



Integrated farming systems leveraging rainwater harvesting for enhanced productivity, profitability, and sustainability in hyper-arid regions of India

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ABSTRACT

Rainfed farming in hyper-arid regions faces significant challenges, including low productivity, poor economic returns and inefficient resource utilization due to erratic rainfall and limited diversification. The study was conducted during July 2019 to June 2023 at ICAR-Central Arid Zone Research Institute, Regional Research Station, Bikaner, Rajasthan to evaluate the productivity, profitability, and resource use efficiency of rainwater harvesting based Integrated Farming System (IFS) model with conventional cropping system of moth bean [*Vigna aconitifolia* (Jacq.) Marechal] and cluster bean [*Cyamopsis tetragonoloba* (L.) Taub] under rainfed condition. Study assessed a 3.0 ha IFS model integrating arable crops, horticulture, fodder, dairy, vermicomposting, and mushroom cultivation, supported by rainwater harvesting. Results showed that compared to conventional sole cluster bean and moth bean cropping systems, IFS exhibited superior productivity with a mean Cluster Bean Equivalent Yield (CEY) of 7608 kg/ha, significantly surpassing the CEY of 274 kg/ha and 191 kg/ha under conventional rainfed cropping. The IFS achieved annual net returns of ₹1,79,899 with a B:C ratio of 2.40, representing 5.6 and 6.2 times higher net returns than sole cluster bean and moth bean, respectively. In terms of income share, dairy contributed 45.8% of net returns, while horticulture and fodder accounted for 17.8% and 16.5%, respectively. The system demonstrated high water use efficiency (2.498 kg/m³) and a reduced water footprint (400 L/kg). With a Sustainable Value Index (SVI) of 0.560, the IFS model proves to be a resilient, sustainable, and economically viable approach for hyper-arid regions.

Keywords: Arid agriculture, Cluster bean equivalent yield, Crop-livestock integration, Sustainable value index, Water footprints

The Indian hot arid zone, spanning 32 million ha and covering approximately 10% of the country's geographical area, presents formidable challenges for agriculture. This region is characterized by low and erratic rainfall (<400 mm annually), high evaporative demand (1600–1900 mm), extreme temperatures, and sandy soils with limited water-holding capacity (Tanwar *et al.* 2018). Despite these constraints, the arid regions contribute significantly to Indian agriculture by producing millets, pulses, and oilseeds, alongside livestock rearing, particularly small ruminants (Reddy *et al.* 2021). However, water scarcity, soil degradation, and traditional rainfed farming limit agricultural productivity, making farming systems highly vulnerable to climatic variability. The dependence on rainfall leads to unstable crop yields, income insecurity,

and unemployment (Ray *et al.* 2019). While desert communities have developed resilient but low-productivity systems, they remain insufficient to meet the needs of a growing population. Addressing these challenges requires innovative, sustainable approaches that enhance resource-use efficiency, stabilize farm incomes, and build resilience against environmental stresses.

The Integrated Farming System (IFS) has been widely recognized for enhancing productivity, profitability, livelihoods, and soil health across India (Tanwar *et al.* 2018). By integrating crops, livestock, and allied enterprises, IFS optimizes resource use, recycles farm by-products, and engages family labour, reducing input costs while improving productivity (Dash *et al.* 2015). Research suggests that IFS mitigates the risks of monocropping and market fluctuations, ensuring economic stability for farmers. Livestock, a major IFS component, provides regular income through milk, meat and manure, improving soil organic matter and crop productivity (Reddy *et al.* 2021). Additionally, horticultural crops such as ber and vegetables enhance profitability while reducing risks from price volatility (Domjan and Fekete 2011).

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Rainwater harvesting is critical for sustaining IFS in arid regions, where stored surplus rainfall ensures reliable irrigation, reducing dependence on erratic monsoons. Studies in Rajasthan highlight its effectiveness in cultivating drought-tolerant crops like cluster bean and moth bean while improving farm profitability (Singh *et al.* 2019). Water productivity increased by 1–2 times when pond water was used efficiently compared to traditional rainfed farming (Das *et al.* 2013). Rainwater storage in farm ponds further stabilizes farming and enhances cropping intensity (Ranade 2014).

