



Scaling Productivity in Harsh Rainfed Ecosystems: The Strategic Role of Frontline Demonstrations (FLDs) in Pali, Rajasthan

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Abstract: Frontline Demonstrations (FLDs) were evaluated to assess the productivity, technological gaps and economic performance of improved crop production technologies under farmers' field conditions in Pali district, Rajasthan, during 2018-19 to 2022-23. Demonstrations were conducted on six major crops green gram, cluster bean, sesame, wheat, mustard and cumin using improved varieties and recommended agronomic practices, with adjacent farmers' fields maintained as local checks. FLDs consistently outperformed farmers' practices, recording yield increases of 43.75-57.35% in green gram, 41.88-64.57% in cluster bean, 55.48-62.83% in sesame, 35.96-50.26% in wheat, 50.12-58.73% in mustard and 42.22-56.57% in cumin. Technology gaps declined across all crops while technology indices decreased progressively, indicating improved realization of yield potential under farmers' field conditions. The decline was associated with repeated exposure to improved production practices, closer technical supervision, better synchronization of agronomic operations and increasing familiarity with recommended technologies, although seasonal and field-level variability remained important. Although extension gaps remained considerable, they highlighted the substantial scope for increasing productivity through wider dissemination of recommended technologies. Frontline Demonstrations also recorded consistently higher benefit-cost ratios than farmers' practices, confirming the economic viability of the improved production packages. Overall, the study demonstrated that FLDs are an effective extension approach for enhancing crop productivity and profitability under the semi-arid conditions of western Rajasthan. Further research should include adoption and long-term impact assessments to evaluate the sustainability and wider diffusion of demonstrated technologies.

Key words: Frontline demonstrations; technology gap; extension gap; semi-arid agriculture; integrated crop management.

Agriculture is the principal source of livelihood for a large proportion of India's rural population and plays a pivotal role in ensuring food security, employment, and

economic development. However, agricultural productivity in the arid and semi-arid regions of the country remains considerably below its attainable potential due to recurrent droughts, erratic rainfall, declining soil fertility, land degradation, and increasing climatic variability. These constraints are particularly severe in Rajasthan, where rainfed agriculture predominates and crop production is characterized by high production risks and substantial inter-annual variability (Kumar *et al.*, 2024a). Under such fragile agro-ecosystems, improving agricultural productivity requires not only the development of location-specific technologies but also efficient extension mechanisms capable of transferring these technologies from research institutions to farmers' fields. Pali district, located in the transitional agro-ecological zone between the arid and semi-arid regions of western Rajasthan (24°45'-26°29' N latitude and 72°47'-74°18' E longitude), represents a typical dryland farming region. The district receives an average annual rainfall of approximately 500 to 550 mm, nearly 85-90% of which is received during the southwest monsoon. Rainfall is highly erratic and frequently interrupted by prolonged dry spells, exposing crops to severe moisture stress during critical growth stages. The soils are predominantly sandy loam to loamy sand, characterized by low organic carbon, poor water-holding capacity, low available nitrogen, moderate phosphorus, and deficiencies of sulfur and micronutrients (Kumar *et al.*, 2024b). Limited irrigation facilities, declining groundwater resources, and high evapotranspiration further aggravate production constraints, resulting in low and unstable yields of major crops such as green gram (*Vigna radiata* L.), cluster bean (*Cyamopsis tetragonoloba* L.), sesame (*Sesamum indicum* L.), wheat (*Triticum aestivum* L.), mustard (*Brassica juncea* L.) and cumin (*Cuminum cyminum* L.).

