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RESEARCH ARTICLE

Effect of improved Establishment Technologies (ET) on growth, yield, economics and energy use in Italian millet

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Abstract

Minor millets are small, seeded grains with enriched minerals and nutrients over other grain crops. Besides its nutritional quality, low yielding potential and lack of available technologies restricted its cultivation area. During the last few decades, most of crop-producing activities turned to mechanization except minor millets due to less focus on minor millet research. In this experiment, various establishment technologies were evaluated through mechanization with the objective of increasing foxtail millet (Italian millet) productivity. The treatments were formulated with various land management [(Ridges & Furrow (RF); Compartmental Bunding (CB); Broad Bed Furrow (BBF); Flatbed (FB)], sowing [Line sowing (LS), Sowing by drone (SD) and Machine sowing (MS)] and irrigation methods (Modified surge irrigation (MSI), Rain gun (RG)). The Randomized Block Design (RBD) was used to lay the experiment with 3 replications during the *Rabi* seasons of 2023 and 2024. Among the Establishment Technologies (ET), higher plant height was measured in ET-7 at 40 DAS (74.87 cm), 60 DAS (109.33 cm) and harvest stage (114.67 cm). Higher dry matter production of foxtail millet was recordedin ET-8 at 40 DAS (3772.40 kg/ha) & CT at 60 DAS (6035.87 kg/ha) and harvest stage (7541.90 kg/ha). In yield and economics parameters, ET-6 produced higher productive tillers (4.44/plant), grain yield (2340 kg/ha) & straw yield (4516 kg/ha) and it reflected on economic indices as higher net return (Rs. 47959) and benefit-cost ratio (1.65). ET-2 recorded the lowest values across all parameters during both the studies.

Keywords: dry matter production; economics; establishment technologies; foxtail millet; plant height; yield

Introduction

Foxtail millet (*Setaria italica*) is one of the earliest cultivated millet crop species, grown over thousands of years across Asia and various parts of Europe. In India, archaeological evidence available for minor millets cultivation from 3300 BC to 500 AD (1). It is known for short duration (70-85 days), which makes it a great option for areas with minimal precipitation and off-season cultivation. Foxtail millet as a naturally resilient and adaptable crop, it thrives in dry and semi-arid regions, where other staple crops struggle to survive (2). Foxtail millet's drought tolerance makes it a crucial component of sustainable agriculture, particularly in water-scarce regions (3). Foxtail millet is nutritious and an excellent provider of vitamins, dietary fiber, protein, energy and essential minerals such as iron (Fe), phosphorus (P), potassium (K), manganese (Mn), calcium (Ca) and zinc (Zn) (4). It is gluten-free and has a low glycemic index, contributing to its increased popularity as a healthy food (5). It has been widely incorporated into balanced diets for its role in preventing lifestyle diseases. The successful cultivation of foxtail millet begins with proper land management technologies, appropriate sowing methods and irrigation. Foxtail millet thrives in various soil types, including sandy loam and red soils with well drainage (6). However, it is sensitive to waterlogging, which require careful land selection and proper moisture management. Sowing method plays a critical role in crop establishment, influencing germination rates and overall yield (7). Line sowing at an optimal depth promotes better root and plant development compared to machine sowing, which can result in uneven seed placement.

Broadcasting is another suitable method, as it ensures better seed germination and maintains plant population density (8). A key advancement in foxtail millet cultivation is the use of seed pelleting. Seed pelleting enhances sowing efficiency by increasing uniform seed size, making handling and mechanization easier. It also improves germination percentage and reduces the seed rate, leading to more uniform crop stands. This technology is particularly beneficial for large-scale millet farming, where mechanized sowing methods are preferred (9). Foxtail millet primarily depends on rainfall for its water requirements, but supplementary irrigation can significantly enhance crop yields. Effective moisture management is essential, particularly during critical growth stages such as germination, tillering and flowering (10). Foxtail millet may require two to five irrigations during the growing season depending on soil type and climatic conditions. Proper irrigation scheduling ensures better root development, higher biomass production and improved grain quality. Excess irrigation or water stagnation should be avoided, as waterlogging can hinder plant growth and reduce yield (11). A key advantage of foxtail millet is its energy efficiency and minimal input requirements. Compared to water-intensive crops like rice and corn, foxtail millet requires significantly less water and more sustainable option for farmers in drought-prone regions. It is cultivated with minimal chemical inputs, reducing dependency on synthetic fertilizers and pesticides, which further enhances its sustainability. As the demand for nutritious and sustainable food options continues to rise, foxtail millet is gaining recognition as a valuable addition to global diets (12). Wider adoption of foxtail millet cultivation can strengthen agricultural resilience, offering long-term benefits to both farmers and consumers. In this study, we attempted to identify the most suitable (land configuration [(Ridges & Furrow (RF); Compartmental Bunding (CB); Broad Bed Furrow (BBF); Flatbed (FB)], sowing methods [Line sowing (LS), Sowing by drone (SD) and Machine sowing (MS)] and irrigation methods (Modified surge irrigation, Rain gun) for foxtail millet cultivation to enhance productivity and production.

