PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol x(x): xx–xx
https://doi.org/10.14719/pst.7751

HORIZON
e-Publishing Group

RESEARCH ARTICLE

Impact of mechanization with improved technologies on germination and crop stand indices of foxtail millet (*Setaria italica*)

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OPEN ACCESS

ARTICLE HISTORY
Received: 15 February 2025
Accepted: 15 March 2025
Available online
Version 1.0 : 27 March 2025

CITE THIS ARTICLE
Keerthanan P, Sivakumar SD, Vijayaprabhakar A, Karthikeyan R, Surendrakumar A, Sivakumar R, Ragunath KP, Vinodhini SM. Impact of mechanization with improved technologies on germination and crop stand indices of foxtail millet (*Setaria italica*). Plant Science Today (Early Access). https:/doi.org/10.14719/pst.7751

Abstract

Minor millets encompass more minerals and nutrients than other food grains. They are being cultivated in limited areas due to poor yielding ability and lack of improved technologies (pelleting, sowing methods, land configurations and supplemental irrigation). Mechanization has been adopted intensively by the farming community, for the last two decades for most of the crop production activities. In minor millet production, mechanization has not been adopted notably and there was no strong evidence for mechanization under the minor millet production system. The present research study assessed the establishment (germination, plant population, seed vigour index, seedling height and root length) of minor millet (Italian millet) under mechanization coupled with improved technologies. The strategies included Pelleting (PS) and Non-pelleting (NPS), land configurations (RF-Ridges and Furrow; CB-Compartmental Bunding; BBF-Broad Bed Furrow; FB-Flat Bed) sowing methods (DS-Drone Sowing; LS-Line Sowing and SDS-Seed Driller Sowing) and irrigation methods (MSI- Modified Surge Irrigation; RG-Rain Gun) for evaluation. A Randomized Block Design with three replications was used for the experiment layout during the Rabi season of 2023 and 2024. Observations were made and data subjected to ANNOVA and t-test. The results revealed that treatments IT-1, (FB+PS+DS+RG) recorded ($P<0.05$) significant higher germination per cent (48.67 %), plant population (88.40/m^2), lower cost of sowing (Rs. 2100/-) and IT-7, (CB+PS+DS+RG) observed higher number of leaves (4.14), seed vigour index (2784.49), seedling height (7.03 cm) and root length (12.50 cm). Treatment IT-3, (BBF+PS+SDS+RG) registered ($P<0.05$) significant lower germination per cent, plant population, number of leaves, seed vigour index, seedling height and root length, registered treatment.

Keywords

foxtail millet; improved technologies; mechanization; pelleting; sowing methods; supplemental irrigation

Introduction

Foxtail millet (*Seteria italica*) is one of the oldest cultivated millet species, primarily grown in Asia, particularly India and China. Renowned for its resilience, it thrives in poor soil conditions and drought-prone regions, making it a reliable crop in challenging environments. Its short growing season and ability to produce significant yields with minimal inputs add to its agricultural value (1). Nutritionally, foxtail millet is rich in dietary fiber, iron and protein and its antioxidant content provides additional health benefits. As a gluten-free grain, it is gaining popularity as a healthy food in modern diets while remaining a staple in traditional cuisine (2). Even though it has enormous health benefits, production and cultivation have declined over the past seven decades. During 1950-1960, millets were cultivated in an area of 5120.8 ha with a production of 2050 tonnes and 399 kg/ha of average productivity. It has been declined to 602.9 ha of cultivated area with 403.25 tonnes productions and 684.4 kg/ha productivity in the last decade (2011-2021). This decline in area and production was due to the increment in paddy, wheat and maize cultivation area and these crops have high yielding potential than minor millets (3). Yield potential of minor millet is very low, since it cultivated in resource poor rain-fed environment.

In addition to that, research and development in minor millets was very less compared to other crops (cereals, millets, pulses and oil seeds), which also the reason to put down the minor millet cultivation area, production and productivity over other food grain crops. Recently millets have gained attention due to their health benefits and it demands to grow more, increase production and productivity to meet the future requirement. Most farmers grow minor millet (foxtail millet) under resource poor rain-fed environment. It restricts the farmers to invest more on millet cultivation, so that farmers raised minor millets with least expenditure due to lower yield potential (4). The cultivation practices start from one primary tillage operation followed by sowing through broadcasting and one secondary tillage operation to cover seeds. Hence, there is a need to identify the alternate establishment methods for minor millet (foxtail millet) to give optimum crop establishment with lower expenditure to sustain growers. The hypothesis was alternate crop establishment methods through improved technologies can helps to attain optimum crop stand of foxtail millet with low cost. Germination and the optimum plant population of any crop are necessary to achieve higher productivity. An appropriate establishment method is ensured by adapting appropriate sowing methods, land configurations and irrigation practices (5, 6).

Broadcasting is widely practiced sowing method in India for many crops due to its less labour requirement. At the same time, it will give uneven and poor germination due to improper placement and covering of seeds (7). Line sowing is a reliable method to obtain higher germination and population subsequently increased production and productivity (5, 8). The main disadvantage of line sowing is the high cost due to more labour requirement and it needs more time to complete the sowing operation (9, 10). Mechanization is booming everywhere in farm operation due to its less labour requirement and time-saving nature (11, 12). For sowing agriculture crops, machinery developed for most of the crops (13).

But in minor millets, mechanized sowing is not familiarized among the farming community due to lack of practical knowledge, demonstration and its suitability at field level (14). Before that, only few studies were addressed the growth and development of minor millets under different land modifications with line-sowing methods. There was no research dealt with mechanized sowing and its effect on millet establishment. To meet out this research gap, experiment was conducted with the objective of studying the effect of improved technologies (pelleted seed, land configuration, sowing method and supplementary irrigation) on crop establishment indices (germination, plant population, seedling height, root length and number of leaves and seed vigour) of foxtail millet.

Materials and Methods

This experiment was conducted during winter season of 2023 -2024 at Institute of Agriculture, Tamil Nadu Agricultural University, Kumulur, Tiruchirappalli. This location is situated at 10.93°N latitude, 78.83° E longitude and at an altitude of 71 meters above mean sea level. During the cropping period of experiment-I (2023), the maximum temperature ranged from 36.75 °C to 38.50 °C and the minimum temperature varied between 26.75 °C and 28.75 °C, with relative humidity levels fluctuating between 60.81 % and 73.04 %. The total rainfall of 14 mm received from the day of sowing to 10th day after sowing. Bright sunshine hours per day averaged 3.60 hours and evaporation ranged from 3.42 mm to 5.24 mm. During the experiment II (2024), the maximum temperature ranged from 30.50 °C to 32.50 °C and the minimum temperature varied from 24.25 °C to 25.75 °C, with relative humidity levels ranging from 74.58 % to 89.24 %. 23.8 mm of rainfall was recorded over four rainy days and bright sunshine hours per day averaged 3.84 hours. Evaporation ranged from 2.7 mm to 6.2 mm. The varietal characteristics of foxtail millet and soil characteristics of the experiment site were furnished in the Table 1 and 2 respectively. The experiment was carried out in Randomized Block Design (RBD) with ten treatments as improved technologies. Improved Technologies (IT) were formulated as a combination of land configuration, pelleting, sowing and irrigation methods. The land configuration techniques of Flat Bed (FB), Broad Bed Furrow (BBF), Compartmental Bunding (CB) and Ridges and Furrow (R&F) were used. For pelleting, pelleted and non-pelleted seeds were included. Different sowing *viz*., of line sowing, drone sowing and seed drill sowing were included in the treatments. In irrigation, conventional irrigation, raingun and modified surge irrigation are included. Seed pelleting is one of the seed enhancement techniques, in which the seeds are coated with help of (seed pelletizer) inert/nutrient (TNAU Pelleting mixture) material with the help of adhesive (Gum acacia) which will increase the seed size to the required level. Pelleting helps to provide uniform plant spacing by mechanized sowing. Sowing pelleted seeds offer protection from rodents, birds and insects.