Agricultural production in Pali district is largely undertaken by small and marginal farmers whose farming decisions are constrained by limited financial resources, inadequate access to quality inputs, and high climatic uncertainty. Although substantial progress has been achieved in crop breeding, nutrient management, integrated pest management, and improved agronomic practices, adoption of these technologies under

farmers' field conditions remains inadequate. Farmers frequently continue to cultivate traditional varieties, use poor-quality seed, apply imbalanced fertilizers, delay sowing operations, and inadequately manage weeds, pests, and diseases. These technological limitations contribute to substantial technology and extension gaps, thereby reducing productivity, input-use efficiency, and farm profitability. Previous studies conducted in western Rajasthan have consistently identified poor-quality seed, delayed sowing, moisture stress, and inadequate nutrient management as the principal causes of low productivity in cereals, pulses, and oilseed crops (Meena and Singh, 2019; Ali *et al.*, 2023; Jat *et al.*, 2023). Bridging the gap between research-generated technologies and farmers' practices has been a major objective of the Indian agricultural extension system. Frontline Demonstrations (FLDs), implemented through the KVKs under the Indian Council of Agricultural Research (ICAR), were introduced during the mid-1980s to evaluate and demonstrate the performance of improved crop production technologies under real farming situations. Unlike conventional extension programmes, FLDs are conducted under the direct supervision of scientists using complete packages of recommended technologies, including improved varieties, quality seed, seed treatment, balanced nutrient management, bio-fertilizers, integrated pest and disease management, and scientific crop husbandry. Demonstrations established under farmers' field conditions provide reliable information on the performance, adaptability and economic feasibility of improved technologies while simultaneously strengthening research-extension-farmer linkages and generating feedback for technology refinement (Singh *et al.*, 2026).

Over the past four decades, numerous studies have demonstrated that FLDs significantly improve crop productivity, profitability, and resource-use efficiency across diverse agro-climatic regions of India (Kumar *et al.*, 2018; Kumar and Singh, 2023). In Rajasthan, FLDs have resulted in substantial yield enhancement in crops such as wheat, chickpea, pearl millet and moth bean (Meena and Singh, 2019; Ali *et al.*, 2023; Jat *et al.*, 2023). Nevertheless, most available studies are crop-specific or confined to short-term evaluations, providing limited

Table 1. Improved Technologies Demonstrated under FLDs for Major Kharif and Rabi crops during 2018-19 to 2023-24

Crop	Farmer's practice (FP)	Improved technology under FLD
Moong (Green gram)	Use of local varieties; broadcasting; no seed treatment; imbalanced fertilizer; late weeding	High-yielding variety (IPM 02-14); seed treatment with Rhizobium + PSB + fungicide; line sowing; recommended NPK + S; timely weeding/herbicides; IPM practices
Guar (Cluster bean)	Traditional varieties; no seed treatment; low fertilizer use; no pest monitoring	Improved variety (RGC 936); biofertilizer seed treatment; soil test-based fertilization; moisture conservation; IPM including HCN traps; timely harvesting
Til (Sesame)	Local low-yielding varieties; broadcasting; low nutrient application; high pest losses	Improved variety (RT 346); fungicide + bio-agent seed treatment; line sowing; recommended NPK + S; need-based plant protection, leaf roller & phyllody management
Wheat	Late sowing; Use of local varieties; imbalance N application; flood irrigation	High-yielding drought-tolerant variety (Raj 4079); seed treatment with fungicide + bio-agents; line sowing; balanced NPK + Zn; irrigation scheduling at CRI, tillering, milking
Mustard	Use of local varieties; low fertilizer; no sulfur; poor weed control	Improved variety (Giriraj); seed treatment; recommended NPK + S + micronutrients; pre- and post-emergence herbicides; IPM for aphid management
Cumin	Traditional varieties; no nutrient management; frequent wilt incidence; manual weed control	Wilt-tolerant improved variety (GC 4); seed treatment with fungicide + bio-agents; balanced fertilization; timely irrigation; weed management with recommended herbicides; IPM for aphid and wilt

evidence on the comparative performance of FLDs across multiple cropping systems. Furthermore, advances in improved varieties, crop management technologies, and changing climatic conditions warrant a contemporary assessment of the programme after nearly four decades of implementation to determine whether FLDs continue to effectively reduce technology gaps and improve productivity under present-day farming conditions. Therefore, the present investigation was undertaken to comprehensively evaluate the performance of Frontline Demonstrations conducted by KVK, Pali, on six major *kharif* and *rabi* crops during 2018-19 to 2022-23 under farmers' field conditions. The study quantified productivity enhancement, technology gap, extension gap, technology index, and economic returns to assess the effectiveness of recommended production technologies under the semi-arid agro-ecological conditions of western Rajasthan. The findings provide robust scientific evidence for strengthening extension strategies, refining location-specific crop production recommendations and supporting evidence-based policies aimed at enhancing the productivity, profitability and sustainability of dryland agriculture.