Materials and Methods

The field trial was carried out at the Institute of Agriculture, TNAU, Kumulur, Tiruchirappalli, during the winter of 2023–2024. The study site is located at an altitude of 71 meters above MSL, at a latitude of 10.93° N and longitude of 78.83° E. In Experiment I (2023), the lowest temperature was 26.75 °C to 28.75 °C, while the highest temperature was 36.75 °C to 38.50 °C during the cropping season. Relative humidity was recorded from 60.81 % to 73.04 %. Mean evaporation varied from 3.42 mm to 5.24 mm and average of 3.60 hr of bright sunshine per day. In Experiment II (2024), the lowest temperature was 24.25 °C to 25.75 °C, while the highest temperature was 30.50 °C to 32.50 °C. Range of relative humidity was 74.58 % to 89.24 %. Mean evaporation varied from 2.7 mm to 6.2 mm, with an average of 3.84 hours of bright sunshine per day. The trial was laid out in a Randomized Block Design (RBD) with ten treatments. Variations in site layout, seed pelleting, sowing technologies and irrigation methods were incorporated into each treatment. Below is a complete treatment schedule.

Ten plots were maintained for each replication and totally 30 plots, were maintain for 3 replication and each measuring 7 × 3 m, with a sowing spacing of 22.5 cm × 10 cm. All packages and practices were followed as per the TNAU Crop Production Guide (2020). Sowing methods followed asper the treatment schedule and regular cultivation practices were strictly followed as per the TNAU Crop Production Guide (2020). The data was used to calculate energy using the following equations.

Treatment details

Treatments	Particulars
CT -	[FB + NPS + LS]
ET_1 -	[FB + PS+ DS + RG]
ET_2 -	[BBF + PS + SDS + MSI]
ET_3 -	[BBF + PS + SDS + RG]
ET_4 -	[BBF + PS + LS + RG]
ET_5 -	[R&F + PS + SDS + MSI]
ET_6 -	[R&F + PS + LS + MSI]
ET_7 -	[CB + PS + DS + RG]
ET_8 -	[CB + PS + LS + RG]
ET_9 -	[CB + PS + SDS + RG]

FB- Flat Bed; NPS- Non-Pelleted Seed; LS-Line Sowing; PS-Pelleted Seed; DS-Drone Sowing; RG -Rain Gun; BBF-Broad Bed Furrow; SDS-Seed Driller Sowing; MSI-Modified Surge Irrigation; R&F- Ridges and furrow; CB-Compartmental Bunding

$$\text{Energy ratio} = \frac{\text{Output energy (MJ/ha)}}{\text{Input energy (MJ/ha)}} \quad \text{Eqn. 1}$$

$$\text{Specific energy (MJ/kg)} = \frac{\text{Energy input (MJ/ha)}}{\text{Output (kg/ha)}} \quad \text{Eqn. 2}$$

$$\text{Energy productivity (kg/MJ)} = \frac{\text{Output (kg/ha)}}{\text{Energy input (MJ/ha)}} \quad \text{Eqn. 3}$$

$$\text{Energy profitability} = \frac{\text{Net energy (MJ/ha)}}{\text{Input energy (MJ/ha)}} \quad \text{Eqn. 4}$$

$$\text{Energy efficiency ratio} = \frac{\text{Energy output of main product (MJ/ha)}}{\text{Energy input (MJ/ha)}} \quad \text{Eqn. 5}$$

$$\text{Net energy (MJ/ha)} = \text{Energy output (MJ/ha) - Energy input (MJ/ha)} \quad \text{Eqn. 6}$$

The field trials were evaluated for different energy efficiency parameters to assess energy consumption and productivity in foxtail millet systems. A key metric for evaluating energy use efficiency is the energy ratio, which represents the ratio of output to input energy. Energy inputs from a variety of sources, such as labour, machinery, fuel for diesel engines, herbicides, fertilizer and seeds, have been assessed to determine the total energy ratio. The growing of crops was the source of the energy output (13). Furthermore, energy from by-products (e.g., straw) was calculated based on their biomass and corresponding energy equivalents. The power equivalents of each contributing factor were added up to determine all the input and output energy (Table 1) (14).

Statistical Analysis

The collected data were subjected to statistical analysis using Analysis of Variance (ANOVA). The significant difference of least (LSD) test was employed to analyse the mean square errors. This procedure calculates a single LSD value at 5 % significance level, which serves as the threshold for determining the significant versus non-significant differences between treatment means.

Table1. Equivalent energy (MJ/ha)

S.No	Power source	Equivalent energy (MJ)	Reference
A.	**Inputs**		
1.	Human labour male (h)	1.96 *8	(30 & 14)
2.	Human labour female (h)	1.57*8	(30 & 14)
3.	Machinery (h)		
a	Tractor	10.94	(31&14)
b	Power weeder ME, HE and FE) (MJ/ha)	493.64	(30)
c	Drone	11.93	(32)
d	Power weeder (MJ/ha)	452.40	(30)
e	Seed Pelleted	40	(33)
f	Cultivator	3.14	(14)
g	Rotavator	10.28	(14)
h	Battery-operated power sprayer	0.50	(14)
i	Boom sprayer tractor-operated	191.77	(34)
j	Reaper harvester (Including ME, HE and FE) (ha)	787.72	(35)
k	Modified surge irrigation (ha)	14107	(36)
l	Rain gun (ha)	8041.17	(36)
4.	Diesel fuel (L)	56.31	(14)
5.	Insecticide (lit)	101.20	(37)
6.	Fertilizer (kg)		
a.	Nitrogen	60.6	(37 & 14)
b.	Phosphate (P_2O_5)	11.1	(14)
e.	Farmyard manure	0.30	(38)
7.	Water for irrigation (m^3)	1.02	(37)
8.	Foxtail millet Seed (kg)	14.70	(30)
9.	Electricity (kWh)	11.93	(14)
B.	**Output (kg)**		
a.	Foxtail millet grain	14.70	(14)
b.	Foxtail millet straw	12.50	(14)