Table 1. Soil physical and chemical properties of experimental field

Particulars	Composition	Methodology
A. Physical properties of soil		
Clay (%)	31.8	International Pipette Method
Silt (%)	25.6	
Sand (%)	41.2	
Textural class	Sandy clay loam	
Bulk density (mg/cc)	1.23	
Porosity (%)	51.0	
Field capacity (per cent)	21.3	
Permanent wilting point (%)	9.20	
B. Chemical properties of soil		
pH	8.12	1:2.5 soil water suspension method
Electrical conductivity (dS/m)	0.25	1:2.5 Soil water suspension method
Organic carbon (%)	0.35	Wet chromic acid digestion method
Available Nitrogen kg/ha)	205 (Low)	Alkaline permanganate method
Available Phosphorus (kg/ha)	11.5 (Medium)	0.5 M Sodium-bi-carbonate extraction using colorimetry
Available Potassium (kg/ha)	150 (Medium)	Neutral normal ammonium acetate method

Table 2. Varietal characteristics of foxtail millet seeds

Characters	Description
Percentage	PS 4 x Ise 198
Duration (days)	80-85 days
Season	Rainfed
Grain yield (kg/ha)	2115 kg/ha
Special features	It is drought tolerant. The plant has 5-7 productive tillers and non-shattering grains. The grains are bold and attractive brownish yellow in colour. The grains are nutritious with preferred grain qualities for cooking and value addition

Treatment details

CT - [Flat Bed (FB) + Non-Pelleted Seed (NPS) + Line Sowing (LS)]

IT1 - [Flat Bed (FB)+ Pelleted Seed (PS) + Drone Sowing (DS) + Rain Gun (RG)]

IT2 - [Broad Bed Furrow (BBF) + Pelleted Seed (PS)+ Seed driller Sowing (SDS) + Modified Surge Irrigation (MSI)]

IT3 - [Broad Bed Furrow (BBF) + Pelleted Seed (PS)+ Seed driller Sowing (SDS) + Rain Gun (RG)]

IT4 - [Broad Bed Furrow (BBF) + Pelleted Seed (PS)+ Line Sowing (LS)+ Rain Gun (RG)]

IT5 - [Ridges and furrow (R&F) + Pelleted Seed (PS)+ Seed driller Sowing (SDS) + Modified Surge Irrigation (MSI)]

IT6 - [Ridges and furrow (R&F) + Pelleted Seed (PS)+ Line Sowing (LS)+ Modified Surge Irrigation (MSI)]

IT7 - [Compartmental Bunding (CB) + Pelleted Seed (PS) + Drone Sowing (DS) + Rain Gun (RG)]

IT8 - [Compartmental Bunding (CB) + Pelleted Seed (PS) + Line Sowing (LS) + Rain Gun (RG)]

IT9 - [Compartmental Bunding (CB) + Pelleted Seed (PS) + Seed driller Sowing (SDS) + Rain Gun (RG)]

Each treatment was replicated three times so there were a total of 30 plots (Fig. 1) with 7×3 m size and spacing of 22.5 cm × 10 cm used for sowing and filed view after establishment in (Fig. 2). All the package and practices followed as per the crop production guide TNAU 2020. Sowing was done as per the treatment schedule with 12.5 kg/ha of seeds and sowing depth was maintained as 1cm, 0 cm and 2.5 cm in line sowing, drone sowing and seed drill respectively. The cost of different improved technologies was furnished in the result and regular cultivation practices followed strictly as per the TNAU crop production guide 2020. From the 5th day onwards, regular observations were recorded to analyse the establishment of foxtail millet. The germination was recorded by using quadrate with size of 0.25 m^2. The quadrate was placed at five different places in a random manner and it was done in every individual experiment plots. From the quadrate, germinated seedlings were counted on 5th day and 10th day of sowing and the data used to work out the germination percentage through the following equation 1.

Number of leaves counted and seedling height and root length were measured from the experiment plots at 5th and 10th day of sowing. These data were used to work out the seed vigour index as per the equation 2 given below.

$$\text{Germination (\%)} = 100 \times \frac{\text{Number of germinated seeds}}{\text{Number of seeds sown}} \quad \text{(Eqn. 1)}$$

$$\text{Seed vigour index (SVI)} = \text{Shoot length + Root length x Germination per cent} \quad \text{(Eqn. 2)}$$

From these collected data, all parameters were interpolated for days from 5th to 10th day after sowing.