Materials and Methods

The study was conducted under the Frontline Demonstration (FLD) programme implemented by ICAR-Central Arid Zone

Research Institute (CAZRI), Krishi Vigyan Kendra (KVK), Pali, Rajasthan, India, during 2018-19 to 2022-23. Demonstrations were carried out in six representative villages (Bitura Kalan, Inderwada, Bhagwanpura, Hingola Kalan, Kherwa and Dhamli) located in the semi-arid agro-ecological region of Pali district (24°45'-26°29' N, 72°47'-74°18' E). The region experiences a hot semi-arid climate with an average annual rainfall of approximately 520 mm, nearly 90% of which is received during the southwest monsoon (June-September) during 2018-19 to 2022-23. The soils are predominantly sandy loam to loamy sand with low organic carbon, low available nitrogen, medium phosphorus, moderate potassium, and poor moisture-holding capacity. Agriculture is largely rainfed and constrained by erratic rainfall, recurrent droughts, high evapotranspiration, and limited irrigation facilities.

Experimental design and implementation: Frontline Demonstrations were conducted annually according to the targets allotted by the ICAR-Agricultural Technology Application Research Institute (ATARI), Zone II, Jodhpur (Rajasthan). The study covered six major crops comprising three *kharif* crops green gram (*Vigna radiata* L.), cluster bean (*Cyamopsis tetragonoloba* L.) and sesame (*Sesamum indicum* L.) and three *rabi* crops wheat (*Triticum aestivum* L.), mustard (*Brassica juncea* L.) and cumin (*Cuminum cyminum* L.). Each demonstration established on an individual farmer's field was considered

one experimental unit, while villages served as geographical blocks under a cluster approach to reduce environmental variability. Farmers were selected through participatory village meetings based on willingness to participate, availability of a relatively uniform field (approximately 0.4 ha), accessibility for scientific supervision and willingness to maintain both demonstration and farmers' practice plots. An adjacent plot of equal size managed under existing farmer practices served as the local check, enabling paired comparisons under similar soil and climatic conditions. Farmer participation varied annually according to programme targets and pooled analysis was performed across years.

Demonstrated technologies: The FLDs evaluated recommended production technologies developed by ICAR and the State Agricultural University for the semi-arid conditions of Rajasthan. Crop-specific technology packages included improved high-yielding varieties, seed treatment with fungicides and bio-fertilizers, balanced nutrient management, line sowing, integrated weed and pest management, moisture conservation practices, and scientific irrigation scheduling where irrigation was available. Farmers' practice plots continued with traditional management, including local varieties, broadcasting, imbalanced fertilizer use, and conventional crop management. All demonstrations were implemented under the direct supervision of KVK scientists through regular field monitoring, technical guidance, diagnostic visits, farmer training programmes, and field days to ensure uniform implementation and quality control.

Data recording: Crop observations were recorded from both the Frontline Demonstration plots and the corresponding farmers' practice plots at physiological maturity. Grain yield was recorded from the net harvested area of each plot and converted into t ha⁻¹ after adjustment to standard moisture content. For each crop and year, yield data were compiled from all participating demonstration plots and pooled to estimate mean performance under FLD and farmers' practice. Potential yields for each crop were obtained from the recommended package of practices published by ICAR and the respective State Agricultural University.

Assessment of technology gaps: The effectiveness of Frontline Demonstrations was assessed using

extension gap, technology gap, technology index and percentage yield improvement following the procedure described by Samui *et al.* (2000).

Extension gap = Demonstration – Farmers practice yield

Technology gap = Potential yield – Demonstration yield

$$\text{Technology Index (\%)} = \frac{\text{Potential Yield} - \text{Demonstration Yield}}{\text{Potential Yield}} \times 100$$

$$\text{Yield Increase (\%)} = \frac{\text{Demonstration Yield} - \text{Farmers' Practice Yield}}{\text{Farmers' Practice Yield}} \times 100$$

where potential yield refers to the experimentally attainable yield under recommended management practices.