Results

Effect of establishment technologies on plant height (cm) of foxtail millet

Plant height (Table. 2) of foxtail millet was measured at 20 DAS, 40 DAS, 60 DAS and harvest stage and it was influenced by different land treatments, sowing methods, seed pelleting and irrigation. At initial stage (20 DAS), there was no statistically significant differences in plant height between the treatments. At 40 DAS, 60 DAS and harvest stages, maximum plant height was measured in establishment technologies ET-7 to 74.87 cm,109.33 cm and 114.67 cm which is on par with ET-1, which recorded 74.43 cm (40 DAS), 109.00 cm (60 DAS) and 113.4 cm (harvest stage). The least height of the plant was noted in treatment ET- 3 as 45.43 cm, 65.83 cm and 70.33 cm at 40 DAS, 60 DAS and harvest stage respectively. The same trend was recorded in experiment II as ET-7 produced taller foxtail plants with the height of 74.01 cm, 106.90 cm and 112.03 cm at 40DAS, 60 DAS and harvest stage respectively. The ET-7 was comparable with the ET-1, which recorded 73.86 cm, 106.21 cm and 110.56 cm of plant height to 40DAS, 60DAS and harvest stage. The shortest plant height was noted in ET-3 as 45.43 cm, 65.83 cm and 70.33 cm at the stage of 40 DAS, 60DAS and harvest respectively.

Effect of establishment technologies on dry matte production (kg/ha) of foxtail millet

Dry matter accumulation (Table 3) at 20 DAS, 40 DAS and 60 DAS, along with the maturity phase, is affected by various land preparations, planting technologies, pelleting of seeds and different watering methods in foxtail millet. No significant variation in dry matter accumulation was observed at 20 DAS. From the 40 DAS day treatment ET-7 (3772.40 kg/ha) was recorded as the greatest producer of dry matter which was comparable with ET-1 (3735.90 kg/ha). At the 60 DAS and harvest stages, more dry weight of accumulation was establishment technologies (CT), 6035.87 and 7541.90 kg/ha which is on pare with ET-6 (5934.77 & 7404.10 kg/ha), ET-8 (5532.30 and 6897.37 kg/ha). The lower weight of dry matter noted in ET-3 (2075.83, 3103.33 and 3949.30 kg/ha) at the 20 DAS, 40 DAS, 60 DAS and harvest stages. During the trial- 2 were obtained as ET-7 (3396.47 kg/ha) on the 40 DAS and CT (5434.38 and 6790.34 kg/ha) at 60 DAS and harvest. The minimum dry matter accumulation was observed in ET-3 (1902.97, 2842.79 and 3511.50 kg ha^{-1}) 40 DAS, 60 DAS and harvest stages.

Table 2. Effect of different establishment technologies on plant height (cm) at 20, 40, 60 DAS and harvest of foxtail millet during 2023 & 2024

Treatments	Experimental -1				Experimental -2			
	20 DAS	40 DAS	60 DAS	Harvest	20 DAS	40 DAS	60 DAS	Harvest
CT	32.83	67.41	97.33	102.80	30.56	66.14	95.51	99.22
ET-1	34.90	74.43	109.00	113.43	32.71	73.86	106.21	110.56
ET-2	30.88	46.00	66.40	71.00	28.74	45.21	65.20	68.36
ET-3	30.50	45.43	65.83	70.33	28.39	44.45	64.26	68.27
ET-4	32.52	60.63	87.50	92.60	30.29	59.50	85.52	89.04
ET-5	31.88	52.97	76.80	82.17	29.88	52.54	75.21	78.70
ET-6	33.44	67.70	98.87	103.23	31.14	66.50	96.05	100.28
ET-7	35.35	74.87	109.33	114.67	33.50	74.01	106.90	112.03
ET-8	33.16	67.58	97.97	103.03	30.92	65.96	95.64	99.55
ET-9	32.28	53.87	77.30	832.43	30.04	52.75	75.36	79.15
S.Ed.	**2.20**	**3.17**	**4.65**	**4.79**	**2.29**	**3.07**	**4.66**	**4.62**
C.D(P=0.05)	**NS**	**6.66**	**9.78**	**10.07**	**NS**	**6.44**	**9.79**	**9.70**

DAS- Day after Sowing; CT- Control; ET- Establishment Technologies

Table 3. Effect of different establishment technologies on dry matter production (kg ha $^{-1}$) at 20, 40, 60 DAS and harvest of foxtail millet during 2023 & 2024

Treatments	Experimental -1				Experimental -2			
	20 DAS	40 DAS	60 DAS	Harvest	20 DAS	40 DAS	60 DAS	Harvest
CT	696.52	3380.00	6035.87	7541.90	627.54	3042.00	5434.38	6790.34
ET-1	714.51	3735.90	4923.33	6128.37	647.93	3371.93	4449.63	5638.72
ET-2	606.92	2075.83	3103.33	3949.30	546.62	1902.97	2842.79	3511.50
ET-3	636.95	2132.03	3128.37	3987.13	573.64	1965.66	2851.90	3569.19
ET-4	648.98	2951.27	4342.47	5433.60	585.12	2670.15	3910.43	4960.17
ET-5	617.27	2520.00	3748.83	4736.37	559.85	2281.78	3383.27	4293.70
ET-6	665.32	3350.00	5934.77	7404.10	599.49	3015.00	5351.65	6676.61
ET-7	734.00	3772.40	4955.70	6198.46	672.96	3396.47	4472.75	5731.00
ET-8	676.42	3324.37	5532.30	6897.37	610.35	2993.01	4992.08	6423.86
ET-9	627.35	2592.80	3716.67	4683.00	564.99	2345.40	3349.23	4224.00
S.Ed.	**44.91**	**168.33**	**269.65**	**328.19**	**43.38**	**148.82**	**234.96**	**309.43**
C.D(P=0.05)	**NS**	**353.64**	**566.51**	**689.51**	**NS**	**312.66**	**493.63**	**650.08**