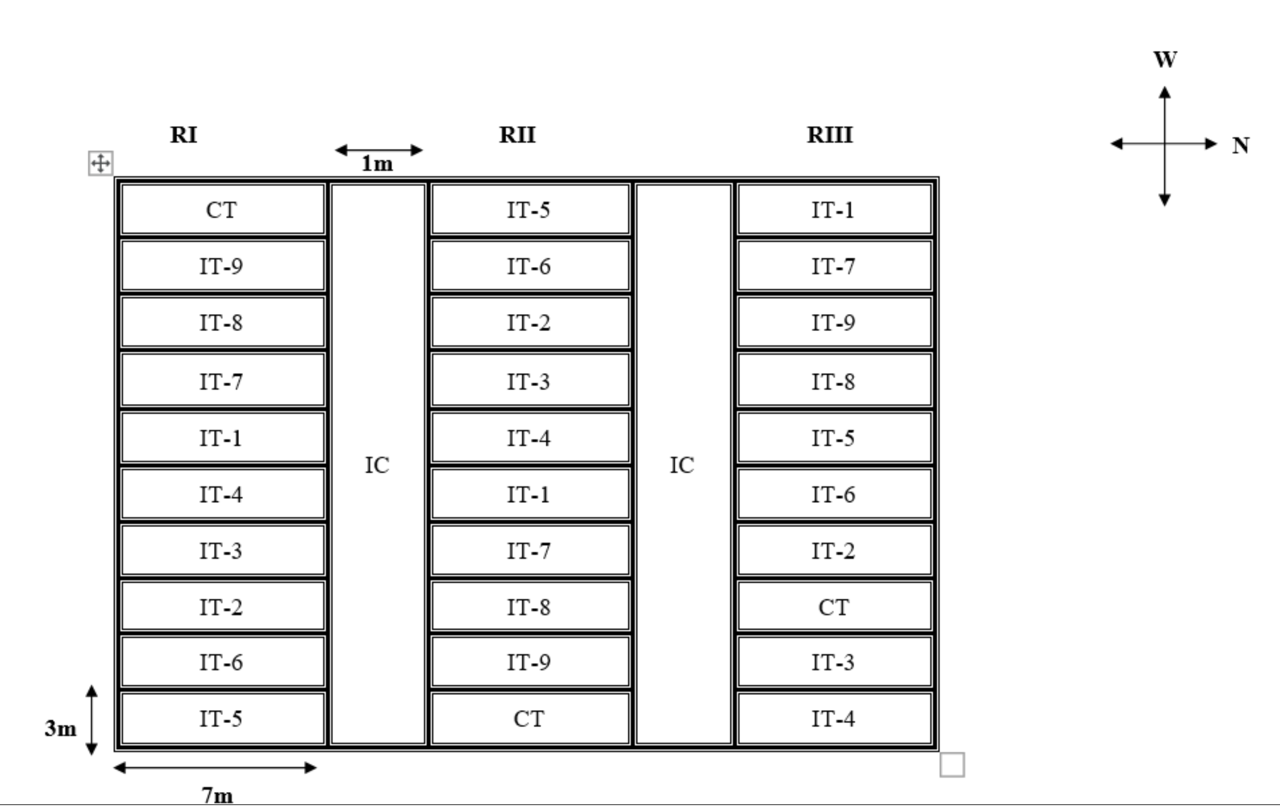

Fig. 1. Experimental layout, [IC -Irrigation Channel].

Fig. 2. Field view after establishment.

Statistical analysis

The germination, crop stand and seedling growth index of foxtail millet computed data was subjected to statistical scrutiny as per the procedure given (15). The analysed data were subjected to Least Square Difference (LSD) test and compare the effect of treatment at $P<0.05$ using language R, version 4.0.1 with package of agricolae. The germination, soil and weather data collected from experiment locations were pooled and used for Pearson's correlation test and correlation coefficient value between 0.5 to 1 considered as strong correlation. The graphical representation done by language R; version 4.0.1 was used with package of corrplot (16).

Results

Effect of different improved technologies on Germination Percentage (GP) and Plant Population (PP)

From the result, on the 5th day of sowing, the highest GP (37.67 %) and PP (69.04/m^2) of foxtail millet were observed in IT-1 (Fig. 3 and Fig. 4) which was statistically on par with IT-7 with 37.59 % of germination and 68.84/m^2 of plant population. Next to that, treatment IT-6, CT and IT-8 recorded higher GP to 33.93 %, 33.82 % and 33.10 %. In plant population, IT-6, IT-8, CT and IT-4 produced more plants/m^2 in order to 61.85/m^2, 59.25/m^2, 58.33/m^2 and 56.61/m^2 and there was no significant difference between them (IT-6, IT-8, CT and IT-4) in both GP and PP. Lower GP and PP was recorded in IT-5, IT-9, IT-2 and IT-4 in order to 22.87 %, 22.24 %, 21.28 % and 20.97 % for GP and 49.52/m^2, 47.69/m^2, 47.19/m^2 and 47.06/m^2 for PP. The same trend continued up to on 10th day of sowing, when IT-1 registered the highest GP (48.67 %) and PP (88.40/m^2) and this was comparable with IT-7, which recorded 48.12 % GP and 87.35/m^2 PP. Lower GP of 32.60 %, 31.91 %, 30.51 % and 30.23 % and PP of 65.51/m^2, 65.13/m^2, 63.75/m^2 and 62.75/m^2 were recorded in IT-5, IT-9, IT-2 and IT-3. During experiment -II, similar results were obtained as IT-1 was dominated in GP (35.95 % & 46.45 %) and PP (65.89/m^2 & 84.36/m^2) on 5th and 10th day of sowing. This was comparable with IT-7, which recorded GP of 35.86 % and 45.90 %; and PP 65.66/m^2 and 83.31/m^2 on 5th and 10th day respectively. The lower GP and PP were recorded in IT-5, IT-9, IT-2 and IT-4 treatments from 5th to 10th day of sowing.

Effect of different improved technologies on Seedling Height (SH) and Root Length (RL)

Seedling height and root length of foxtail millet were measured at 5th and 10th day of sowing to analyse the impact of various improved technology. From the observation on

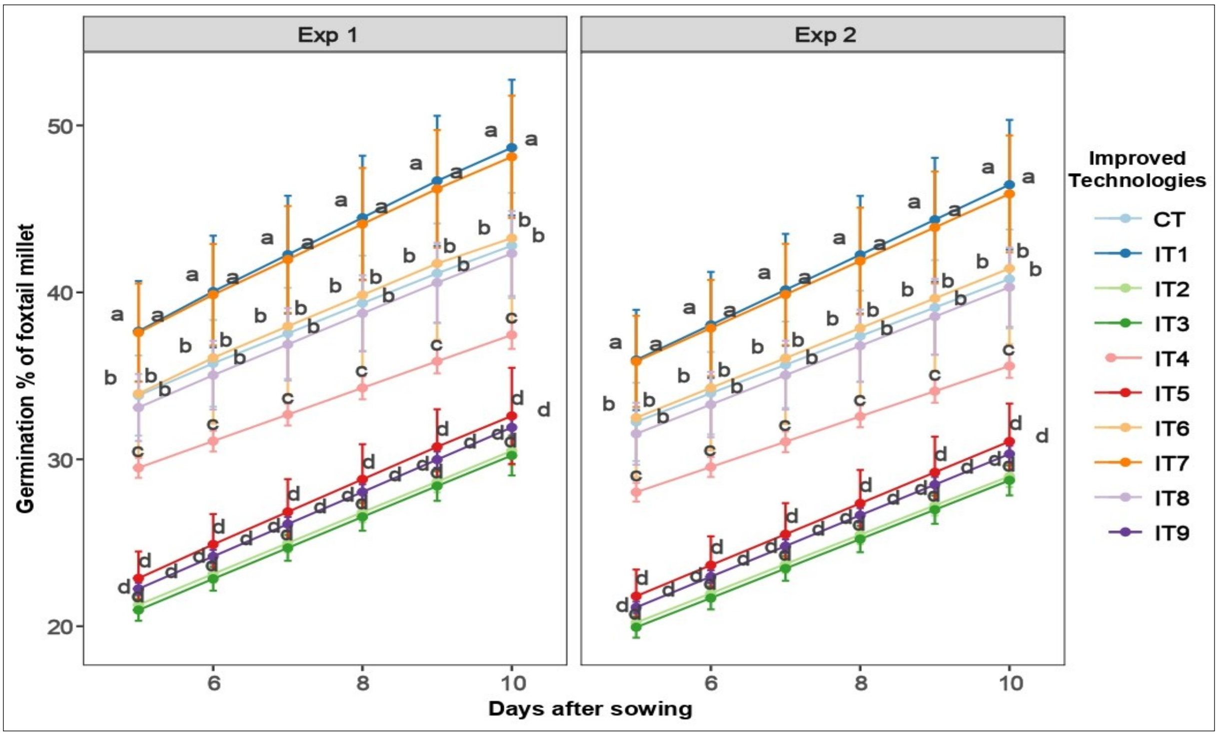

Fig. 3. Effect of different improved technologies (IT) on germination % of foxtail millet from 5 DAS to 10 DAS during the experiment 1 and 2. Standard error of the average values was mentioned as vertical bars. Significant variations (P<0.05) between the treatments were mentioned as letters.