Economic analysis: The economics of Frontline Demonstrations and farmers' practice were evaluated separately for each crop and each year using prevailing market prices and actual input costs recorded during the respective cropping seasons. The total cost of cultivation included expenditure on seed, fertilizers, bio-fertilizers, plant protection chemicals, labour, machinery, irrigation (where applicable) and other field operations. Gross return was calculated by multiplying grain yield with the prevailing minimum support price (MSP) or average local market price during the respective year. Net return was estimated by subtracting total cost of cultivation from gross return, while the benefit-cost ratio (B:C) was calculated as

$$\text{B:C Ratio} = \frac{\text{Gross Return}}{\text{Cost of cultivation}}$$

Additional return and additional cost associated with the improved technology were also calculated to determine the economic advantage of FLDs over farmers' practice.

Results and Discussion

Performance of Frontline Demonstrations on Kharif Crops

Frontline Demonstrations (FLDs) significantly improved the productivity and profitability of major *kharif* crops over farmers' practices through the integrated use of improved varieties and scientific crop management. The demonstrated technologies consistently performed better despite rainfall variability and resource-constrained semi-arid conditions.

Table 2. Yield performance and technological indicators of green gram (*Vigna radiata* L.) under Frontline Demonstrations and farmers' production practices in Pali district, Rajasthan, during 2018-19 to 2022-23

Years	Area (ha)	FLDs (n)	FLD yield (t ha ⁻¹)	Farmers' practice (t ha ⁻¹)	Yield increase (%)	Extension gap (t ha ⁻¹)	Technology gap (t ha ⁻¹)	Technology index (%)	B:C ratio (FLD)	B:C ratio (FP)
2018-19	6	15	0.69	0.48	43.75	0.21	0.91	56.88	2.3	1.8
2019-20	4	10	0.73	0.50	47.19	0.24	0.87	54.19	2.5	1.9
2020-21	4	10	0.93	0.61	51.64	0.32	0.68	42.19	2.7	2.0
2021-22	2	05	1.00	0.64	55.28	0.36	0.60	37.50	2.8	2.1
2022-23	2	05	1.07	0.68	57.35	0.39	0.53	33.13	3.0	2.1

Potential yield = 1.60 t ha⁻¹. Source: Singh *et al.*, 2023.

Green gram (*Vigna radiata* L.): Frontline Demonstrations on green gram showed increase in grain yield from 0.69 to 1.07 t ha⁻¹, whereas farmers' practice produced only 0.48-0.68 t ha⁻¹ during 2018-19 to 2022-23 (Table 2). The demonstrated technology increased seed yield by 43.75-57.35% over the existing production system. The higher productivity resulted from the combined effects of improved variety IPM 02-14, seed treatment with *Rhizobium* and phosphate-solubilizing bacteria, balanced fertilization, line sowing, timely weed control and integrated pest management. These interventions improved nodulation, nutrient uptake, photosynthetic efficiency and moisture-use efficiency, thereby enhancing biomass production and grain filling under rainfed conditions (Singh *et al.*, 2023). The technology gap declined from 0.91 to 0.53 t ha⁻¹, while the technology index decreased from 56.88% to 33.13%, indicating that the recommended production technologies were increasingly able to exploit their genetic yield potential under farmers' field conditions. The reduction in technology gap also reflects better synchronization of agronomic operations and increasing familiarity of farmers with improved production practices. The extension gap increased from 0.21 to 0.39 t ha⁻¹, suggesting that the productivity advantage

of demonstrated technologies over traditional management became more pronounced with time. Economically, the benefit-cost ratio under FLDs increased from 2.3 to 3.0, compared with 1.8 to 2.1 under farmers' practice, confirming that investment in quality inputs was economically rewarding. Similar responses of green gram to improved production technologies have been reported by Singh *et al.* (2016) and Sharma *et al.* (2019).