DAS- Day after Sowing; CT- Control; ET- Establishment Technologies

Effect of establishment technologies on grain and straw yield of foxtail millet

The increase in foxtail millet yield is influenced by various sowing methods, land management practices, different watering technologies and seed pelleting treatments. Various establishment technologies are used to determine the yield of foxtail millet. The yield value is presented in Table 4. The treatment ET-6 produced significantly higher grain (2340 kg/ha) and straw yield (4516.33 kg/ha) than the other treatments. It is on par with ET-8 (2290, 4441 kg/ha). Lower grain and straw yield were observed in ET-2 (1362.37 and 2702 kg/ha). Continuous season two the highest grain and straw yield recorded in ET-6 (2139.47 & 4231.63 kg/ha). The lower observed in ET-2 (1275.35 and 2560.08 kg/ha) of grain and straw yield.

Effect of establishment technologies on productive tillers per hill of foxtail millet

Tillers production in foxtail millet was influenced by adequate nutrient supply, proper moisture availability, various sowing methods, land management technologies and irrigation practices (Table. 4). Among the various establishment technologies, ET-6 recorded the highest number of tillers (4.44/ hill) which was at par ET-9 (4.38/hill) and CT (4.21/hill). The minimum tillers recorded in ET-2 (1.37/hill). In the second trial comes same trend continued ET-6 was recorded in more tillers (4.31/hill) which was comparable with ET-9 (4.26/hill) and CT (4.09/hill). The lower tiller produced ET-2 (1.34/hill).

Effect of establishment technologies on the economics of foxtail millet

The economics was calculated as per the treatments. The maximum gross return (₹121291/ha) was recorded with ET-6 of foxtail millet and it's on par treatment ET-8 was observed ₹118719 /ha. The data revealed that the maximum net return (₹47959/ha) was obtained under the same treatment in combination with the benefit-cost ratio value of 1.65. The lower gross return, net return and benefit cost ratio were concluded in treatment ET-2 (₹70685, 7453 and 1.12). Higher gross income, net income and benefit-cost ratio were simply due to higher yield during both years of experimental (Table 5). Continued trend recorded in both years of the experiment.

Effect of establishment technologies on the energetics of foxtail millet

Energy analysis showed variation in foxtail millet varied performance under different land configurations and establishment technological practices. In the treatments, the highest energy was used in ET-6 (30308.51 MJ/ha). Followed by ET-5 (29989.76 MJ/ha). Lower energy input was used in treatment ET-7 (22950.98 MJ/ha). The net energy (MJ/ha), energy ratio, specific energy, energy productivity (MJ/ha), energy profitability and energy efficiency ratio, noted in treatment ET-7 (65136.66, 3.57, 0.28, 2.71 and 1.40). The lower net energy (MJ/ha), the ratio of energy, specific energy, the productivity of energy (MJ/ha), the profitability of energy and the ratio of energy efficiency recorded in treatment ET-2

Table 4. Effect of different establishment technologies on productive tillers/ hill, grain and straw yield (kg/ha) of foxtail millet during 2023 & 2024

Treatments	Experimental -1			Experimental -2		
	Productive tillers hill $^{-1}$	Grain yield (kg ha $^{-1}$)	Straw yield (kg ha $^{-1}$)	Productive tillers hill $^{-1}$	Grain yield (kg ha $^{-1}$)	Straw yield (kg ha $^{-1}$)
CT	4.21	2097.67	4067.67	4.09	1926.87	3815.36
ET-1	3.44	1860.00	3650.67	3.36	1731.90	3414.19
ET-2	1.37	1362.37	2702.00	1.34	1275.35	2560.08
ET-3	1.40	1391.67	2742.00	1.36	1303.57	2613.42
ET-4	2.93	1666.33	3273.33	2.84	1549.11	3067.04
ET-5	2.43	1470.37	2893.00	2.36	1366.58	2717.96
ET-6	4.44	2340.00	4516.33	4.31	2139.47	4231.63
ET-7	3.57	1906.97	3694.67	3.53	1741.02	3454.41
ET-8	4.38	2290.00	4441.00	4.26	2111.70	4198.26
ET-9	1.90	1438.00	2819.33	1.84	1317.27	2643.43
S.Ed.	**0.23**	**90.20**	**177.03**	**0.21**	**84.64**	**163.49**
C.D(P=0.05)	**0.47**	**189.69**	**371.93**	**0.44**	**177.82**	**343.47**

DAS- Day after Sowing; CT- Control; ET- Establishment Technologies

Table 5. Effect of different establishment technologies on the economics of foxtail millet during 2023 & 2024