In western Rajasthan, where large landholdings prevail, developing a rainwater harvesting-based IFS model can optimize family labour, ensure year-round livestock fodder and improve sustainability. This study evaluates the potential of such an approach to enhance productivity, profitability and resilience in the hyper-arid regions of Rajasthan.

MATERIALS AND METHODS

The study was conducted during July 2019 to June 2023 at ICAR-Central Arid Zone Research Institute Regional Research Station, Bikaner (28.07° N and 73.32° E, with an elevation of 225 m amsl), Rajasthan. The region falls in the Hyper-Arid Partial Irrigated Zone (Zone II A) agro climatic zone of Rajasthan. The climate of the region is characterized by low rainfall (247 mm) and most (70–80%) of which occurs during July–September. The soil of the site was sandy, alkaline in reaction with pH 8.2, low in organic carbon (0.112%), available N 89.7 kg/ha, available P₂O₅ 8.0 kg/ha and available K₂O 234 kg/ha.

The experiment compared arable cropping of moth bean and cluster bean with an IFS model, each covering a 3.0 ha area. For comparison, the yields of moth bean and cluster bean within the IFS were converted to their equivalent yields as sole crops over the same 3.0 ha area. Established in 2018, the IFS included multiple 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. A catchment area of 1000 m² was constructed for rainwater harvesting (Fig. 1). The harvested water (65% average collection efficiency) was stored in a reservoir (*diggi*) and used for irrigating various IFS components.

A 10 m × 10 m × 3 m shed, covering 30 m², was constructed for oyster mushroom (*Pleurotus sajor-caju*) cultivation (Fig. 2). The structure featured a three-tier arrangement with walls made of sarkanda grass (*Triplidium bengalense*) stems, plastered with clay and cow dung, and whitewashed with lime for durability. The roof was insulated with a thatching of kheep biomass (*Leptadenia* spp.), supported by an iron wire mesh, asbestos sheeting and a polyethylene layer. To maintain optimal growth conditions, foggers provided cooling and humidification, complemented by natural ventilation. The setup accommodated 300 bags per batch, with three batches cultivated annually from February to November. The spent mushroom substrate was efficiently recycled into compost, enhancing resource

utilization. For vermicomposting, four pits were constructed, each measuring 3 m × 1 m × 1 m, providing a total area of 50 m² dedicated to vermicompost production. Two 12 ft × 4 ft × 1 ft beds lined with 500 GSM HDPE tarpaulin sheets were established for azolla cultivation.

Data on productivity, economics, water-use efficiency, and employment generation were recorded for each component annually. Productivity of arable crops was measured in terms of grain and fodder yield. For horticultural crops, fruit and vegetable yields 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.

Since diversified enterprises were taken for study, the farming systems were analysed by quantifying productivity and income in terms of net returns. The productivity of various enterprises was converted to system equivalent yield expressed in Cluster bean Equivalent Yield (CEY) as:

$$\text{CEY} = (\text{Yield of an enterprise} \times \text{Market value of produce}) / \text{Market value of cluster bean}$$

Economics of production of each of the enterprises was calculated by keeping a record on number of labourers 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 is the value of all products and by-products 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.

Water-use efficiency (WUE) was calculated as the ratio of system equivalent yield (kg) to the volume of water applied (m³). Water foot-print were calculated as litre of water used per kg of economic produce. Similarly, economic water productivity was calculated as amount of net returns earned per cubic metres of water utilized and expressed as ₹/m³. Employment generation was measured in terms of person-days of labour created for each component. The Sustainable Yield Index (SYI) and Sustainable Value Index (SVI) were computed by using the formula given by Vittal *et al.* (2002). The production data of different enterprises for five consecutive years were presented year-wise and average under respective parameter. The conventional farming system (cluster bean/ moth bean) was considered as a control to compare with the IFS.

