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Enhancing farm productivity, sustainability, and resilience through farmer participatory integrated farming systems in the arid regions of western Rajasthan

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ABSTRACT

A study was carried out during 2021 and 2023 at four villages in Jodhpur, Rajasthan under the ICAR-Farmer FIRST project to assess the productivity, resilience, and sustainability of Integrated Farming Systems (IFS) under rainfed and irrigated conditions in the arid region of western Rajasthan. The study evaluated 15 IFS models (seven rainfed, eight irrigated), of 2.0 ha each. The findings revealed the greater performance of irrigated IFS, which achieved a mean pearl millet (*Paspalum scrobiculatum* L.) equivalent yield (PEY) of 20,662 kg compared to 7,049 kg in rainfed systems. Enhanced productivity in irrigated IFS was attributed to the inclusion of high-value cash crops such as cumin and onion, alongside innovative components like azolla cultivation and vermicomposting. Economic analysis demonstrated a higher benefit-cost (B:C) ratio for irrigated IFS (3.10) compared to rainfed IFS (2.13), highlighting the economic advantages of resource integration and diversification. Irrigated IFS also exhibited enhanced resource recycling, with significant contributions from crop stover, farmyard manure, and mushroom spent residue. Employment generation was notably higher in IFS systems, providing 271 man-days annually compared to 160 in rainfed IFS systems. Although IFS systems exhibited resilience through resource conservation and stable livestock contributions, their productivity remained constrained by climatic variability. The study highlights the transformative potential of participatory IFS models in optimizing resource use, enhancing farm sustainability and improving livelihoods in resource-scarce arid regions.

Keywords: Arid agriculture, Participatory research, Pearl millet equivalent yield, Resource recycling, Sustainability livelihood index

Arid climate of western Rajasthan, with annual rainfall ranging between 100–400 mm, makes agriculture highly dependent on rainfall and vulnerable to droughts. The sandy soils of the region have low organic matter, leading to poor water retention and fertility. Overexploitation of groundwater has further exacerbated water scarcity, necessitating sustainable agricultural practices that enhance productivity while conserving resources (Kar 2014, Rathore *et al*. 2019).

Integrated Farming Systems (IFS) have emerged as a viable strategy to address these challenges by improving resource use efficiency, productivity, and farm income through diversification and enterprise integration. IFS synergistically combine crops, livestock, horticulture, and agroforestry, optimizing resource use, reducing external input dependence, and enhancing resilience to climatic and economic uncertainties. In arid and semi-arid regions, IFS improves soil fertility, increase water use efficiency, and provide multiple income sources, contributing to long-term agricultural sustainability (Kumar *et al*. 2021).

Participatory research approaches play a crucial role in ensuring the effective implementation of agricultural technologies; by directly involving farmers in the research process. This collaborative methodology strengthens the relevance of agricultural interventions, leading to higher adoption rates and sustainable impacts. In IFS, participatory research fosters the integration of traditional knowledge with scientific advancements, creating resilient and sustainable farming systems (Sharma 2017). Integrating arable crops with horticultural components such as ber (*Ziziphus mauritiana*) has shown higher profitability than sole cropping systems in Bikaner, Rajasthan (Rathore *et al*. 2019). Similarly, incorporating livestock into farming enhance resource use efficiency and generates additional income, securing livelihoods in semi-arid areas (Kumar *et al*. 2021). Participatory approaches have also been instrumental in the dissemination of agricultural innovations.

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Despite these benefits, limited research has assessed the performance of IFS models under farmer-managed conditions, particularly comparing rainfed and irrigated systems. Addressing this gap is crucial for developing scalable and adaptable IFS models for diverse agro-ecological settings. This study aims to evaluate 15 IFS models over three years in western Rajasthan, ensuring active farmer participation to develop context-specific, resilient farming solutions.