Treatments	Experimental -1				Experimental -2			
	Cost of cultivation (₹ /ha)	Gross return (₹ /ha)	Net return (₹ /ha)	BCR	Cost of cultivation (₹ /ha)	Gross return (₹ /ha)	Net return (₹/ha)	BCR
CT	84587	108748	24161	1.29	78687	99968	21281	1.27
ET-1	66212	96468	30256	1.46	62512	89838	27326	1.44
ET-2	63232	70685	7453	1.12	58532	66200	7668	1.13
ET-3	62232	72188	9956	1.16	58532	67661	9129	1.16
ET-4	69732	86426	16694	1.24	66032	80369	14337	1.22
ET-5	63632	76267	12635	1.20	59932	70911	10979	1.18
ET-6	73332	121291	47959	1.65	69632	110994	41362	1.59
ET-7	69212	98858	29646	1.43	65512	90333	24821	1.38
ET-8	72732	118719	45987	1.63	69032	109573	40541	1.59
ET-9	65232	74578	9346	1.14	61532	68375	6843	1.11

(*Statically not analyzed) DAS- Day after sowing; CT- Control; ET- Establishment Technologies

(23903.54, 1.80, 7.36, 0.14, 0.80 and 0.67). A similar trend was observed in both years of the experiment.

Discussion

Plant height (cm)

Plant height of foxtail millet varied significantly between different establishment technologies (ET). ET-7 recorded the tallest plant height compared to other treatments (Fig. 1). This might be the reason of cumulative effect of compartmental bunding, pelleted seeds, drown sowing and rain gun irrigation. Compartmental bunding may favoured to uniform distribution of water within the bed by restricting runoff and increasing soil profile moisture (15).

Palletisation increased the size of seeds and ensured soil moisture supply to the seeds by acting as a coated media and bridging soil and seeds (16). Drone sowing placed the seeds on soil surface of bed, which favoured to early germination of foxtail millet seeds and acquiring soil moisture and nutrients subsequently it results taller plants than other treatments (17). Rain gun irrigation provided moisture like natural rainfall and wetted the soil surface and seeds without losing much soil moisture (18). The least plant height observed in treatment ET-3 with cumulative effective of brad bed furrow land configuration, pelleted seeds, rain gun and machine sowing were due to improper seed placement, excessive sowing depth and inadequate moisture and nutrient availability (19).

Dry matter production (kg/ha)

Dry matter production was higher in treatments CT, ET-6 and ET-8 compared to other treatments of foxtail millet (Fig. 2). This might be the reason of cumulative effect of line sowing, pelleted seeds and supplements irrigation & land configuration. Line sowing promoted uniform plant spacing, reducing competition for nutrients, water and sunlight, leading to better root development and higher biomass production (20). Additionally, supplementary irrigation ensured consistent moisture availability during critical growth stages, enhancing nutrient uptake, photosynthesis and overall metabolic activities. These factors collectively contributed to increased dry matter accumulation, ultimately improving crop performance and yield potential (21). In contrast, lower dry matter accumulation was observed in seed drill sowing, it was due to ununiform sowing depth and soil moisture availability. Excessive seed depth negatively affected germination, as millet seeds are small and highly sensitive to deep placement (22). Proper soil management plays an essential role in plant growth and efficiency.

Yield (kg/

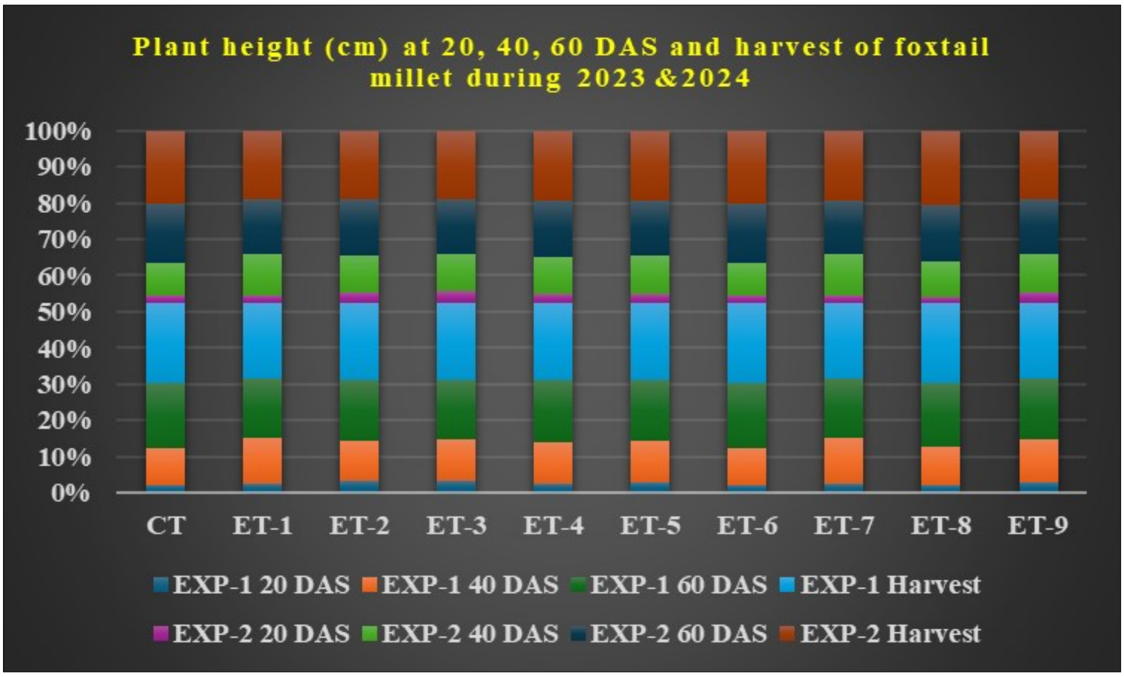

Fig. 1. Effect of different establishment technologies on plant height (cm) at 20, 40, 60 DAS and harvest of foxtail millet during 2023 and 2024. EXP- Excremental; DAS- Day after sowing; CT- Control; ET- Establishment Technologies.

