM) practices should be promoted among

Table 3: Impact of farmers practices on cost of cultivation and output of chickpea.

Particulars	FP cost (Rs ha^{-1})					Remarks
	2018-19	2019-20	2020-21	2021-22	2022-23	
A. Particulars						N:P @ 18:46 kg ha^{-1} (DAP Rs 1956)
1. Inputs (Seed and other)	7822	11125	14956	14956	9456	Fertilizer Application Charges (1 Man days)
2. Labour and machinary	15850	18436	15825	15825	16836	RS 2500 per irrigation (Paleva + one irrigation at
Total cost	23672	29561	30781	30781	26292	30-40 DAS) Dimethoate 30 EC @ 1 Litr ha^{-1}
B. Output						
1. Main product (Grain)	76629.4	86190	86775	96964	97957	1905 kg ha^{-1} (@ 48.75 Rs kg^{-1})
2. By product (Straw)	3353	3652	3235	3680	3680	3235 kg ha^{-1} (@ 1.0 Rs kg^{-1})
3. Green leaves (Nipping)	0	0	0	0	0	00
Total cost	79982.4	89842	90010	100644	101637	

Table 4: Impact of integrated crop management practices on total energy input, output, net energy, energy use efficiency and employment generation.

Particulars	ICM									
	Quantity per unit area (ha)					Total energy equivalent (MJ ha^{-1})				
	2018-19	2019-20	2020-21	2021-22	2022-23	2018-19	2019-20	2020-21	2021-22	2022-23
A. Inputs										
1. Human labour	34.00	34.00	35.00	35.00	35.00	66.64 (1.28)	66.64 (1.28)	68.6 (1.24)	68.6 (1.24)	68.6 (1.31)
2. Machinery	9.75	9.75	9.75	9.75	9.75	611.33 (11.71)	611.33 (11.71)	611.33 (11.08)	611.33 (11.08)	611.33 (11.71)
3. Diesel	29.25	29.25	29.25	29.25	29.25	1647.07 (31.56)	1647.07 (31.56)	1647.07 (29.86)	1647.07 (29.86)	1647.07 (31.55)
4. Nitrogen (N)	20.00	20.00	20.00	20.00	20.00	1212 (23.22)	1212 (23.22)	1212 (21.98)	1212 (21.98)	1212 (23.21)
5. Phosphous (P)	40.00	40.00	40.00	40.00	40.00	444 (8.51)	444 (8.51)	444 (8.05)	444 (8.05)	444 (8.5)
6. Micronutrient (Zn)	5.00	5.00	5.00	5.00	5.00	42 (0.8)	42 (0.8)	42 (0.76)	42 (0.76)	42 (0.8)
7. Water for irrigation	120.00	120.00	120.00	120.00	120.00	122.4 (2.35)	122.4 (2.35)	122.4 (2.22)	122.4 (2.22)	122.4 (2.34)
8. Seed	60.00	60.00	80.00	80.00	60.00	882 (16.9)	882 (16.9)	1176 (21.32)	1176 (21.32)	882 (16.89)
9. Bio-inoculants	3.30	3.30	3.30	3.30	3.30	3.37 (0.06)	3.37 (0.06)	3.37 (0.06)	3.37 (0.06)	3.37 (0.06)
10. Insecticide	0.60	0.60	0.60	0.60	0.60	110.78 (2.12)	110.78 (2.12)	110.78 (2.01)	110.78 (2.01)	110.78 (2.12)
11. Fungicide	0.80	0.80	0.80	0.80	0.80	77.6 (1.49)	77.6 (1.49)	77.6 (1.41)	77.6 (1.41)	77.6 (1.49)
Total			-			5219.18	5219.18	5515.14	5515.14	5221.14
B. Output										
1. Seed (Chickpea)	2092.00	2176.00	2156.00	2162.00	2171.00	30764	31987	31667	31793	31914
2. By product (Straw)	4140.00	4196.28	4230.47	4310.00	4310.00	51303	52453	52880	52875	53875
Total			-			82067	84440	84584	85668	85789
Net energy (MJ ha^{-1})			-			76847	79221	79033	80153	80568
Energy use efficicency			-			15.72	16.17	15.33	15.53	16.43
Employment (Mandays ha^{-1})			-			35.00	35.00	35.00	35.00	35.00
Energy productivity						0.40	0.41	0.39	0.39	0.41

Table 5: Impact of farmers practices on total energy input, output, net energy, energy use efficiency and employment generation.