RESULTS AND DISCUSSION

Rainwater harvesting and utilization: Rainwater harvested from a 1000 m² catchment area was effectively utilized across various components of the IFS model. Between 2019 and 2022, rainfall fluctuated significantly, ranging from a low of 91 mm in 2020 to a high of 379.6 mm in 2019, with water harvesting efficiencies varying from 72.7–89.5% (Supplementary Table 1). In 2019, 77.7% of

Table 1 Details of different components of the IFS model.

Enterprise	Component	Area (m ²)	Raising Period	Variety/breed	Spacing	Seed rate (kg/ha)
Arable crops	Cluster bean (<i>Cyamopsis tetragonoloba</i>)	5400	Kharif	RGC-1033	30 cm × 10 cm	20
	Moth bean (<i>Vigna aconitifolia</i>)	5175	Kharif	RMO-40	30 cm × 10 cm	15
Horticulture	Acid lime (<i>Citrus aurantiifolia</i>)	1750	Perennial	Acid lime	10 m × 5 m	75 plants
	Pomegranate (<i>Punica granatum</i>)		Perennial	Bhagwa	10 m × 5 m	75 plants
	Ber (<i>Ziziphus mauritiana</i>)		Perennial	Gola	10 m × 5 m	75 plants
	Budded Khejri (<i>Prosopis cineraria</i>)		Perennial	Thar Sobha	10 m × 5 m	75 plants
	Snap melon (<i>Cucumis melo</i> var. <i>momordica</i>)	1350	Kharif	AHS 82	1 m × 0.3 m	1.0
	Kachri (<i>Cucumis callosus</i>)	675	Kharif	AHK 119	1 m × 0.3 m	1.0
	Tinda (<i>Praecitrullus fistulosus</i>)	675	Kharif	Sel. 1	1 m × 0.3 m	2.0
	Matira (<i>Citrullus lanatus</i>)	675	Kharif	Local	1 m × 30m	2.5
	Dhaman grass (<i>Cenchrus ciliaris</i>)	3100	Kharif	CAZRI-375	60 cm × 20 C CMcm	7.0
Fodder (Dry/Green)	Pearl millet (rainfed) (<i>Pennisetum glaucum</i>)	10000	Kharif	RHB-1620	45 cm × 10 cm	10
	Azolla (<i>Azolla pinnata</i>)	20	Year round	<i>A. Pinnata</i>	-	3 kg/bed
	Cow (<i>Bos indicus</i>) - Rathi breed	100	-	Rathi	-	-
Mushroom	Oyster mushroom	30	Thrice/year (Feb–Nov)	<i>Pleurotus sajor-caju</i>	-	150 g/3.5 kg wet bag
Compost	Vermicompost (<i>Eisenia fetida</i>)	50	-	<i>Eisenia fetida</i>	-	2 kg/bed

the harvested water were utilized, respectively. In 2020, 2021 and 2022, water utilization exceeded the harvested amounts, which was made possible through recycling, particularly from the azolla unit (Supplementary Table 2).

Productivity of different components: The economic produce from different enterprises and components of the IFS across four years (Table 2) highlights variations in



Fig. 1 Rainwater harvesting catchment area (1000 m²) of the IFS model.



Fig. 2 Outer and inner view of the mushroom production shed made of indigenous material.

production trends influenced by rainfall. The arable crops like cluster bean and moth bean, grown under rainfed conditions, showed a strong dependence on annual rainfall. The highest yields were recorded in 2019, when rainfall was 379.6 mm, with cluster bean producing 675 kg of fodder and 251 kg of grain, while moth bean achieved 731 kg of fodder and 305 kg of grain. However, during the drought year of 2020 (91.0 mm rainfall), yields dropped significantly due to moisture stress, indicating the critical role of rainfall and the need for moisture availability in rainfed arable cropping systems. Among the horticultural crops the fruit crops were in establishment phase throughout the study while vegetables like snap melon, kachri, tinda, and matira performed exceptionally well in 2019, benefiting from the highest rainfall (379.6 mm). Snap melon recorded a peak production of 1405 kg in 2019 and 2450 kg in 2020, while kachri, tinda, and matira produced 920 kg, 695 kg, and 510 kg, respectively, in 2019.