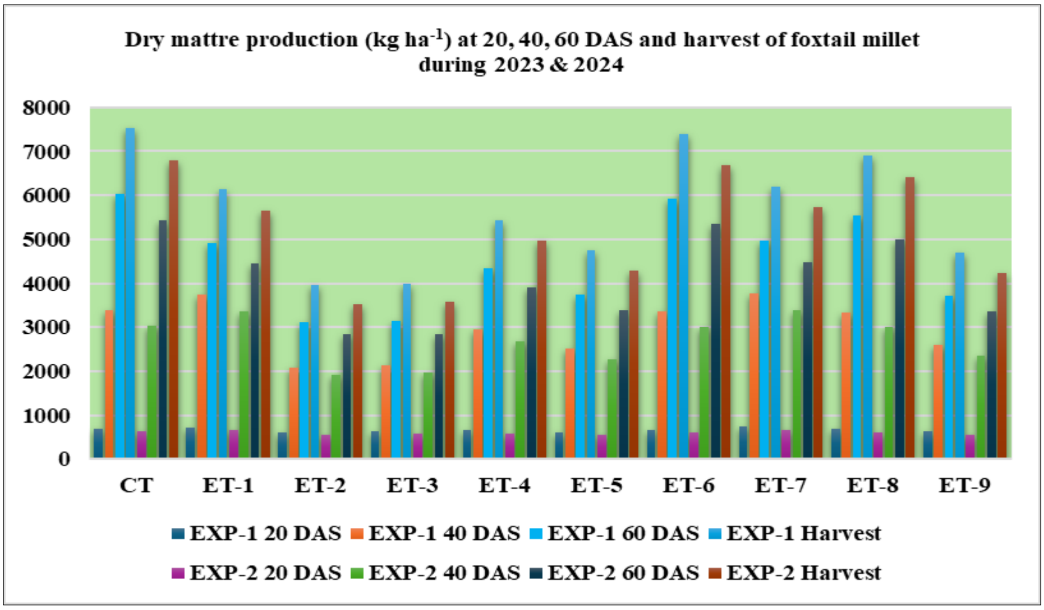

Fig. 2. Effect of different establishment technologies on dry matter production (kg/ha) at 20, 40, 60 DAS and harvest of foxtail millet during 2023 and 2024. EXP- Excremental; DAS- Day after sowing; CT- Control; ET- Establishment Technologies.

ha) and productive tillers/plant

Among the different technologies, line sowing and ridge and furrow land management proved to be the most effective. ET-6 achieved the highest yield and number of tillers due to improved root growth, water availability and nutrient uptake (Fig. 3 & 4). The ridge-and-furrow land management system performed better as it increased yield, like previous studies that reported enhanced results due to better aeration and the ability to store and continuously supply moisture and nutrients (23). In line sowing, seeds are placed at a depth of 1 cm in the soil, allowing for efficient nutrient and moisture uptake (24). The pelleting process helps reduce the seed rate, maintain proper plant spacing and improve crop establishment. Additionally, modified surge irrigation is more suitable for ridge -and-furrow land systems as it minimizes seepage losses, runoff and soil erosion, ultimately leading to higher yields and tillers (25). Conversely, ET-2 recorded a lower grain yield, likely due to insufficient photosynthetic accumulation, which resulted in poor vegetative growth. Moreover, deep seed placement in machine sowing negatively affected seedling emergence and root establishment, further reducing yield potential and tillers (26).

Economics

Economic indicators such as gross return, net return, cultivation cost and cost-benefit ratios were evaluated to assess the economic analysis for foxtail millet production. The findings revealed that ridge-and-furrow land preparation and line sowing with manual labour yielded higher net returns in ET -6 compared to other treatments. Seed pelleting played a crucial role by enhancing seedling vigour and tiller survival. This, in turn, improved productive tiller count and significantly boosted yield potential. Additionally, these technologies improved soil aeration, moisture retention and root expansion, creating favorable conditions for optimal crop growth (27). Conversely, machine sowing resulted in fewer productive tillers, primarily due to improper seed placement, excessive