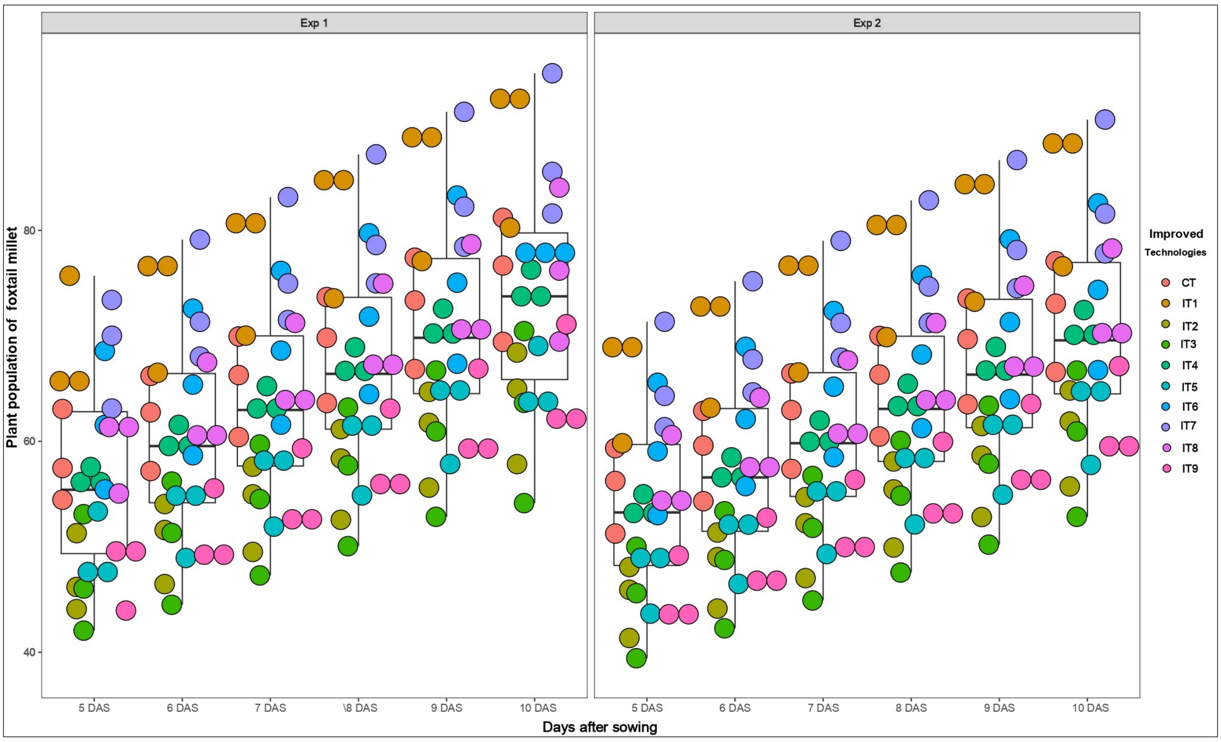

Fig. 4. Effect of different Improved Technologies (IT) on plant population/m^2 of foxtail millet from 5 DAS to 10 DAS during the period of experiment 1 and 2. Box plot given to each day of the observation to explain the data distribution at various treatments.

5th day of sowing, the higher SH (4.01 cm) and RL (4.94 cm) was measured in IT-7 and it was statistically on par with IT-1 with the SH of 3.86 cm and RL of 4.92 cm (Fig. 5 and Fig. 6). Next to that, treatment IT-6, IT-8 and CT recorded higher SH to 3.45 cm, 3.38 cm & 3.37 cm; and RL of 4.35 cm, 4.28 cm & 4.21 cm and there was no significant difference between them (IT-6, IT-8 and CT). Lower SH was observed in IT-5, IT-9, IT-2 and IT-3 with values of 2.49 cm, 2.43 cm, 2.23 cm & 2.19 cm and likewise, RL was 3.09 cm, 3.06 cm, 3.00 cm and 2.95 cm respectively. The same trend continued up to 10th day of sowing, when IT-7 registered the highest SH of 7.03 cm and RL of 12.50 cm and it was comparable with IT-1 with 6.95 cm of SH and 12.45 of RL. After that, IT-6 IT-8 and CT recorded higher SH (5.96 cm, 5.69 cm & 5.57 cm respectively) and RL (10.76 cm, 10.62 cm &10.48 cm). These all were on par with each other's. Lower SH was recorded in IT-5, IT-9, IT-2 and IT-3 with values of 3.57 cm, 3.39 cm, 3.26 cm & 3.23 cm respectively. The same treatments were produced lower RL of 3.23 cm 7.07 cm, 6.76 cm, 6.63 cm & 6.56 cm respectively. Similar results were obtained in experiment- (II) as higher SH of 3.89 cm and RL of 4.80 cm on 5th day of sowing and SH of 6.83 cm and RL of 12.13 cm in IT-7 on 10th day of sowing. This was comparable with IT-1, which recorded SH of 3.79 cm and 6.76 cm and RL of 4.79 cm

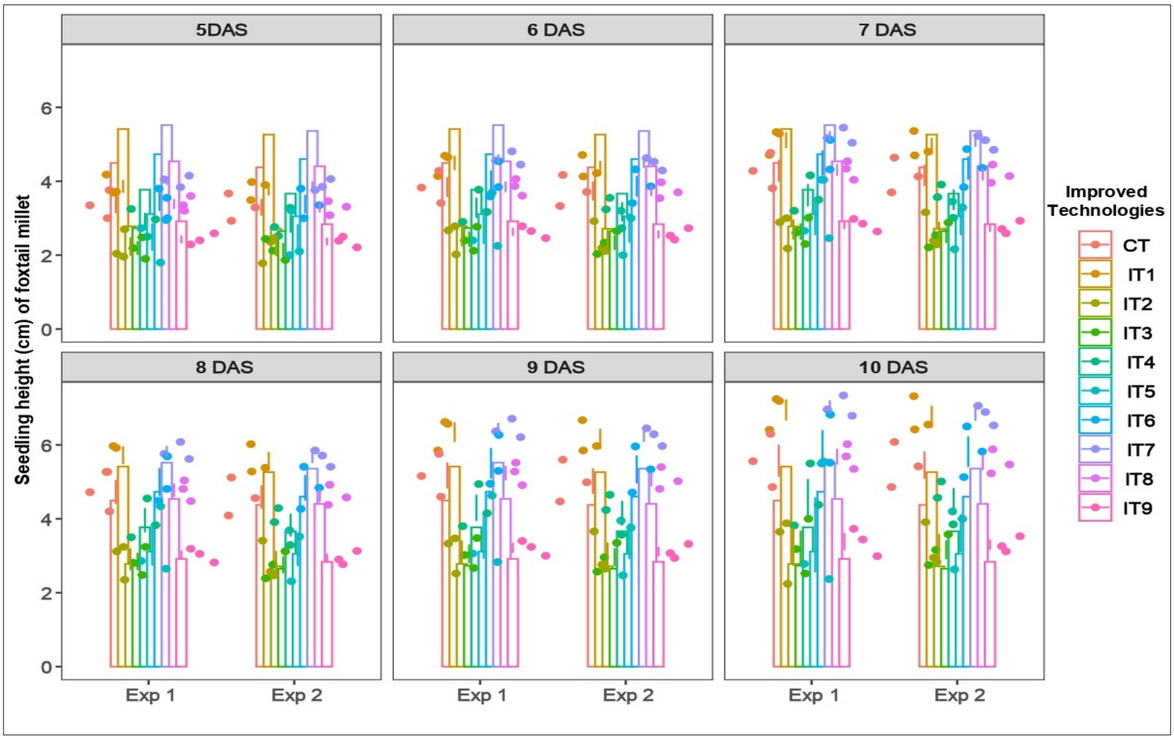

Fig. 5. Effect of different improved technologies (IT) on seedling height (cm) of foxtail millet from 5 DAS to 10 DAS during the period of experiment 1 and 2. Dots in the plot shows the distribution of seedling height (cm) at each treatment. Standard error of the average values was mentioned as vertical bars.