Cluster bean (*Cyamopsis tetragonoloba* L.): Cluster bean exhibited a continuous increase in productivity throughout the study period (Table 3). Grain yield under FLDs increased from 0.73 to 1.10 t ha⁻¹, while farmers' practice recorded only 0.51-0.67 t ha⁻¹, resulting in yield improvements ranging from 41.88% to 64.57%. The higher productivity was mainly associated with the cultivation of improved variety RGC 936, seed inoculation with bio-fertilizers, soil test-based nutrient management, moisture conservation and timely pest management. Being a drought-tolerant legume, cluster bean responded efficiently to scientific crop management by utilizing available soil moisture more effectively under semi-arid conditions. The technology gap declined substantially from 0.58 to 0.20 t ha⁻¹, whereas the technology index decreased from 44.23% to 15.31%, indicating

Table 3. Yield performance and technological indicators of cluster bean (*Cyamopsis tetragonoloba* L.) under frontline demonstrations and farmers' production practices in Pali district, Rajasthan, during 2018-19 to 2022-23

Years	Area (ha)	FLDs (n)	FLD yield (t ha ⁻¹)	Farmers' practice (t ha ⁻¹)	Yield increase (%)	Extension gap (t ha ⁻¹)	Technology gap (t ha ⁻¹)	Technology index (%)	B:C ratio (FLD)	B:C ratio (FP)
2018-19	4	10	0.73	0.51	41.88	0.20	0.58	44.23	2.1	1.7
2019-20	4	10	0.85	0.57	49.47	0.28	0.45	34.46	2.3	1.8
2020-21	4	10	0.97	0.59	63.07	0.37	0.33	25.62	2.5	1.9
2021-22	2	05	1.00	0.61	63.72	0.39	0.30	22.92	2.6	2.0
2022-23	2	05	1.10	0.67	64.57	0.43	0.20	15.31	2.8	2.1

Potential yield = 1.30 t ha⁻¹. Source: Jain *et al.* (2019).

Table 4. Yield performance and technological indicators of sesame (*Sesamum indicum* L.) under Frontline Demonstrations and farmers' production practices in Pali district, Rajasthan, during 2018-19 to 2022-23

Years	Area (ha)	FLDs (n)	FLD yield (t ha ⁻¹)	Farmers' practice (t ha ⁻¹)	Yield increase (%)	Extension gap (t ha ⁻¹)	Technology gap (t ha ⁻¹)	Technology index (%)	B:C ratio (FLD)	B:C ratio (FP)
2018-19	6	15	0.48	0.31	55.48	0.17	0.42	46.44	2.2	1.6
2019-20	4	10	0.51	0.33	57.54	0.19	0.39	43.11	2.4	1.7
2020-21	4	10	0.69	0.43	60.37	0.26	0.21	23.56	2.7	1.9
2021-22	2	5	0.79	0.40	62.83	0.39	0.11	11.89	2.9	2.0
2022-23	2	5	0.80	0.42	59.36	0.38	0.10	11.11	3.1	2.2

Potential yield = 0.90 t ha⁻¹ Source: Kumhar, *et al.*, 2009.

progressive realization of crop yield potential. However, the extension gap increased from 0.20 to 0.43 t ha⁻¹, suggesting that farmers continuing traditional management practices were unable to benefit from improved production technologies. The consistently higher benefit-cost ratio under FLDs confirmed the economic feasibility of adopting the recommended production package. Similar improvements in cluster bean productivity under FLDs have been reported by Kiresur *et al.* (2013) and Bamboriya *et al.* (2023).

Sesame (*Sesamum indicum* L.): Sesame demonstrated the highest relative yield improvement among the kharif crops evaluated. Seed yield under FLDs increased from 0.48 to 0.80 t ha⁻¹, whereas farmers' practice produced only 0.31-0.42 t ha⁻¹, corresponding to yield advantages of 55.48 to 62.83% (Table 4). The remarkable increase in productivity resulted from the adoption of improved variety RT 346, seed treatment, balanced fertilization, line sowing and effective management of phyllody disease and leaf roller. Because sesame is highly sensitive to plant population, nutrient deficiency and disease incidence, improvements in these management practices resulted in substantial gains in seed yield. The technology gap declined sharply from 0.42 to 0.10 t ha⁻¹, accompanied by a reduction in technology index from 46.44% to 11.11%, demonstrating excellent adaptation of the improved technology package under farmers' field conditions. The increasing extension gap (0.17 to 0.38 t ha⁻¹) reflects the considerable yield advantage that can still be achieved by replacing traditional production practices with recommended technologies. Furthermore, the steady improvement in benefit-cost ratio confirmed that adoption of the improved package was economically viable under rainfed conditions. Similar findings have

been reported by Verma *et al.* (2015), Yadav *et al.* (2016) and Singh *et al.* (2017).

