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Preliminary study on unlocking growth and yield potential of USDA foxtail millet (*Setaria italica* L.) lines with NPK fertilization

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Abstract

Foxtail millet (*Setaria italica* L.) is nutritionally superior to other cereals of the family *Poaceae*, with the potential to perform better in marginal environments. In the present context of climate change, ecologically sound and low-input foxtail millet varieties can be chosen for agricultural sustainability. The planned research was carried out at the green house of the Department of Agronomy, University of Agriculture, Faisalabad, Pakistan, to investigate the impact of various levels of NPK fertilizer on the growth, development, and yield of foxtail millet lines from USDA germplasm. Eight lines of foxtail millet; U2, V19, V73, V93, V101, V106, V107, and V111, were under study along with NPK fertilizers' treatments; T_1 = 000 NPK as a control, T_2 = 20:15:15 NPK, T_3 = 30:20:20 NPK, T_4 = 40:25:25 NPK, and T_5 = 50:30:30 NPK (kg ha^{-1}). NPK treatments were applied twice during the study periods: first dose was applied after one week of the emergence of seedlings and the second dose was applied at the age of four weeks of seedlings. The time to 50% emergence ranged from 4.33 (V111) to 5.92 (U2) days, and the emergence was highest in V111 (10.02), and V19 had the lowest emergence index of 4.95. Furthermore, all genotypes achieved a complete final emergence percentage of 100, except U2 (92.89%) and V19 (89.33%). The highest growth rate and assimilation rate were observed in V111 and V107 under the impact of treatment 5. Among the different treatments, T_3 resulted in the maximum plant height, panicle length, and grain yield per panicle. The highest panicle weight and grain yield per panicle were observed in line V106. Line V107 synthesized the highest chlorophyll *a* while V93 produced highest chlorophyll *b* contents which is statistically similar toV19. Line V19 had the highest total chlorophyll and V93 produced the highest carotenoid contents. Application of NPK at the rate of 50:30:30 kg ha^{-1} produced maximum chlorophyll *a* (23%), *b* (15.8%), total chlorophyll contents (14.2%), plant fresh biomass (2.06%), and grain yield (23.6%) as compared to control treatment. Overall, T_3 (30:20:20) and T_5 (50:30:30) were observed to be better as compared to other treatments. With respect to growth, yield, and chlorophyll contents, lines U2, V19, V93, V106, V107, and V111 were observed to be potentially superior.

Keywords Genotypes, Fertilizers, Foxtail, Millet, Photosynthesis

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Introduction

Millets, recognized as nutri-cereals, were domesticated in central China's highlands 8000 years ago, thriving in marginal farming and addressing nutritional challenges, poverty, and hunger [1–3]. Regaining prestige for their nutritional benefits, millets, the most domesticated cereal grain from the *Poaceae* family, offer protein (8–15%), dietary fiber (156–325 g kg^{-1}), and neutraceutical qualities, surpassing other cereals [3, 4]. Playing a crucial role in modern food design, millets contribute to multigrain and gluten-free products [5]. Foxtail millet (*Setaria italica* L.), originating in North China 7400–7935 years ago, is one of the world's oldest crops, known for self-pollination and a short lifespan. Initially native to China, it is now grown globally in Asia, Europe, North America, and Africa [6, 7]. As the second most cultivated millet, after pearl millet, foxtail millet is rich in nutrients, providing 331 kcal of calories, 60.9 g of carbohydrates, 12.3 g of protein, 8.0 g of fiber, 3.3 g of minerals, 2.8 mg of iron, and 31 mg of calcium per 100 g [4]. Known for its amino acids and dietary minerals, foxtail millet al.so offers health benefits, including improved glycemic, prevention of hyperinsulinemia, and lower lipid concentrations in type 2 diabetic patients [8].