Particulars	Farmers practice									
	Quantity per unit area (ha)					Total energy equivalent (MJ ha^{-1})				
	2018-19	2019-20	2020-21	2021-22	2022-23	2018-19	2019-20	2020-21	2021-22	2022-23
A. Inputs										
1. Human labour	26.00	26.00	26.00	26.00	26.00	50.96 (0.85)	50.96 (0.85)	50.96 (0.85)	50.96 (0.85)	50.96 (0.85)
2. Machinery	11.00	11.00	11.00	11.00	11.00	689.7 (11.54)	689.7 (11.54)	689.7 (11.54)	689.7 (11.54)	689.7 (11.54)
3. Diesel	33.00	33.00	33.00	33.00	33.00	1858.23 (31.09)	1858.23 (31.09)	1858.23 (31.09)	1858.23 (31.09)	1858.23 (31.09)
4. Nitrogen (N)	18.00	18.00	18.00	18.00	18.00	1090.8 (18.25)	1090.8 (18.25)	1090.8 (18.25)	1090.8 (18.25)	1090.8 (18.25)
5. Phosphous (P)	46.00	46.00	46.00	46.00	46.00	510.6 (8.54)	510.6 (8.54)	510.6 (8.54)	510.6 (8.54)	510.6 (8.54)
6. Micronutrient (Zn)	0.00	0.00	0.00	0.00	0.00	0 (0)	0 (0)	0 (0)	0(0)	0 (0)
7. Water for irrigation	120.00	120.00	120.00	120.00	120.00	122.4 (2.05)	122.4 (2.05)	122.4 (2.05)	122.4 (2.05)	122.4 (2.05)
8. Seed	100.00	100.00	100.00	100.00	100.00	1470 (24.59)	1470 (24.59)	1470 (24.59)	1470 (24.59)	1470 (24.59)
9. Bio-inoculants	0.00	0.00	0.00	0.00	0.00	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
10. Insecticide	1.00	1.00	1.00	1.00	1.00	184.63 (3.09)	184.63 (3.09)	184.63 (3.09)	184.63 (3.09)	184.63 (3.09)
11. Fungicide	0.00	0.00	0.00	0.00	0.00	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Total						5977.32	5977.32	5977.32	5977.32	5977.32
B. Output										
1. Seed (Chickpea)	1637.00	1768.00	1780.00	1854.00	1873.00	30764.16	25989.60	26083.99	27255.27	27542.90
2. By product (Straw)	3433.15	3637.64	3404.64	3629.80	3629.80	42914.16	45470.50	42553.40	45372.50	45372.50
Total						66987	71460	68637	72627	72915
Net energy (MJ ha^{-1})						61009	65482	62660	66650	66938
Energy use efficicency						11.20	11.95	11.48	12.15	12.19
Employment (Mandays ha^{-1})						26.00	26.00	26.00	26.00	26.00
Energy productivity						0.27	0.30	0.30	0.31	0.31

Table 6: Comparison of integrated crop management practices and farmers practices for total energy, net energy, over five years using paired t-Test (α = 5%).

Characters	Years	Demo (Mean)	Local (Mean)	t value	Significance
Total energy	2018	82067.16	66987.12	76.903	Significant
	2019	84440.7	71460.1	6.117	Significant
	2020	84548.59	68637.28	23.99	Significant
	2021	85668.9	72627.77	9.924	Significant
	2022	85789.44	72915.4	41.895	Significant
Net energy	2018	76847.98	61009.8	80.77	Significant
	2019	79221.52	65482.78	6.475	Significant
	2020	79033.59	62660.28	24.685	Significant
	2021	80153.9	66650.77	10.275	Significant
	2022	80568.27	66938.4	44.354	Significant
Energy use efficiency	2018	15.72	11.21	128.91	Significant
	2019	16.18	11.96	10.44	Significant
	2020	15.33	11.48	32.8	Significant
	2021	15.53	12.15	15.299	Significant
	2022	16.43	12.20	80.569	Significant
Energy productivity	2018	0.40	0.27	59.383	Significant
	2019	0.42	0.30	22.337	Significant
	2020	0.39	0.30	21.173	Significant
	2021	0.39	0.31	6.124	Significant
	2022	0.42	0.31	46.944	Significant

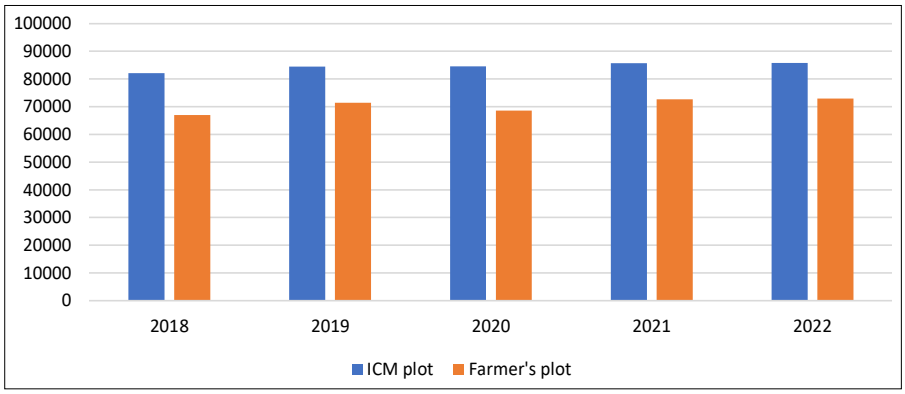


Fig 1: Comparative analysis of ICM plots and farmers practices in terms of total energy (MJ ha^{-1}).