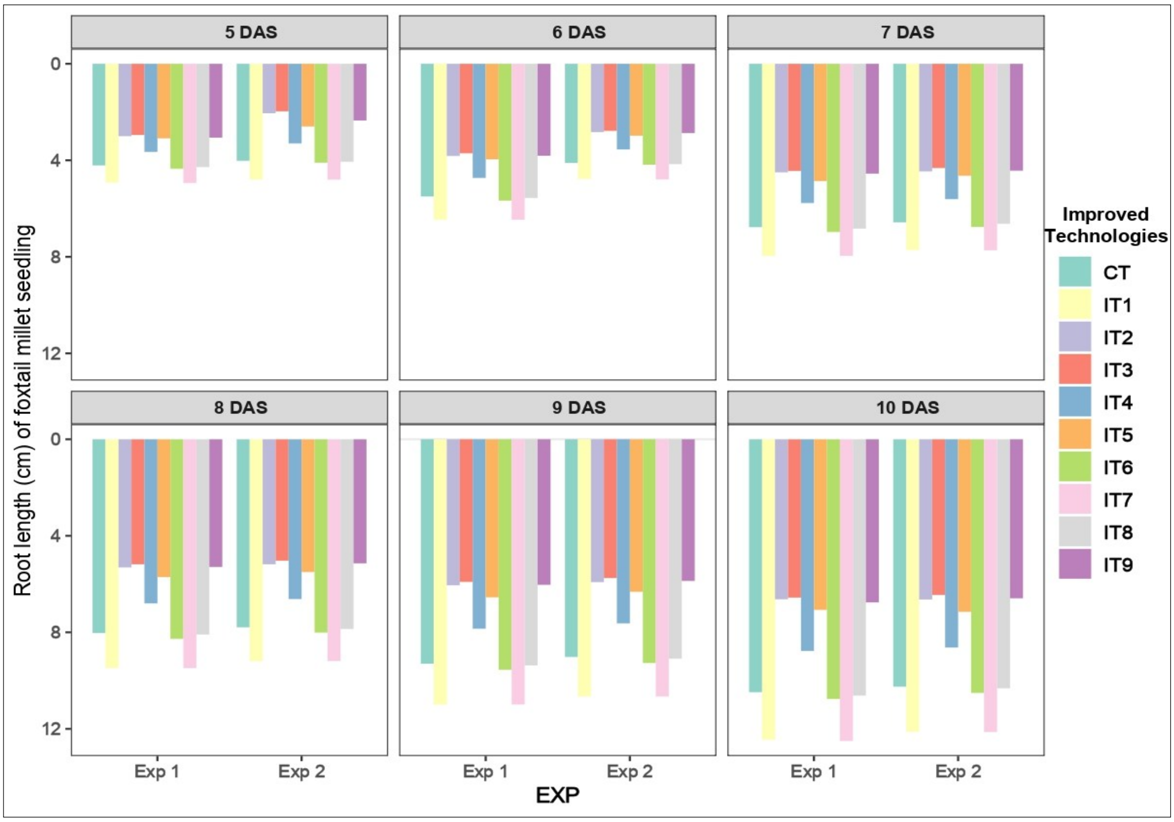

Fig. 6. Effect of different Improved Technologies (IT) on root ength (cm) of foxtail millet from 5 DAS to 10 DAS during the period of experiment 1 & 2. Inverted bars shows the root length (cm) of seedlings at treatment wise.

and 12.12 cm on 5th and 10th day of sowing respectively. The lower SH and RL were recorded in IT-2 and IT-3 treatments from 5th to 10th day of sowing.

Effect of improved technologies on Number of Leaves/ plant (NL)

The number of leaves significantly influenced by improved technologies (IT) in foxtail millet. The maximum NL (1.88) was counted in IT-7 on 5th day of sowing and which was statistically on par with IT-1 with NL of 1.86 (Fig. 7). Next to that, treatment IT-6, CT and IT-8 were recorded higher NL to 1.66, 1.65 and 1.65and there was no significant difference between them (IT-6, CT and IT-8). Lower NL was counted in IT-2 and IT-4 with values of 1.00 for both treatments. The same trend continued up to on 10th day of sowing, when IT-7 registered the highest NL of 4.14, which was comparable with IT-1 with 4.00 NL. After that, IT-6, CT and IT-8 recorded higher NL to 3.60, 3.45 and 3.31and there was no significant