Fodder components such as dhaman grass (*Cenchrus ciliaris*) produced the highest fodder yield of 830 kg in

2019 but declined steadily to 256 kg in 2022, reflecting the impact of reduced rainfall and soil moisture availability. Similarly, fodder pearl millet peaked in 2019 with 6000 kg, but yields dropped sharply during the drought of 2020. Azolla, introduced in 2020, showed consistent

Table 2 Annual economic production from various components of an IFS on a net area basis

Enterprise	Components	Production (kg or L)							
		2019		2020		2021		2022	
		Fodder	Grain/ Veg./Fruit/ Milk	Fodder	Grain/ Veg./Fruit/ Milk	Fodder	Grain/ Veg./Fruit/ Milk	Fodder	Grain/ Veg./Fruit/ Milk
Arable crops	Cluster bean	675	251	301	62	635	300	568	115
	Moth	731	305	110	68	285	80	298	156
Horticulture	Fruits	-	-	-	-	-	-	-	150
	Snap melon	-	2450	-	1380	-	890	-	95
	Kachri	-	920	-	275	-	190	-	30
	Tinda	-	695	-	340	-	245	-	145
	Matira	-	510	-	203	-	187	-	18
Fodder	Dhaman grass	830	-	480	-	300	0	256	0
	Fodder pearl millet (Dry)	6000	-	450	-	1940	350	1790	315
	Azolla (green)	-	-	875	-	1070	0	956	-
Dairy	Cattle (2)	-	3850	-	3720	-	3620	-	3632
Compost	Vermicompost	-	-	-	4500	-	4430	-	4350
Mushroom	Oyster	-	-	-	300	-	340	-	290
	Total								

performance with yields ranging from 875–1070 kg, demonstrating its resilience as a fodder source in water-limited conditions. Dairy remained a stable component of the IFS. The steady performance of the dairy enterprise highlights its reliability as a source of income and nutrition, unaffected by annual variations in rainfall. Vermicompost production showcasing efficient organic waste recycling. Similarly, oyster mushroom cultivation contributed additional value, with yields of 300–340 kg between 2020 and 2022. These components added stability to the system and diversified farm income.

Rainfall variability was the primary driver of yield trends in arable, fodder and horticultural crops, with peak production observed in 2019, a year of favourable rainfall. Severe declines during 2020, a drought year, emphasize the vulnerability of rainfed systems to moisture stress.

Economics of different components: The economic evaluation of the IFS, averaged over four years, highlights notable variations across its components. Among arable crops, cluster bean demonstrated the highest profitability, with net returns of ₹4,092 and a B:C ratio of 2.67, followed by moth bean (Supplementary Table 3). The strong economic performance of these crops can be attributed to their relatively low input costs and ability to thrive under rainfed conditions.

Among vegetables, snap melon proved to be the most profitable component, with net returns of ₹19,644 and the highest B:C ratio of 5.32, driven by strong market demand and productivity. Tinda, kachri and matira also showed strong economic viability. In contrast, the fruit component incurred a net loss of ₹3,544 due to establishment costs. Azolla achieved the highest economic efficiency, with net

returns of ₹10,473 and a B:C ratio of 7.98. Fodder pearl millet generated ₹18,110 in net returns, but had a lower B:C ratio of 4.55. Dhaman grass provided minimal returns, contributing ₹1,019. The dairy enterprise played a vital role in system stability, producing consistent net returns of ₹82481 and a B:C ratio of 2.12. Additionally, diversification through vermicomposting and oyster mushroom cultivation highlighted the value of resource recycling and high-value enterprises. Vermicomposting generated net returns of ₹10,788 with a B:C ratio of 2.80, emphasizing its efficiency in converting farm waste into productive resources. Similarly, oyster mushroom cultivation, with net returns of ₹11,213 and a moderate B:C ratio of 1.67, validated its potential as a profitable enterprise despite higher initial investment costs.

Overall, the IFS achieved total net returns of ₹1,79,899 with an average B:C ratio of 2.40. The integration of high-value, low-cost components such as Azolla and mushrooms, alongside reliable enterprises like dairy and vermicomposting, highlights the potential of a well-diversified IFS to optimize resource use, enhance economic resilience, and ensure sustainable productivity in rainfed agricultural systems.