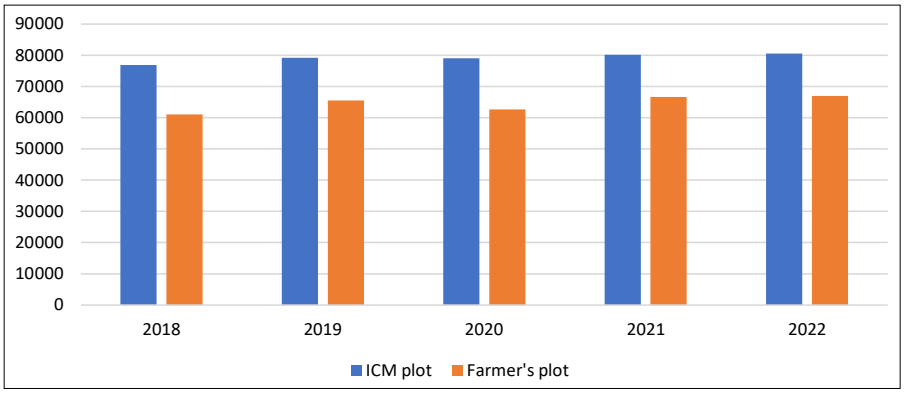


Fig 2: Comparative analysis of ICM plots and farmers practices in terms of net energy (MJ ha^{-1}).

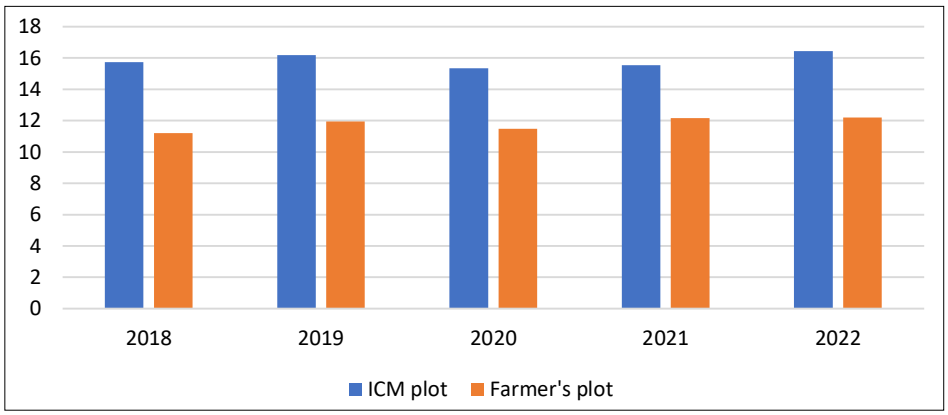


Fig 3: Comparative analysis of ICM plots and farmers practices in terms of energy use efficiency.

farmers as an energy-efficient and sustainable production approach. Farmers are advised to adopt balanced nutrient management, precise fertilizer application and optimum crop geometry (30 × 10 cm spacing) to enhance energy productivity and profitability. Extension workers should emphasize capacity-building programs and on-farm demonstrations to improve awareness of input optimization and labour management. Policymakers should incentivize the adoption of ICM through subsidies on energy-efficient equipment, soil health cards and training initiatives, particularly in semi-arid regions. These interventions will help reduce production costs, minimize environmental impact and enhance rural employment opportunities while ensuring long-term agricultural sustainability.

CONCLUSION

The findings of this study underscore the significant advantages of Integrated Crop Management (ICM) practices over traditional Farmers' Practices (FP) in terms of energy metrics from 2018 to 2022. The analysis demonstrated that ICM not only utilizes total energy more efficiently but also results in higher net energy outputs, increased energy use efficiency and enhanced energy productivity. The consistent superiority of ICM practices, highlighted by significant t-values across all measured parameters, indicates their effectiveness in optimizing resource use in agricultural production. As agriculture faces increasing challenges related to sustainability and resource management, the adoption of ICM practices emerges as a viable strategy to enhance productivity while minimizing environmental impacts. These results advocate for the broader implementation of ICM in farming systems to improve overall agricultural performance and contribute to sustainable agricultural practices.

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Authors' contributions

Nupur Sharma: Conceptualized the study, conducted the literature review and led the data analysis, designed the methodology, performed the experiments and contributed to the interpretation of results, writing original draft. Bhanwar Lal Dhaka: Designed the methodology, formal analysis, data curation. Bharat Lal Meena: Assisted in data collection. Ankita Ankita: Statistical analysis, graphs and table formations, review draft and data curation. All authors reviewed and approved the final version of the manuscript for submission. Each author agrees to be accountable for all aspects of the work.

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Ethical statement

This research did not involve any studies with human participants or animals performed by the authors. All necessary institutional approvals for conducting field experiments were obtained from the Agriculture University, Kota and the trials were carried out in accordance with standard agronomic and ethical research practices.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article. No external funding

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