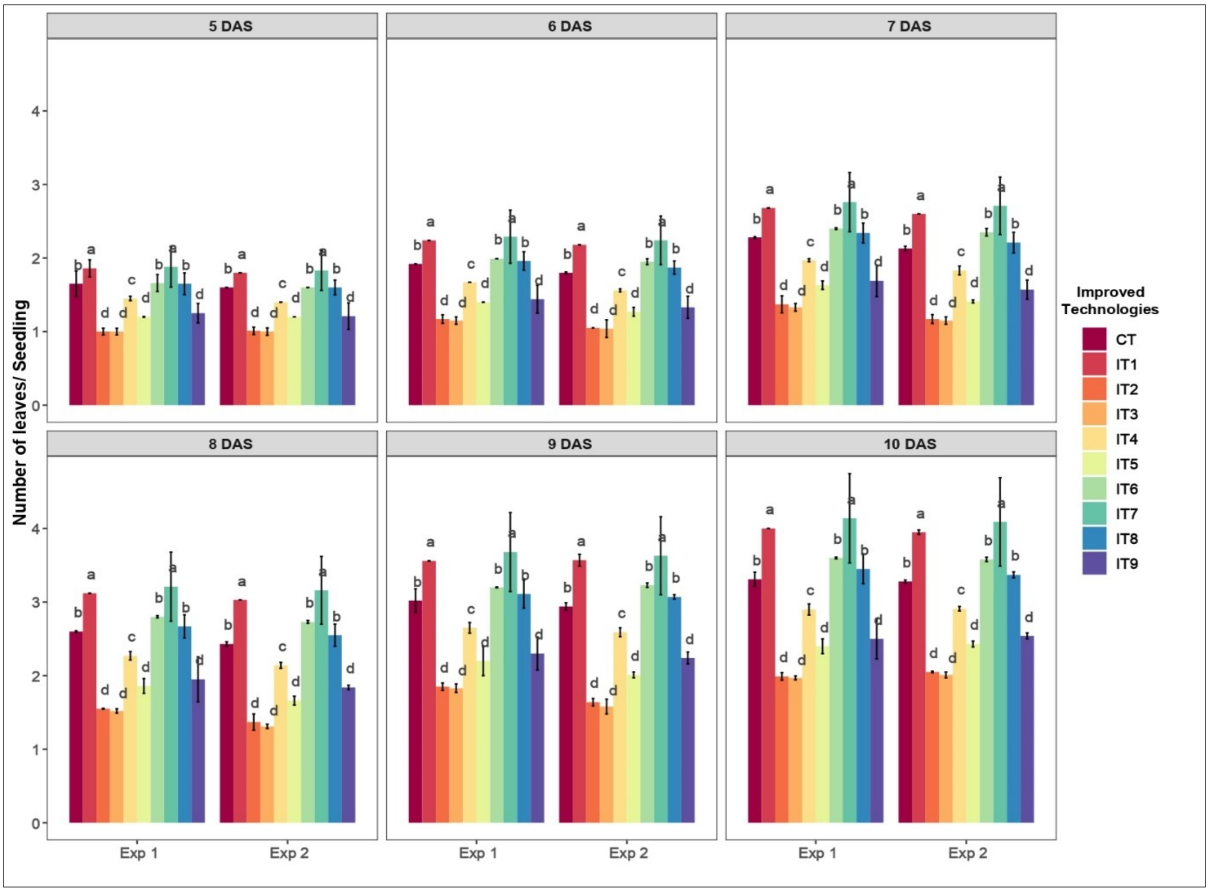

Fig. 7. Effect of different Improved Technologies (IT) on number of leaves per seedling of foxtail millet from 5 DAS to 10 DAS during the period of experiment 1 & 2. Standard error of the average values was mentioned as vertical bars. Significant variations (P<0.05) between the treatments were mentioned as letters.

difference among them (IT-6, CT and IT-8). Lower NL was recorded in IT-2 and IT-3, with respective NL of 1.99 and 1.97. The same result was obtained in Experimental - (II) as higher NL of 1.83 and 4.09 in IT-7 during 5th and 10th day, respectively. This was comparable with IT-1, which recorded 1.80 and 3.95 on 5th and 10th day of sowing, respectively. The lower NL was recorded in IT-2 and IT-4 treatments from 5th to 10th day of sowing.

Effect of different improved technologies on Seed Vigour Index (SVI)

The Seed vigour index (SVI) was worked out for foxtail millet under various improved technologies. Among the different treatments, IT-7 and IT-1 gave higher SVI of 984.19 and 954.52 respectively during the 5th day of sowing (Fig. 8). It was followed by treatments IT-6, IT-8 and CT were recorded SVI of 871.55, 785.64 and 765.68 respectively. Lower SVI was calculated in IT-2 and IT-4 with values of 473.37 and 451.37, respectively. During 10th day of sowing, a similar trend was continued, when IT-7 registered the highest SVI of 2784.49, which was comparable with IT-1 with 2745.07. Followed by IT-6, IT-8 and CT recorded higher SVI to 2518.22, 2297.35 and 2219.39. Lower SVI was recorded in IT-2 and IT-3, with respective SVI of 1449.56 and 1426.90. In experiment - (II), the same trend was recorded as higher SVI of 935.85 and 2655.81 in IT-7 in respective of 5th and 10th day of sowing. This was on par with IT-1, which recorded 911.85 and 2639.49 during 5th and 10th day of sowing respectively. The lower SVI was recorded in IT-2 and IT-4 treatments from 5th to 10th day of sowing.

Cost of improved technologies (IT)

Cost of operation decides the success of any agro techniques in farming activity. In this experiment, various improved technologies were evaluated in relation to crop establishment of foxtail millets. Among the various improved technologies, IT-1 gave lower expenditure of Rs. 2100/ha to carryout field preparation and sowing. Next to that, IT-2 and IT-3 recorded lower expenditure to prepare field and sowing. Followed by IT -7 gave lower expenditure of Rs. 5100/ha to prepare field and sowing operation. The maximum cost was spent in IT-6, IT-8 and IT-4 as Rs. 16100/ha, Rs. 11550/ha and Rs. 125000/ha respectively to carryout field preparation and sowing operations (Table 3).

Correlation

Correlation analysis between weather parameters and early growth traits of foxtail millet revealed significant positive relationships for maximum and minimum temperatures across treatments from the 5th to the 10th day of sowing.

Table 3. Cost of establishment under different Improved Technologies (IT) for foxtail millet

Treatments	Total cost (Rs. /ha)
CT	12000
IT-1	2100
IT-2	5000
IT-3	5000
IT-4	12500
IT-5	6400
IT-6	16100
IT-7	5100
IT-8	15550
IT-9	8000
SEd	-
CD (0.05)	-

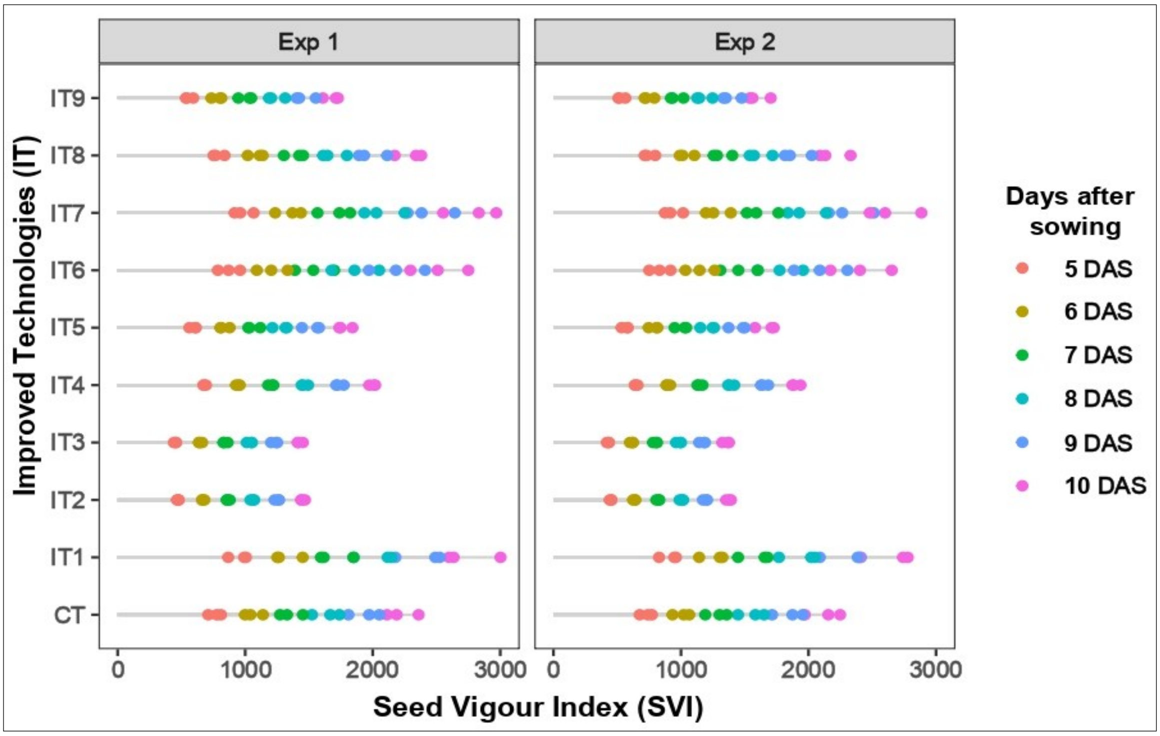

Fig. 8. Effect of different Improved Technologies (IT) on Seed Vigour Index (SVI) of foxtail millet from 5 DAS to 10 DAS during the period of experiment 1 & 2. Dots in the plot indicate the SVI at treatment wise.