Economics of IFS: The economic analysis of the IFS, averaged over four years, highlights advantages of diversification over conventional cropping (Table 3). The IFS generated a total gross return of ₹3,08,157/annum and net returns of ₹1,79,899/annum, with an overall B:C ratio of 2.34. Among the components, dairy emerged as the most significant contributor, accounting for 43.75% of the total net returns with an average net return of ₹80,384 and a B:C ratio of 2.40. This consistent performance emphasizes

the importance of livestock as a stable and reliable income source, particularly in rainfed farming systems where crop production is subject to variability. These results support the findings of Paramesh *et al.* (2022).

Horticulture followed (17.8%), driven by high-value crops like snap melon and tinda. Fodder production proved highly efficient, yielding ₹29,601 with the highest B:C ratio (4.43). Value-added enterprises, including vermicomposting (₹10,788, B:C 2.80) and mushroom production (₹11,213, B:C 1.67), further enhanced profitability through diversification and organic waste recycling.

Overall, the IFS demonstrated a 5.6-fold increase in net returns over cluster bean and a 6.2 fold increase over moth bean. This remarkable increase can be attributed to the inclusion of high-value enterprises, and the efficient recycling of resources among system components, which reduced input requirements and minimized costs (Ravi Sankar *et al.* 2007).

System productivity: The system productivity expressed in terms of Cluster bean Equivalent Yield (CEY), demonstrates a substantial advantage of the diversified IFS approach across four years (Supplementary Table 4). The IFS, implemented over a 3 ha area, achieved a mean CEY of 7608 kg, significantly surpassing the yields from conventional cropping with cluster bean and moth bean produced mean CEY of only 274 kg and 191 kg, respectively (Supplementary Table 4). Compared to cluster bean monocropping, the IFS achieved yield increases ranging from 20.2–57.3 times and 24.0–86.6 times higher than that of moth bean. This higher productivity of crop and vegetable components was attributed to residue recycling, enhanced nutrient addition from vermicompost, and FYM, which improved soil fertility and subsequently increased crop productivity. These findings align with Goverdhan *et al.* (2020). In 2019, which received the highest rainfall during the study period (379.6 mm), the IFS achieved its highest CEY of 9211 kg, reflecting the ability of the IFS to capitalize on favourable growing conditions. The results clearly indicate that by integrating multiple components that

complement each other, the IFS not only ensures higher yields but also enhances resource use efficiency and system resilience for rainfed and resource-limited regions.

Employment generation: The IFS demonstrated a significant advantage over conventional cropping systems in terms of employment generation (Supplementary Table 4), creating 285 man-days/year on a 3 ha farm. This is markedly higher compared to the 108 man-days and 96 man-days provided by conventional cropping systems of cluster bean and moth bean, respectively. IFS resulted into 177 and 189 man-days additional employment generation over monocropping of cluster bean and moth bean, respectively. The higher employment potential of the IFS can be attributed to the integration and diversification of activities, including crops, livestock, and horticulture (Rathore and Bhatt 2008).

Water use indices: The IFS significantly outperformed conventional cropping systems in terms of water use indices. The IFS achieved a remarkable WUE of 2.498 kg/m³, far above over cluster bean (0.033 kg/m³) and moth bean (0.025 kg/m³) under conventional systems. The water footprint of the IFS further underscores its efficiency, requiring only 400 litre/kg of produce, compared to the significantly higher values of 30,009 litre/kg for cluster bean and 39,225 litre/kg for moth bean. Additionally, the economic water productivity of the IFS was ₹62.54/m³, reflecting much higher economic returns per unit of water consumed compared to ₹4.04/m³ for cluster bean and ₹4.95/m³ for moth bean.