MATERIALS AND METHODS

The present study was carried out during 2021 to 2023 at ICAR-Central Arid Zone Research Institute, Jodhpur, Rajasthan under the ICAR-Farmer FIRST Project across two villages in the Keru block of Jodhpur, Rajasthan. The objective was to compare rainfed and irrigated IFS models, with conventional cropping systems of pearl millet-fallow (rainfed) and pearl millet-cumin (irrigated) as controls. The study region falls under the IA-agro-climatic zone of the arid western plains of Rajasthan, characterized by sandy loam soils with low organic carbon and alkaline *p*H. The annual rainfall ranges from 200–370 mm, 70–80% of which occurs between July and September, while the mean annual maximum and minimum temperatures are 40°C and 8°C, respectively. The experiment compared seven rainfed and eight partially irrigated IFS model, each covering a 2.0 ha area. The IFS modules included multiple components with integration of improved technologies for different components (Table 1). The management of component crops in a cropping systems mode and other allied activities were done as per the standard recommended practices.

The high yielding, drought tolerant varieties of field crops, onion and ber were provided as per farmer preference and adaptation to prevailing agro-climatic conditions. To supplement minerals, vitamins, and protein for lactating animals, 2.0 kg of a multi-nutrient feed block (Jat *et al.* 2024) was provided weekly to each animal. The feed block was offered through free licking during stall-feeding sessions. Mushroom cultivation was carried out in a cool, shaded, and dark room with adequate ventilation. A batch of 30 bags of wheat straw mushroom (*Pleurotus sajar-caju*) was raised during the winter months from December–February. After harvesting, the spent mushroom substrate was effectively recycled into compost, promoting efficient resource utilization. For composting, vermicomposting beds made of 450 GSM HDPE UV-stabilized material, measuring 8 ft × 4 ft × 2 ft, were installed under a shaded, cool thatched structure. Worms of *Eisenia fetida* were introduced into these beds, and three batches of vermicompost were successfully produced annually. The prepared vermicompost was applied to vegetable and fruit crops, enhancing soil fertility and productivity. Additionally, an HDPE Azolla bed (10 ft × 4 ft × 1.5 ft, 370 GSM) was set up for year-round azolla cultivation, except during extreme temperature months. Azolla served as a nutrient-rich feed for livestock, complementing other feeding practices. An improved low-cost animal feed solar cooker, designed and developed at ICAR-Central Arid Zone Research Institute, Jodhpur, Rajasthan was introduced and evaluated. This innovative cooker, based on the concept of a non-tracking solar system with a length-to-width ratio exceeding 3:1, was utilized for preparing animal feed concentrates efficiently (Poonia *et al*. 2023).

Data on productivity, economics, and employment generation were recorded for each component annually. Productivity of arable crops was measured in terms of seed yield and fodder yield, except cumin and mustard of which only seed yield was taken as economic produce. For horticultural crops, ber fruit yield and bulb yield of onion were recorded. Livestock performance was evaluated based on milk yield and manure output. Mushroom yield was quantified in terms of fresh weight and vermicompost yield was accounted based on the finished material.

The performance of the animal feed solar cooker was assessed based on the annual monetary savings from reduced firewood consumption, the time saved in boiling animal feed. The monetary savings of cooking animal feed was added into the gross returns of the IFS model. The stover of pearl millet, cluster bean, mung bean and wheat were made available for livestock. Onion leaves after harvest, mushroom spent substrates and other organic waste of farm with cow dung were utilized for compost making. The FYM prepared from the surplus cow dung was used as manure in the arable crops of *kharif*.

Since diversified enterprises were taken for study, the farming systems were analyzed by quantifying productivity and income in terms of system equivalent yield expressed in pearl millet:

Pearl millet equivalent yield (PEY) = (Yield of an enterprise × Market price of produce)/Market price of pearl millet.

Economics of production of each of the enterprises was calculated by keeping a record on number of laborers engaged and input utilized. The cost of inputs and the price of produce at prevailing market rates were considered for working out the cost of cultivation, returns, and B:C ratio. Gross return included all products and byproducts generated on farm including family consumption and recycling. Net returns were obtained by subtracting the cost of cultivation from the gross return for each component. The B:C ratio was calculated as ratio of gross return to the cost of cultivation.