Germination, plant population, number of leaves, seed vigour index, seedling height and root length showed peak correlations with maximum temperature, especially in treatments such as IT-2, IT-3, IT-4, IT-5, IT-7, IT-8 and IT-9. Minimum temperature also contributed positively, with higher correlations observed in treatments like IT-2, IT-3 and IT-4 for germination and IT-8 for seed vigour index. Relative humidity positively influenced germination (IT-9), number of leaves (IT-3), seedling height (IT-1 and IT-7) and seed vigour index (IT-5), although its effects were less significant than temperature its presented Table 4 and 5. These findings highlight the crucial role of favourable temperature and humidity conditions in supporting the initial growth and development of foxtail millet. Conversely, bright sunshine hours and evaporation consistently exhibited negative correlations with all growth traits, including germination, plant population and seedling attributes, with no statistical significance in their relationships. This suggests that excessive exposure to sunlight and evaporation during the early growth stage may have a detrimental effect, possibly due to moisture stress. Treatments such as IT-3, IT-5 and IT-9 demonstrated a balanced response to weather parameters, emphasising the importance of optimising environmental conditions for better growth. Overall, maximum temperature emerged as the most critical weather factor influencing the early growth traits of foxtail millet, followed by minimum temperature and relative humidity, while excessive sunlight and evaporation had an inhibitory effect.

Discussion

In changing climate, rainfed farming in more difficult than earlier due to change of monsoon pattern and rainfall distribution. This aids rick and failure of rainfed crops from germination to flowering germination and crop stand is a key basic criterion for increased production and productivity. Minor millet are high climate resilient crops, mostly cultivated in rainfed condition. Its germination and crop stand were studies and discussion below in relation to various improved technologies from the farmers response.

Germination and plant population

Crop establishment is crucial for obtaining higher yield and production in any crop. Proper germination and an optimum plant population are the principal components of successful crop establishment (17). This experiment analysed germination and plant populations foxtail millet under different improved technologies (IT). The highest germination was observed in IT-1 and IT-7 compared to other treatments. The germination of crop plants is influenced by various biotic and abiotic factors (5). In IT-1 and IT-7, pelleted seeds were placed on the soil surface and irrigated using a rain gun. The rain gun irrigation immediately wetted the pelleted foxtail millet seeds more effectively than other methods. The moisture retention of the seeds lasted longer due to the eleven-layer pelleting using the TNAU pelleting mixture. Significantly, surface placement of seeds required less energy for emergence compared to other treatments involving line sowing and seed drilling, where seeds were placed below the soil surface. These factors collectively contributed to the higher germination rate of foxtail millet. Similar findings were reported earlier in tobacco (18 and 19). Sowing below the soil surface in deep may face insufficient food reserve in seeds and decreases germination (20 and 21).

Generally, the initial energy required for foxtail millet seed germination is estimated to be around 0.0008 to 0.0016 MJ per gram of seed, translating to 0.8 to 1.6 MJ per kg of seed. The increased germination resulted in a higher plant population from the 5th to the 10th day after sowing. Treatments IT-6, CT and IT-8 had lower germination rates than IT-1 and IT-7, likely due to seed placement below the soil surface under the line sowing method. Placing seeds at an appropriate depth is essential for optimal germination,

Table 4. Correlation between the germination, plant population and number of leaves of foxtail millet with climatic factors

					Germination percentage					
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Max.T	0.698**	0.697**	0.703**	0.703**	0.703**	0.700**	0.692**	0.698**	0.700**	0.703**
Min. T	0.453**	0.453**	0.461**	0.461**	0.461**	0.457**	0.445**	0.454**	0.457**	0.461**
RH	0.2792*	0.27724	0.2852*	0.2849*	0.2853*	0.2816*	0.26911	0.27811	0.2813*	0.2861*
BSH	-0.64027	-0.63920	-0.64680	-0.64692	-0.64700	-0.64322	-0.63189	-0.64030	-0.64308	-0.64730
EVP	-0.36516	-0.36592	-0.36846	-0.36857	-0.36803	-0.36693	-0.36404	-0.36632	-0.36689	-0.36812
					Plant population/m^2					
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Max.T	0.389**	0.3560*	0.365**	0.3480*	0.3570*	0.3560*	0.3340*	0.3440*	0.372**	0.386**
Min. T	0.10356	0.06940	0.07872	0.06065	0.07105	0.07011	0.04684	0.05735	0.08626	0.10084
RH	0.15321	0.13904	0.14362	0.13332	0.14291	0.14102	0.12814	0.13487	0.14704	0.15279
BSH	-0.28711	-0.25098	-0.26089	-0.24186	-0.25257	-0.25174	-0.22714	-0.23824	-0.26876	-0.28423
EVP	-0.11788	-0.09389	-0.09992	-0.08913	-0.09293	-0.09331	-0.07902	-0.08480	-0.10514	-0.11554
					Number of leaves/ plants					
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Max.T	0.751**	0.723**	0.796**	0.802**	0.767**	0.793**	0.722**	0.714**	0.738**	0.772**
Min. T	0.498**	0.474**	0.544**	0.549**	0.508**	0.532**	0.477**	0.477**	0.481**	0.511**
RH	0.3080*	0.2910*	0.400**	0.422**	0.3190*	0.389**	0.2890*	0.2900*	0.2980*	0.3240*
BSH	-0.69676	-0.66704	-0.75246	-0.76030	-0.71253	-0.74552	-0.66715	-0.66098	-0.68104	-0.71813
EVP	-0.39605	-0.37916	-0.37569	-0.36684	-0.39516	-0.37129	-0.38332	-0.38035	-0.38650	-0.39510

(Max. T- Maximum temperature; Min. T- Minimum temperature; RH- Relative humidity; BSH- Bright sunshine hours and EVP- Evaporation)

Table 5. Correlation between the seed vigour index, seedling height and root length of foxtail millet with climatic factors