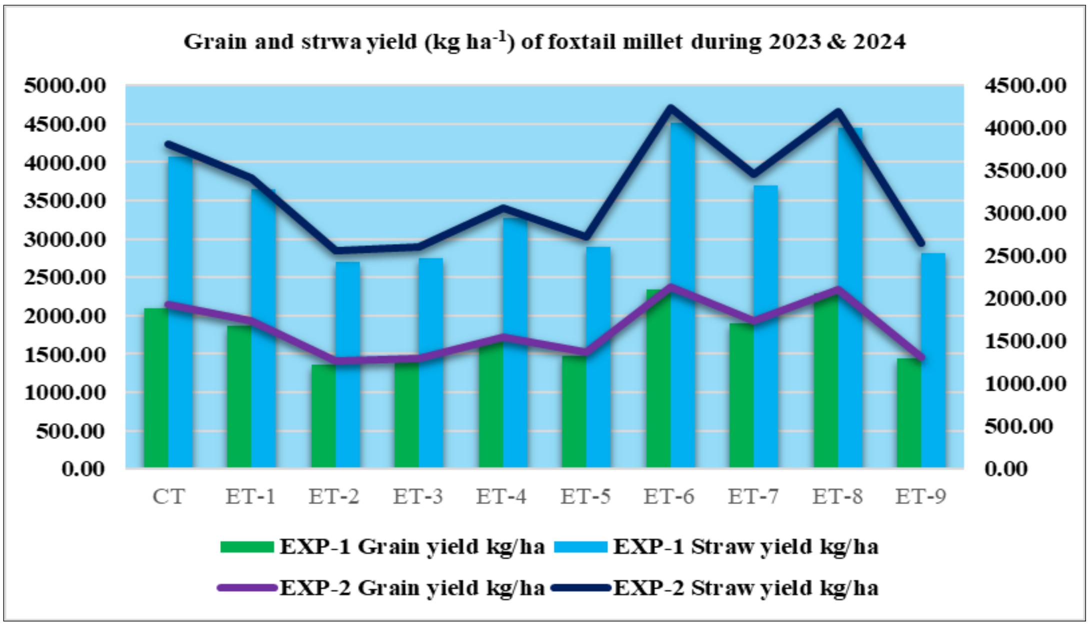

Fig. 3. Effect of different establishment technologies on grain and straw yield (kg/ha) of foxtail millet during 2023 and 2024. EXP- Excremental; DAS- Day after Sowing; CT- Control; ET- Establishment Technologies.

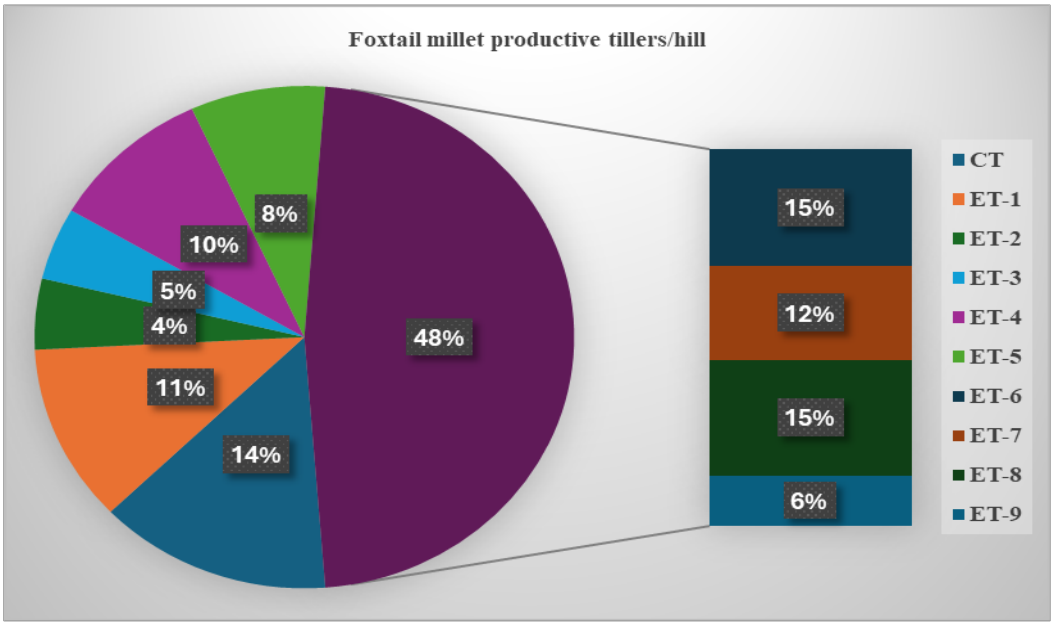

Fig. 4. Effect of different establishment technologies on productive tiller/ plant of foxtail millet during 2023 and 2024. EXP- Excremental; DAS-Day after Sowing; CT- Control; ET- Establishment Technologies.

sowing depth and inconsistent moisture distribution. Delayed and uneven emergence from deep seed placement negatively impacted secondary tiller formation, while higher plant density in machine-sowing treatments increased competition for nutrients, further restricting yield potential (19).

Energy (MJ/ha)

Among the various sowing methods, line sowing with pelleted seeds emerged as the most efficient in energy use (MJ/ha) and cost-effective approach (Fig. 5 & 6). This technology optimizes seed placement, reduces seed wastage and ensures uniform plant spacing by maintaining uniform depth and spacing, which enhances germination rates and crop establishment. Additionally, lower input costs from minimized re-sowing and reduced seed usage contribute to lower energy consumption per unit of output. The benefits of seed pelleting extend beyond the establishment, as it improves nutrient uptake, increases tiller production and enhances biomass accumulation, ultimately leading to yields (28). These improvements result in greater energy output (MJ/ha) and increased economic returns through better marketable produce and reduced input costs. In contrast, drone sowing, despite its technological advancements, showed lower energy efficiency and economic viability due to uneven seed distribution, inconsistent sowing depth and reduced plant establishment rates. The high initial investment, operational costs and need for skilled labour make drone sowing less practical, especially for small and medium-scale farmers. As a result, line sowing with pelleted seeds remains the most sustainable and profitable method for maximizing both energy efficiency and economic returns in foxtail millet cultivation (29).