Performance of Frontline Demonstrations on Rabi Crops

Frontline Demonstrations (FLDs) conducted during the *rabi* seasons of 2018-19 to 2022-23 consistently produced higher grain yields and economic returns than the prevailing farmers' production practices (Tables 5-7). Unlike the kharif season, crop performance during *rabi* was less influenced by rainfall because crops were grown under limited irrigated conditions. Nevertheless, residual soil moisture, winter rainfall and the low organic carbon content of the sandy loam soils influenced nutrient availability and water-use efficiency, thereby affecting annual yield variation (Kumar *et al.*, 2024b).

Wheat (*Triticum aestivum* L.): Frontline Demonstrations (FLDs) on wheat variety Raj 4079 consistently recorded significantly higher grain yield than farmers' practice throughout the study period (Table 5). Grain yield under FLDs increased from 4.65 to 5.19 t ha⁻¹, compared with 3.14 to 3.45 t ha⁻¹ under farmers' practice, resulting in a 35.96 to 50.26% yield advantage. The higher productivity was mainly attributed to the adoption of improved cultivar, timely sowing, seed treatment, balanced fertilization (NPK + Zn), and irrigation scheduling at critical growth stages, which collectively improved crop establishment, nutrient uptake and grain filling. The technology gap decreased from 1.35 to 0.81 t ha⁻¹, while the technology index declined from 22.50% to 13.45% over the study period, indicating progressive realization of the crop's yield potential under farmers' field conditions. This improvement suggests that continuous technical supervision, timely input supply and greater farmer familiarity with the

Table 5. Yield performance and technological indicators of wheat (*Triticum aestivum* L.) under Frontline Demonstrations and farmers' production practices in Pali district, Rajasthan, during 2018-19 to 2022-23

Years	Area (ha)	No. of FLDs (n)	FLD yield (t ha ⁻¹)	Farmers' practice (t ha ⁻¹)	Yield increase (%)	Extension gap (t ha ⁻¹)	Technology gap (t ha ⁻¹)	Technology index (%)	B:C ratio (FLD)	B:C ratio (FP)
2018-19	6	15	4.65	3.14	40.09	1.51	1.35	22.50	2.6	2.0
2019-20	6	15	4.70	3.22	35.96	1.48	1.30	21.67	2.7	2.1
2020-21	4	10	4.91	3.35	46.45	1.56	1.09	18.13	2.9	2.2
2021-22	2	5	5.08	3.42	48.76	1.67	0.92	15.33	3.1	2.3
2022-23	2	5	5.19	3.45	50.26	1.74	0.81	13.45	3.3	2.4

Potential yield = 6.00 t ha⁻¹. Source: Shivran *et al.*, 2020

recommended production package enhanced technology performance over successive years. Conversely, the extension gap increased from 1.51 to 1.74 t ha⁻¹, reflecting the widening productivity difference between improved technologies and existing farmer practices and emphasizing the need for wider dissemination of recommended production technologies. The benefit-cost ratio remained consistently higher under FLDs than under farmers' practice, demonstrating the economic feasibility of the improved package through higher productivity and better input-use efficiency. These findings are consistent with those of Samui *et al.* (2000), Kiresur *et al.* (2013), Meena and Singh (2019), Dhillon *et al.* (2018) and Desai *et al.* (2024), who also reported that integrated crop management under FLDs significantly enhanced wheat productivity, reduced technology gaps and improved farm profitability under semi-arid conditions.

Mustard (*Brassica juncea* L.): Frontline Demonstrations (FLDs) on mustard variety 'Giraj' consistently recorded higher grain yield than farmers' practice throughout the study period (Table 6). Grain yield under FLDs increased from 1.28 to 1.70 t ha⁻¹, compared with 0.85 to 1.07 t ha⁻¹ under farmers' practice, resulting in yield improvements of 50.12-58.73%.