					Seed Vigour index					
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Max.T	0.704**	0.702**	0.703**	0.703**	0.705**	0.706**	0.703**	0.702**	0.704**	0.703**
Min. T	0.459**	0.458**	0.461**	0.461**	0.461**	0.461**	0.460**	0.460**	0.462**	0.460**
RH	0.2840*	0.2840*	0.2860*	0.2860*	0.2900*	0.2950*	0.2870*	0.2840*	0.2910*	0.2850*
BSH	-0.64712	-0.64525	-0.64707	-0.64719	-0.64891	-0.64978	-0.64648	-0.64561	-0.64811	-0.64649
EVP	-0.36846	-0.36688	-0.36797	-0.36811	-0.36650	-0.36307	-0.36579	-0.36803	-0.36558	-0.36809
					Seedling height (cm)					
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Max.T	0.698**	0.706**	0.689**	0.697**	0.695**	0.642**	0.699**	0.704**	0.702**	0.701**
Min. T	0.454**	0.464**	0.437**	0.449**	0.449**	0.393**	0.454**	0.462**	0.458**	0.456**
RH	0.27816	0.2860*	0.26619	0.27103	0.26908	0.20403	0.27509	0.2860*	0.2850*	0.2830*
BSH	-0.64013	-0.65072	-0.62683	-0.63771	-0.63574	-0.57397	-0.64100	-0.64768	-0.64501	-0.64330
EVP	-0.36623	-0.37139	-0.35838	-0.36661	-0.36805	-0.36064	-0.36905	-0.36825	-0.36559	-0.36435
					Root length (cm)					
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Max.T	0.710**	0.715**	0.658**	0.657**	0.700**	0.684**	0.709**	0.716**	0.711**	0.679**
Min. T	0.518**	0.524**	0.451**	0.453**	0.505**	0.484**	0.518**	0.526**	0.520**	0.483**
RH	0.23902	0.24226	0.20413	0.21074	0.23022	0.20591	0.23502	0.24552	0.24258	0.22495
BSH	-0.66946	-0.67537	-0.60527	-0.60604	-0.65628	-0.63643	-0.66788	-0.67665	-0.67082	-0.63274
EVP	-0.45057	-0.45380	-0.41184	-0.41005	-0.44415	-0.44068	-0.45305	-0.45288	-0.44946	-0.42769

(Max. T- Maximum temperature; Min. T- Minimum temperature; RH- Relative humidity; BSH- Bright sunshine hours and EVP- Evaporation) ensuring a continuous moisture supply for emergence above the soil surface. In these treatments, line-sown seeds had an optimum germination rate, though it was quantitatively lower than in IT-1 and IT-7 but higher than in IT-4. In IT-4, seeds were sown using the line sowing method under a Broad Bed and Furrow (BBF) system, which may have reduced soil moisture availability compared to IT-6, CT and IT-8, which used Ridges and Furrows, Flat Bed and Compartmental Bunding, respectively. Earlier reports confirmed the findings of this result (22, 23). The lowest germination and plant population were observed in seed drill-sown treatments (24), including IT-5, IT-9, IT-2 and IT-3, under modified surge irrigation and rain gun irrigation. In these treatments, the irrigated water may not have been sufficient to meet the seeds' water requirements for imbibition and germination due to the increased sowing depth caused by seed drill sowing (20, 21).

Seedling height and root length (cm)

Shoot and root length are primarily influenced by seed reserves, soil nutrients, moisture levels and the genetic potential of the plant species. The maximum shoot and root length were recorded in treatments IT-7 and IT-1. In these treatments, more energy was available for tissue development due to reduced energy expenditure on seed germination, which resulted in greater shoot and root length (25). Treatments IT-6, IT-8 and CT produced greater shoot and root lengths compared to IT-9, IT-5, IT-2 and IT-3 but were still lower than IT-7 and IT-1. Seeds sown using the line sowing method in IT-6, IT-8 and CT benefited from a favourable soil environment, ensuring optimal depth, good seed-soil contact and a continuous supply of moisture and nutrients under ridges and furrows, compartmental bunding and flatbed systems, respectively. In IT-9, IT-5, IT-2 and IT-3, shoot and root length were significantly reduced compared to other treatments. This reduction was likely due to the increased sowing depth caused by seed drill sowing, which may have affected early seedling development (26, 27).

Number of Leaves per plant

The number of leaves per plant is primarily influenced by seed reserves, soil nutrients, moisture levels and the genetic potential of the plant species (28). The maximum number of leaves per plant was recorded in treatments IT-7 and IT-1. In these treatments, more energy was available for tissue development due to reduced energy expenditure on seed germination, resulting in a higher number of leaves per plant. Treatments IT-6, IT-8 and CT produced more leaves per plant compared to IT-9, IT-5, IT-2 and IT-3 but fewer than IT-7 and IT -1. In IT-6, IT-8 and CT, seeds were sown using the line sowing method, which provided a favourable soil environment by ensuring optimum depth, good seed-soil contact and a continuous supply of moisture and nutrients under Ridges and Furrows, Compartmental Bunding and Flat Bed systems, respectively (29). In IT-9, IT-5, IT-2 and IT-3, the number of leaves per plant was reduced compared to other treatments, likely due to increased sowing depth caused by seed drill sowing, which may have affected early plant growth.

Seed Vigour Index

The highest seed vigour index was observed in treatments IT-7 and IT-1. In these treatments, pelleted seeds placed on the soil surface required less energy for emergence than other treatments involving line sowing and seed drilling, where seeds were placed below the soil surface (30, 26). Treatment IT-6 had a lower seed vigour index compared to IT-7 and IT-1, likely due to seed placement below the soil surface under the line sowing method. Placing seeds at an appropriate depth is essential for optimal germination, ensuring a continuous moisture supply for emergence above the soil surface. In these treatments, line-sown seeds had an optimum Seed Vigour Index but were quantitatively lower than in IT-7 and IT-1 and higher than in IT-8 and CT. The lowest seed vigour index was recorded in seed drill-sown treatments, including IT-5, IT-9, IT-2 and IT-3. In these treatments, the irrigated water may not have been sufficient to meet the seeds' water requirements for imbibition and germination due to the increased sowing depth caused by seed drill sowing (31).

Cost of Improved Technologies (IT)

Lowest cost of establishment was recorded in IT-1, which was due to the lower hiring charge of drone (Rs. 800/hr) to carry out sowing operation with flat bed. Followed by IT-2 and IT-3 requires lower expenditure to carry out establishment of foxtail millet due to the less labour requirement and lower hiring charge of seed drill machineries (Rs. 900/hr). The highest expenditure was recorded in IT-6 treatment due to the more labour requirement for forming ridges and furrow and in addition to that, cost of sowing (Rs. 600/man day; 20 labourers/ha) to establish foxtail millet crop.

Conclusion

Improved Technologies (IT) are necessary to effective crop establishment in foxtail millet to achieve higher production and productivity, since there were no technologies identified. From this study utilizing drones for sowing of foxtail millet under flatbed and compartmental bunding enhances germination, higher plant population and other crop stand indices. Again, drone sowing cost effective technology compared to other improved technologies studied. Hence foxtail millet growers advised to use drones for pelleted seeds sowing instead of conventional broadcasting and other techniques under rainfed condition. For hiring drones or purchasing drones for agricultural propose, govt provides subsidies schemes in drone usage by farmers are to over labour constrains. Next to that, farmers can use tractor operated seed drills, if drones not available. At the same time, further research must be done to examine the growth and yield of drone sown foxtail millet under assured irrigation. Similarly, optimizing depth of sowing in seed drill must be done to avoid deep placement of foxtail millet and to improve crop stand.

Acknowledgements

The authors thankfully acknowledge the research support by The Principal, Institute of Agriculture, as well as Dean and Professor & Head, Farm Machinery and Power Engineering, Agricultural Engineering and Research Institute, Kumulur, Tamil Nadu Agricultural University.

Authors' contributions

KP carried out the experiment, took observations, analysed the data and wrote original draft. Conceptualization, supervision, funding acquisition, writing - review & editing were done by SSD. AV helped in summarizing and revising the manuscript and RK helped in summarizing and revising the manuscript. AS summarizing and revising the manuscript. RS, KPR and SMV helped in editing, 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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