Recyclable resources: The four-year study on the IFS demonstrated efficient resource recycling, contributing to sustainability and improved farm productivity. Crop stover, including fodder pearl millet and Dhaman grass was recycled at an average of 3912 kg/year, serving as livestock fodder. The livestock enterprise produced 3.4 tonnes of farmyard manure (FYM) annually, with a portion used for vermicompost production (4.42 tonnes/year) and the surplus applied to crop fields, enhancing soil fertility. Azolla production averaged 967 kg/year, supporting

Table 3 Profitability analysis of farm enterprises in the 3 ha IFS model averaged over four years

Component		Total cost (₹)	Gross returns (₹)	Net returns (₹)	B:C ratio	Contribution in total net returns (%)
Arable cropping		7652	21528	13876	2.81	7.7
Horticulture		15671	47613	31942	3.04	17.8
Fodder		8628	38230	29601	4.43	16.5
Dairy		73670	156150	82481	2.12	45.8
Vermicompost		6000	16788	10788	2.80	6.0
Mushroom		16638	27850	11213	1.67	6.2
Total		128258	308157	179899	2.40	100.0
Conventional cropping (3 ha)	Cluster bean	22733	60799	38066	2.67	
	Moth bean	20638	61357	40719	2.97	
Fold change (times)	Over Cluster bean	5.6	5.1	4.7		
	Over Moth bean	6.2	5.0	4.4		

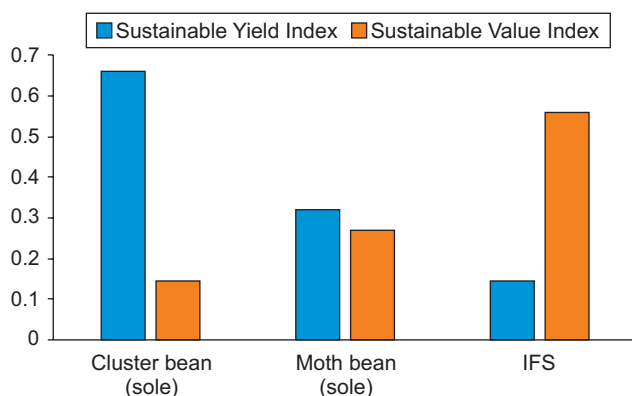


Fig. 3 Sustainability indices of rainfed crops and rainwater harvesting based IFS.

livestock nutrition and contributing to water recycling within the system (Supplementary Table 5). Water usage fluctuated over the years, averaging 28,607 litre annually. Mushroom cultivation utilized 3.15 tonnes of wheat straw per year, yielding 3.53 t of spent substrate, which was composted and returned to the soil. These results highlight the effectiveness of IFS in optimizing resource utilization, improving nutrient cycling, and enhancing sustainability compared to conventional farming systems (Sahoo and Behera 2017).

Sustainability of IFS model: The sustainability indices provide valuable insights into long-term viability of the IFS (Fig. 3). The SYI, which measures yield stability, was highest for cluster bean at 0.660, followed by moth bean at 0.321 and IFS at 0.143. The relatively lower SYI for the IFS reflects the variability in yields due to its diverse components and reliance on external factors like market demand and climatic variability. However, yield stability alone does not capture the broader benefits of the IFS. In terms of SVI, the IFS achieved the highest value of 0.560, reflecting its ability to generate significant economic value while optimizing resource use. In comparison, moth bean had an SVI of 0.268 and cluster bean had the lowest SVI of 0.143, indicating limited contributions to long-term sustainability. These results suggested that while monocropping systems may provide stable yields, they fall short in terms of overall sustainability. The IFS, with its diversified structure and efficient resource utilization, offers a more resilient and economically viable approach for rainfed agriculture (Sahoo and Behera 2017).

The present study conclusively demonstrated that over four years, the IFS achieved a mean Cluster Bean Equivalent Yield (CEY) (7608 kg/ha), net returns (₹1,79,899/year) and B:C ratio (2.40) considerably better than conventional cropping systems of the region. It generated 285 man-days/year employment, highlighting its contribution to rural employment. The IFS exhibited superior WUE (2.498 kg/m³), a low water footprint (400 litre/kg), and a higher Sustainable Value Index (SVI) of 0.560. These results affirm the IFS as a sustainable, resource-efficient

and economically viable model for hyper-arid region of the country.

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