The superior productivity was attributed to the adoption of improved variety, balanced fertilization including sulfur and micronutrients, seed treatment, effective weed management, and integrated aphid management. Sulfur application, together with balanced nutrition, enhanced seed development and oilseed formation under the sulfur-deficient soils of western Rajasthan. The technology gap declined from 0.72 to 0.30 t ha⁻¹, while the technology index decreased from 36.20% to 15.00%, indicating progressive realization of the crop's yield potential under farmers' field conditions. The increasing extension gap (0.43 to 0.63 t ha⁻¹) highlighted the considerable scope for enhancing regional productivity through wider adoption of the demonstrated technologies. The benefit-cost ratio also increased from 2.3 to 3.4 under FLDs compared with 1.9 to 2.1 under farmers' practice, confirming the economic superiority of the improved production package. These findings indicate that integrated nutrient management, particularly sulfur supplementation, combined with improved crop protection and scientific crop management, substantially enhanced mustard productivity and profitability under the semi-arid conditions of Rajasthan. Similar improvements in yield, technology gap, and economic returns under FLDs have been

Table 6. Yield performance and technological indicators of mustard (*Brassica juncea* L.) under Frontline Demonstrations and farmers' production practices in Pali district, Rajasthan, during 2018-19 to 2022-23

Years	Area (ha)	No. of FLDs (n)	FLD yield (t ha ⁻¹)	Farmers' practice (t ha ⁻¹)	Yield increase (%)	Extension gap (t ha ⁻¹)	Technology gap (t ha ⁻¹)	Technology index (%)	B:C ratio (FLD)	B:C ratio (FP)
2018-19	4	10	1.28	0.85	50.12	0.43	0.72	36.20	2.3	1.9
2019-20	4	10	1.36	0.88	54.20	0.48	0.64	32.00	2.6	2.0
2020-21	6	15	1.53	0.99	54.44	0.54	0.47	23.55	2.9	2.0
2021-22	4	10	1.63	1.04	56.54	0.59	0.37	18.60	3.2	2.1
2022-23	4	10	1.70	1.07	58.73	0.63	0.30	15.00	3.4	2.1

Potential yield = 2.00 t ha⁻¹. Source: Singh *et al.*, 2018a.

Table 7. Yield performance and technological indicators of cumin (*Cuminum cyminum* L.) under Frontline Demonstrations and farmers' production practices in Pali district, Rajasthan, during 2018-19 to 2022-23

Years	Area (ha)	No. of FLDs (n)	FLD yield (t ha ⁻¹)	Farmers' practice (t ha ⁻¹)	Yield increase (%)	Extension gap (t ha ⁻¹)	Technology gap (t ha ⁻¹)	Technology index (%)	B:C ratio (FLD)	B:C ratio (FP)
2018-19	2	5	0.64	0.45	42.22	0.19	0.56	46.67	1.9	1.2
2019-20	2	3	0.71	0.49	44.02	0.22	0.49	40.83	2.2	1.4
2020-21	1	2	0.89	0.58	53.99	0.31	0.31	26.08	2.5	1.7
2021-22	2	5	0.91	0.59	54.24	0.32	0.29	24.17	2.7	1.9
2022-23	1	2	0.93	0.59	56.57	0.34	0.27	22.50	2.9	2.0

Potential yield = 1.20 t ha⁻¹. Source: Singh *et al.*, 2018b

reported by Singh *et al.* (2018a), Mehriya *et al.* (2020) and Yadav and Khan (2025).