The production data of different components of the respective IFS models for three consecutive years were averaged under respective parameter. The conventional farming system, viz. pearl millet-fallow for rainfed and pearl millet-cumin for partially irrigated was considered as a control to compare with the performance of rainfed and irrigated IFS models. Employment generation was measured in terms of person-days of labour created for each component. For assessing the livelihood from the farming systems the Sustainable Livelihood Index (SLI) was calculated as per Shyam *et al*. (2023). To measures the degree of income diversification among different income sources in a farming system, income diversification index

Table 1 Enterprises and technology integration for rainfed IFS model and irrigated

Enterprise	Component	Area (ha)/unit	Rainfed	Irrigated	Improved technology
Arable crops	Pearl millet	0.8	✓	✓	cv. MPMH-17
	Mung bean	0.4	✓	✓	cv. IPM 205-7, MH-421
	Cluster bean	0.4	✓	✓	cv. RGC-1066, RGC-1055
	Cumin	0.4		✓	cv. GC-4
	Wheat	0.4		✓	cv. GW-11
	Mustard	0.4		✓	cv. NRCHB-101
Horticulture	Onion	0.4		✓	NHRDF Red-4
	*Ber	40 plants		✓	cv. Gola
Dairy	Livestock (1)		✓	✓	Multi-nutrient feed blocks and Azolla
Ancillary enterprises	Mushroom unit (1)		✓	✓	*Pleurotus sajor-caju*
	Compost (1)	0.4		✓	Vermicompost (*Eisenia fetida)*
	Animal feed solar cooker (1)		✓	✓	-
	Total	2.0			

*Area covered under pulses grown intercropped with ber

(IDI) was calculated through Simpson's Diversity Index as per Nayak *et al*. (2024).

RESULTS AND DISCUSSION

The baseline survey of Baroo and Dediapada villages in Jodhpur, Rajasthan, revealed that 79% of households are primarily engaged in farming. Approximately 80% of the total geographical area is net sown; however, only 14% of this area is irrigated, highlighting significant water resource limitations. Borewells contribute to 97% of the irrigation, with flood irrigation used on 62% of the gross irrigated area, indicating the need for improved irrigation efficiency. Livestock plays a vital role in the farming systems, with 59% of households owning buffalos and 77% owning at least one milch cow. Despite these resources, poor soil fertility, low water holding capacity, and salinity are critical challenges affecting agricultural productivity. The lack of mechanization, limited cold storage facilities, and unavailability of quality inputs further hinder farm profitability. To address these challenges, farming priorities of the region include water harvesting, diversification of farming systems, value addition to farm produce, and capacity building for stakeholders, IFS present a sustainable solution, emphasizing resource optimization and productivity enhancement.

Productivity of different components: The analysis of rainfed and irrigated IFS presented in Table 2 highlights significant trends in productivity and resilience under varying resource conditions. In rainfed IFS, pearl millet seed yields ranged from 865 kg in 2022–23 to 916 kg in 2023–24, with fodder yields increasing from 1663–1833 kg. These results reflect the adaptability of improved cultivars under favourable climatic conditions. However, the complete crop failure during *kharif* 2021 due to severe drought underscores the vulnerability of rainfed systems to climatic extremes, consistent with findings by Rao *et al*. (2016). In irrigated IFS, pearl millet seed yields remained stable at 840–890 kg, with corresponding fodder yields of 1,584–1,762 kg, highlighting the role of irrigation in mitigating climate-induced stress, as also reported by Patel *et al*. (2019).

Leguminous crops such as mung bean and cluster bean performed consistently in both systems. In rainfed IFS, mung bean yielded 286–326 kg, while cluster bean achieved 317–356 kg, with notable increases in fodder yields. In irrigated IFS, mung bean yielded 278–317 kg, and cluster bean achieved 308–345 kg, benefiting from reduced moisture stress. The economic advantage of irrigated IFS is evident in the performance of high-value cash crops. Wheat yields ranged from 1306 kg in 2021–22 to 1,411 kg in 2023–24. Cumin yields increased slightly from 214 –224 kg, while mustard yields declined marginally from 926 to 845 kg, possibly due to management challenges. Onion, a high-value crop, exhibited remarkable productivity, peaking at 10,864 kg in 2021–22.