Conclusion

The study demonstrated that establishment technologies significantly influenced plant height, dry matter production,

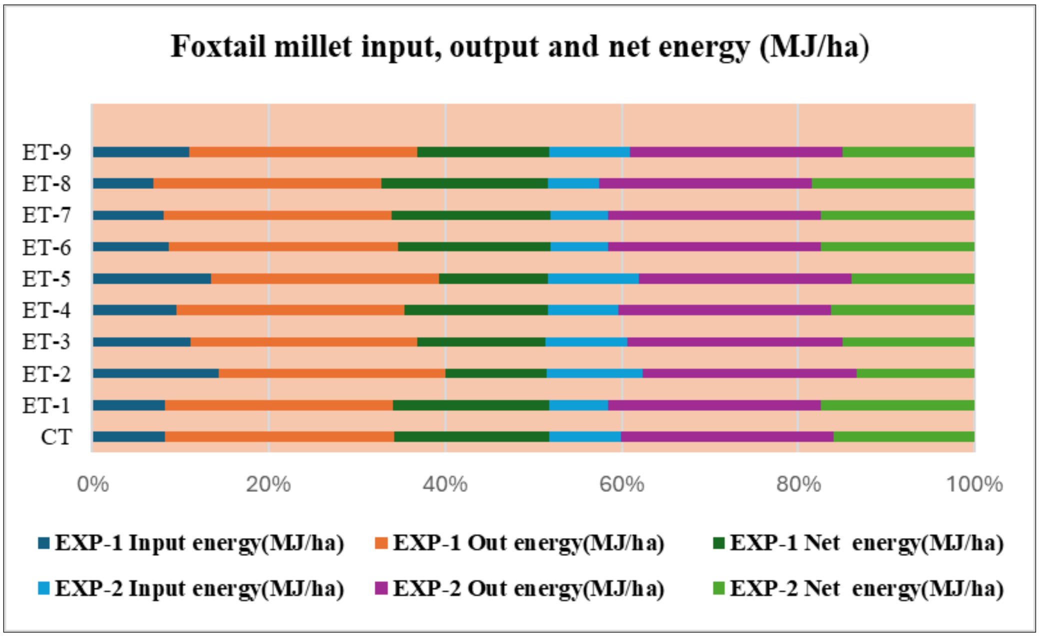

Fig. 5. Effect of different establishment technologies on input, output and net energy (MJ/ha) foxtail millet during 2023 and 2024. EXP-Excremental; DAS- Day after Sowing; CT- Control; ET- Establishment Technologies.

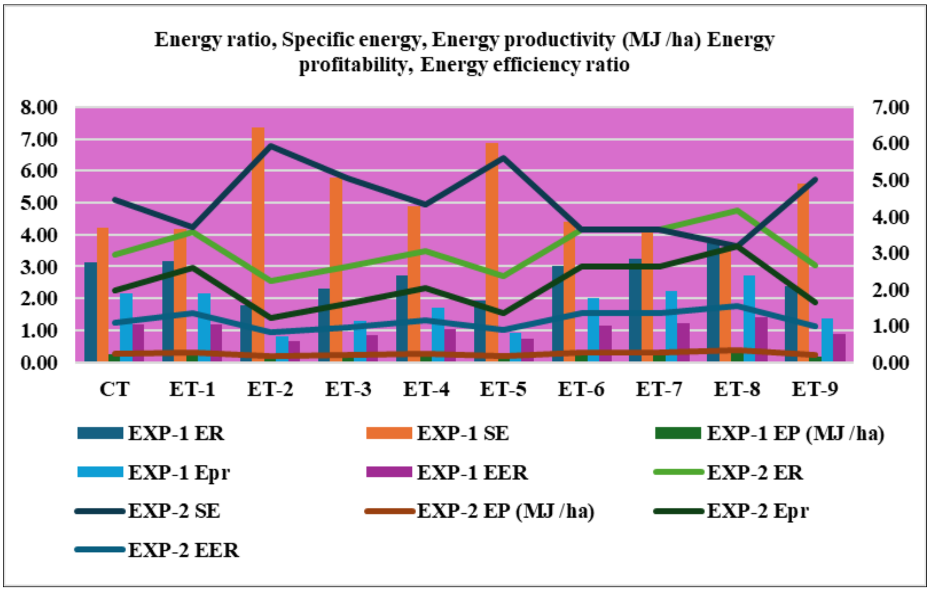

Fig. 6. Effect of different establishment technologies on Energy ratio, Specific energy, Energy productivity (MJ /ha) Energy profitability, Energy efficiency ratio foxtail millet during 2023 and 2024. EXP- Excremental; DAS- Day after sowing; CT- Control; ET- Establishment technologies; ER-Energy ratio; EP (MJ/ha)-Energy productivity; EPR=Energy profitability; ER- Energy ratio; SE-Specific energy.

yield, economic returns and energy efficiency in foxtail millet cultivation. Among the treatments, ET-6 consistently recorded the highest grain and straw yield, net returns and benefit-cost ratio, making it the most profitable method. ET-7 produced the tallest plants, while ET-3 recorded the minimal height of plant across all growth stages. Dry matter content was highest in ET-7 at early stages and CT at maturity, highlighting the impact of proper soil and sowing management. Additionally, ET-8 showed the highest energy efficiency, while ET-2 had the lowest yield and economic returns. Overall, ridge-and-furrow land preparation, line sowing and pelleted seeds (ET-6) emerged as the most effective technologies, ensuring higher productivity, sustainability and profitability in foxtail millet cultivation.

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Authors' contributions

KP carried out the experiment, took observations, analysed the data and writing -original draft. Conceptualization, supervision, funding acquisition, writing the review and editing was performed by SDS. AV, RK, AS, RS and KPR helped in summarizing and revising the manuscript.

Compliance with ethical standards

Conflict of interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical issues: None

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