Cumin (*Cuminum cyminum* L.): Frontline Demonstrations (FLDs) on cumin variety 'GC 4' consistently produced higher seed yields than farmers' practice throughout the study period (Table 7). Grain yield under FLDs increased from 0.64 to 0.93 t ha⁻¹, compared with 0.45-0.59 t ha⁻¹ under farmers' practice, resulting in a 42.22-56.57% yield advantage. The higher productivity was primarily attributed to the adoption of the wilt-tolerant variety GC 4, seed treatment, balanced nutrient management, timely irrigation, and integrated disease management, which effectively reduced wilt incidence and improved crop establishment under the semi-arid conditions of western Rajasthan. Consequently, the technology gap declined from 0.56 to 0.27 t ha⁻¹, while the technology index decreased from 46.67% to 22.50%, indicating better realization of the crop's yield potential under farmers' field conditions. Conversely, the extension gap increased from 0.19 to 0.34 t ha⁻¹, highlighting the considerable scope for enhancing cumin productivity through wider adoption of the demonstrated technologies. The benefit-cost ratio also increased from 1.9 to 2.9, compared with 1.2-2.0 under farmers' practice, demonstrating the economic viability of the improved production package. The higher profitability was mainly associated with increased seed yield and reduced disease-related losses, particularly from wilt. Despite its comparatively lower grain yield, cumin generated attractive economic returns because of its high market value, making it a suitable diversification crop for semi-arid production systems. Similar improvements in cumin productivity, reduction in technology gaps, and enhancement in farm profitability under

FLDs have been reported by Verma *et al.* (2015), Kumar *et al.* (2018) and Dhillon *et al.* (2018).

Integrated Performance of Frontline Demonstrations across kharif and rabi Crops

The overall evaluation of FLDs across six major crops demonstrated the effectiveness of integrated crop management under the semi-arid conditions of Pali district. Across all crops, FLDs consistently outperformed farmers' practices, with yield increases of 41.88 to 64.57%, reflecting the benefits of improved varieties, quality seed, balanced nutrient management, seed treatment, integrated pest management, and scientific supervision. Similar findings have been reported by Samui *et al.* (2000), Kiresur *et al.* (2013), and Kumar *et al.* (2018). Technology gaps declined substantially from 0.91 to 0.53 t ha⁻¹ in green gram, 0.58 to 0.20 t ha⁻¹ in cluster bean, 0.42 to 0.10 t ha⁻¹ in sesame, 1.35 to 0.81 t ha⁻¹ in wheat, 0.72 to 0.30 t ha⁻¹ in Indian mustard, and 0.56 to 0.27 t ha⁻¹ in cumin, accompanied by a continuous reduction in technology index. These trends indicate better adaptation of the recommended technologies and improved farmer management over successive years, consistent with earlier studies (Meena and Singh, 2019; Ali *et al.*, 2023). In contrast, extension gaps remained relatively high, indicating considerable scope for increasing crop productivity through wider adoption of improved technologies. Despite seasonal rainfall variability, particularly during the kharif season, FLDs maintained superior performance, demonstrating the resilience of integrated crop management under rainfed conditions. Moreover, consistently higher benefit-cost ratios across all crops confirmed the economic superiority of FLDs. Overall, the findings reaffirm that FLDs are an effective

extension approach for improving productivity, profitability, and technology dissemination in the dryland farming systems of western Rajasthan (Dhillon *et al.*, 2018; Singh *et al.*, 2016; Verma *et al.*, 2015).

Conclusions

Frontline Demonstrations (FLDs) significantly improved the productivity and profitability of green gram, cluster bean, sesame, wheat, mustard and cumin under the semi-arid conditions of Pali district, Rajasthan. The higher yields obtained in FLD plots were attributed to the integrated use of improved varieties, quality seed, balanced nutrient management, seed treatment, timely agronomic practices and effective pest and disease management. The progressive reduction in technology gap and technology index indicated that the demonstrated technologies were well suited to local agro-ecological conditions and increasingly approached their attainable yield potential. Higher benefit-cost ratios under FLDs confirmed the economic feasibility of the recommended production packages, while the persistence of extension gaps highlighted substantial scope for improving productivity through wider dissemination of scientific crop management practices. Overall, the study demonstrates that FLDs are an effective extension approach for enhancing crop productivity and farm profitability in semi-arid regions. However, as the study assessed only agronomic and economic performance, future research should include adoption surveys and long-term impact assessments to evaluate the sustainability and wider uptake of demonstrated technologies.

Authors' Contribution

All the authors involved in this study contributed to the fieldwork, data collection, analysis, interpretation and writing of manuscript.

Conflict of Interest

All authors agree to publication and there is no any conflict of interest.

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