Horticultural and livestock components further reinforced the superior performance of irrigated IFS. Ber fruit yields ranged from 55 to 72 kg/plant, while livestock productivity, measured through milk yields, remained stable across systems, ranging from 1,511–1,584 litre/year. Supplementary enterprises played a pivotal role in resource recycling and sustainability, especially in irrigated systems. Azolla production increased from 194 kg in 2021–22 to 238 kg in 2023–24, demonstrating its utility as a sustainable feed. Compost production ranged from 1.45–1.52 t/year, reflecting efficient utilization of organic residues, while mushroom yields remained stable. These trends underscore the productivity advantages of irrigated IFS due to reliable water availability, crop diversity, and resource integration. However, rainfed systems, despite lower yields, contribute to sustainability through resource conservation and reduced

Table 2 Component-wise yield of rainfed and irrigated IFS across different years

Component yield	Rainfed IFS				Irrigated IFS					
	2022–23		2023–24		2021–22		2022–23		2023–24	
	Seed/Veg./ Fruit/Milk etc.	Fodder	Seed/Veg./ Fruit/Milk etc.	Fodder	Seed/Veg./ Fruit/Milk etc.	Fodder	Seed/Veg./ Fruit/Milk etc.	Fodder	Seed/Veg./ Fruit/Milk etc.	Fodder
Pearl millet (kg)	865	1,663	916	1833	747	1,336	840	1,584	890	1,762
Mung bean (kg)	286	769	326	835	242	652	278	732	317	803
Cluster bean (kg)	317	651	356	773	223	459.2	308	620	345	743
Wheat (kg)	-	-	-	-	1,365	1962	1,306	1,929	1,411	2,005
Cumin (kg)	-	-	-	-	214	-	203	-	224	-
Mustard (kg)	-	-	-	-	926	-	872	-	845	-
Onion (kg)	-	-	-	-	10,864	-	9,780	-	10,232	-
*Ber (kg/plant)	-	-	-	-	55	-	68	-	72	-
Livestock (litre/year)	1,574	-	1,511	-	1,561	-	1,584	-	1,498	-
Azolla (kg/year)	0	-	0	-	-	194	0	218	0	238
Mushroom (kg/season)	13	-	12	-	14	-	13	-	11	-
Compost (t/year)	-	-		-	1.45	-	1.52	-	1.48	-

Crop failure occurred in rainfed IFS during *kharif* 2021 due to severe drought.
*Intercropped with mung bean

external input dependency. Strengthening rainfed IFS with drought-resilient crops, water harvesting, and integrated resource management can bridge productivity gaps and enhance resilience, as suggested by Patel *et al*. (2019).

Economic analysis of farming systems: The comparative economic performance of rainfed and irrigated IFS revealed notable disparities in profitability and income stability across enterprises, emphasizing the transformative role of irrigation and diversification in enhancing farm incomes and resilience (Table 3.). Arable crops were the primary income source in both systems but differed significantly in profitability. In rainfed IFS, they contributed 58.7% of income with a B:C ratio of 2.40 and net returns of ₹47,535, alongside good income stability (CV = 9.03%). However, climatic variability and limited resources constrained returns. In contrast, irrigated IFS achieved higher net returns of ₹1,41,885, a B:C ratio of 2.60, and better stability (CV = 4.85%), demonstrating the role of irrigation in stabilizing productivity and profitability (Patel *et al*. 2019).

Horticulture, exclusive to irrigated IFS, emerged as the most profitable enterprise, contributing 48.7% of income with net returns of ₹1,72,044 and a B:C ratio of 5.33. Nevertheless, higher income variability (CV=11.58%) highlighted challenges related to input dependency and market volatility. Livestock was a stable income source in both systems, with net returns of ₹31,202 in rainfed IFS and ₹30,650 in irrigated IFS. High income stability (CV = 3.02% and 2.46%, respectively) underscores livestock's critical role in ensuring economic resilience, as noted by Walia *et al*. (2019).

Irrigated IFS also included innovative supplementary enterprises such as azolla (B:C ratio 7.48, net returns ₹1,877) and compost production (B:C ratio 2.97, net returns ₹4,917), which enhanced resource recycling and economic returns. Mushroom cultivation, present in both systems, showed slightly higher profitability in irrigated IFS (net returns ₹1,160, B:C ratio 2.55) compared to rainfed IFS (net returns ₹1,095, B:C ratio 2.46). The total economic performance of irrigated IFS (gross returns ₹5,22,279, net returns ₹3,53,633, B:C ratio 3.10) significantly outperformed rainfed IFS (gross returns ₹1,52,505, net returns ₹80,932, B:C ratio 2.13). While irrigated IFS demonstrated higher profitability, the resilience and sustainability of rainfed IFS through resource efficiency and stable income components like livestock highlight its importance in resource-scarce regions (Singh *et al*. 2020).

In terms of income share, in rainfed IFS arable crops contribute the highest share (58.7%) to income, followed by livestock (38.6%) and mushroom (1.35%). In irrigated IFS, horticulture dominates (48.7%), followed by arable crops (40.1%), livestock (8.7%), and smaller contributions from azolla (0.53%), compost (1.39%) and others (Fig 1.). These results indicate that the higher income share from diversified components in irrigated IFS highlights the role of resource availability in improving farm profitability and stability.

System productivity: The system productivity of various farming systems, expressed as Pearl millet Equivalent Yield (PEY), reflects the influence of cropping practices, resource availability, and diversification (Fig. 2). The pearl millet–fallow system recorded the lowest PEY (3853 kg), highlighting the inefficiencies of monocropping in rainfed conditions, as noted by Kingra and Kaur (2017). In contrast, the pearl millet-cumin system under irrigation achieved a significantly higher PEY (19,798 kg), benefiting

Table 3 Comparative economics of rainfed and irrigated IFS (average over the years)

Enterprise	Rainfed IFS					Irrigated IFS				
	Total cost (₹)	Gross return (₹)	Net return (₹)	B:C ratio	Income stability (CV%)	Total cost (₹)	Gross returns (₹)	Net returns (₹)	B:C ratio	Income stability (CV%)
Arable crops	34,073	81,608	47,535	2.40	9.03	88,665	2,30,550	1,41,885	2.60	4.85
Horticulture						39,692	2,11,736	1,72,044	5.33	11.58
Livestock	35,850	67,052	31,202	1.87	3.02	35,850	66,500	30,650	1.85	2.46
Azolla						290	2,167	1,877	7.48	8.06
Mushroom	750	1,845	1,095	2.46	6.85	750	1,910	1,160	2.55	9.22
Compost						2,500	7,417	4,917	2.97	2.92
Animal feed cooker	900	2,000	1,100	2.22	0.00	900	2,000	1,100	2.22	0.0
Total	71,573	1,52,505	80,932	2.13		1,68,646	5,22,279	3,53,633	3.10	

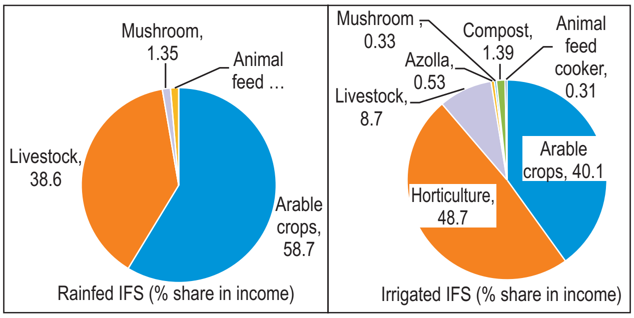

Fig. 1 Income shares of different components in rainfed and irrigated IFS.

from cumin's high market value. The rainfed IFS yielded 7,049 kg, demonstrating the benefits of diversification, though constrained by water availability, consistent with Patel *et al*. (2019). The irrigated IFS had the highest PEY (20,662 kg) due to year-round cropping and resource optimization, aligning with Din *et al*. (2019). These findings emphasize the role of irrigation and diversification in enhancing productivity. Strengthening rainfed systems with drought-resilient crops, improved water management, and resource recycling, as suggested by Kingra and Kaur (2017), can enhance sustainability.

Sustainability indices: The comparative evaluation of employment generation, income diversification, and the Sustainable Livelihood Index (SLI) across various farming systems underscores the benefits of diversification and resource integration, particularly within IFS (Supplementary Table 1). The pearl millet-fallow system exhibited the lowest performance, generating only 90 man-days of employment annually. This lack of diversification resulted in an Income Diversification Index (IDI) of 0.00 and the lowest SLI (0.102), indicating significant economic vulnerability. In contrast, the pearl millet-cumin system under irrigated conditions showed improvements, with employment generation increasing to 150 man-days annually. The inclusion of cumin, a high-value cash crop, elevated the IDI to 0.424 and improved the SLI to 0.218. This supports studies emphasizing that high-value crops can enhance income and stability under irrigated conditions.

Rainfed IFS further increased employment generation to 160 man-days per annum due to diversified cropping and livestock integration. The IDI rose to 0.506, reflecting enhanced income sources; however, the SLI remained at 0.218, highlighting challenges posed by climatic variability and resource limitations. This aligns with findings that, despite sustainability constraints, diversification in rainfed systems offers resilience benefits (Kumar *et al.* 2022). Notably, irrigated IFS outperformed all farming systems, generating 271 man-days annually, with the highest IDI (0.594) and SLI (0.929). The integration of high-value crops, horticulture, and supplementary enterprises (e.g. azolla cultivation, compost production) demonstrated its transformative potential. These results corroborate studies highlighting the role of irrigation and diversification in enhancing sustainability (Panwar and Ravisankar 2022). While irrigated systems excel in economic and sustainability parameters, it is crucial to strengthen rainfed systems through targeted interventions, such as drought-resilient crops and efficient water management strategies, to mitigate inherent vulnerabilities.

Resource recycling: The analysis of resource recycling in IFS under rainfed and irrigated conditions revealed distinct differences influenced by system diversification and biomass productivity. Crop stover recycling was significantly

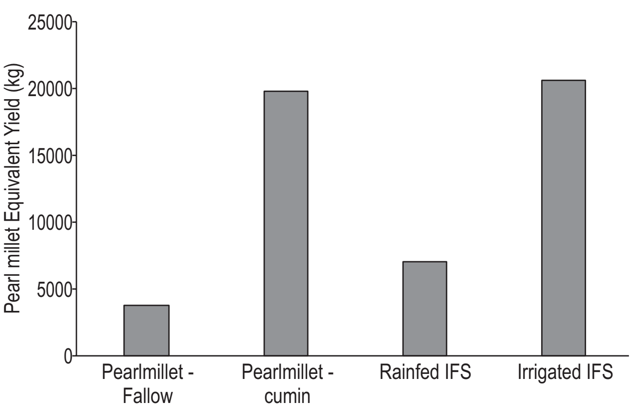

Fig. 2 System productivity in terms of Pearl millet Equivalent Yield of different farming systems.

higher in irrigated IFS, with a mean rate of 5089 kg/year compared to 3262 kg/year in rainfed IFS. This aligns with the findings of Patel *et al*. (2019), indicating that greater biomass productivity in irrigated systems resulted in increased residue availability, enhancing soil organic matter and nutrient cycling. FYM recycling showed comparable values between systems, with means of 2.1 t/year in rainfed IFS and 2.22 t/year in irrigated IFS, reflecting livestock's integral role in replenishing organic matter. Mushroom spent residue recycling was slightly higher in irrigated IFS (14.9 kg/year) compared to rainfed IFS (14.2 kg/year), underlining its contribution to system sustainability. Unique to irrigated IFS, azolla recycling averaged 228 kg/year, demonstrating its utility as a sustainable feed. Vermicompost production, exclusive to irrigated systems, averaged 1.5 t/year, significantly contributing to soil health improvements (Meena *et al*. 2022). These results emphasize the enhanced resource recycling potential of diversified irrigated systems, affirming the value of integration in improving sustainability and resource efficiency.

The study highlights the transformative potential of IFS in enhancing productivity, resilience, and sustainability in the arid regions of western Rajasthan. IFS demonstrated superior performance, achieving higher productivity, economic returns, and resource recycling compared to crop-based farming systems. Diversification through high-value crops, livestock integration, and innovative components like azolla cultivation and vermicomposting significantly contributed to these outcomes. While rainfed IFS showcased resilience and resource conservation, their productivity remained constrained by climatic variability. Strengthening rainfed systems through targeted interventions such as drought-resilient crops and improved water management is essential. The participatory approach ensured context-specific solutions, paving the way for scalable and adaptable models to improve livelihoods in resource-scarce regions.

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