Foxtail millet, which has a reputation for adaptability and can grow in a variety of climates, has emerged as a possible alternative crop in the face of shifting global agricultural demands and climate change. The strategic application of vital nutrients, such as nitrogen (N), phosphorous (P), and potassium (K), through NPK fertilizers is crucial for increasing yields and ensuring sustainable production. Hussan et al. [9] reported that the application of mineral elements significantly enhanced the productivity and yield of wheat crop. N is one of the primary nutrients in chlorophyll and is essential for photosynthesis in plants. The lack of N adversely influences the photosynthesis rate by dispersing the chlorophyll molecules [10]. The correlation between nitrogen levels and pigment rate is influenced by the concentration of chlorophyll [11]. Ciecko et al. [12] reported that yield was positively linked with the amount of chlorophyll in the leaves of potatoes. The shortage of P is responsible for the reduction of photo-synthetic pigments, including chlorophyll and carotenoids [13]. Photosynthesis activity is normally decreased by the shortage of phosphorus, ultimately reducing the leaf mass per unit leaf area [14]. K is critically involved in the process of photosynthesis and the ultimate long-distance translocation of photosynthates. K regulates various physiological, phenological, and biochemical processes in the plant as it is among the essential macronutrients [15]. Foxtail millet benefits from N in terms of its growth and yield characteristics [16]. According to Basavarajappa et al. [17], foxtail millet yield increases in response to various N application levels.

Several studies have reported the positive effects of integrated fertilization on foxtail millet, emphasizing the importance of achieving a balanced supply of N, P, and K to boost crop productivity and improve the quality of the harvested produce [18, 19]. Experiments on the application of N, P, and K to foxtail millet revealed that the use of balanced fertilizer increased its productivity. Integrated application of various management practices is a promising strategy to boost the growth and yield of field crops [20–22]. Reasonable N: P:K ratios improve nutrient absorption, biomass accumulation, and crop yield; this phenomenon has also been observed in rice and other foxtail millet studies [18, 23]. Application of NPK at 160:90:150 kg ha^{-1} resulted in the highest plant height, leaf area, and stem thickness. Stem thickness was well developed under application of NPK at 160:90:150 kg ha^{-1} during the heading and grain-filling stages. It depicted that reasonable NPK-balanced fertilization of NPK at 160:90:150 kg ha^{-1} promoted growth and development [24]. The water use efficiency of foxtail millet under the NP at 60:30 and 90:45 kg ha^{-1} significantly increased by 33.40–62.39% [25].

Foxtail millet is an emerging crop in Pakistan, as it was not cultivated before in this region. Different trails regarding the production technology are in the preliminary stages. The farmers' community is cultivating the crop on a large scale due to its nutritional value and high net returns. To the best of our knowledge, no study has been conducted on the optimization of fertilizer application for foxtail millet in the region. Keeping in view of the above rationale, the present study was planned to assess the optimum combination of NPK fertilizer with respect to crop growth, productivity, and yield of foxtail millet. We hypothesize that the optimum combination of NPK fertilizers can increase crop productivity by reducing input costs.

Materials and methods

Experimental location and materials

The planned research was carried out at the green house of Department of Agronomy, University of Agriculture, Faisalabad, Pakistan, during spring season to investigate the effect of NPK fertilizer on growth, development, and yield of foxtail millet (*Setaria italica* L.). There was a total of eight lines of foxtail millet; U2, V19, V73, V93, V101, V106, V107 and V111, under study with three replications. In the case of fertilizer (NPK) treatment, there were a total of five treatments; T_1=000 NPK as a control, T_2=20:15:15 NPK, T_3=30:20:20 NPK, T_4=40:25:25 NPK and T_5=50:30:30 NPK (50 kg of N, 30 kg of P_2O_5, and 30 kg of K_2O ha^{-1}). Source of N was urea (46% N), while source of P was triple super phosphate (46% P_2O_5), and source of K was murate of potash (K_2O). All the products are manufactured by the Foji Fertilizer Company (FFC)

Private Limited, Pakistan. The whole P and K with half of nitrogen dose were applied after one week of emergence of seedlings and second half dose of N was applied at age of four weeks of seedlings. Seeds of the lines of foxtail millet were taken from the germplasm of United States Department of Agriculture (USDA) provided by Alternate Crops Lab, Department of Agronomy, University of Agriculture, Faisalabad, Pakistan.

Crop husbandry

Earthen pots, having dimensions of 30 cm in height and 22 cm in diameter, were filled with 5 kg of soil in each pot and soil was taken from the research area of Department of Agronomy. The soil was loam in texture with pH and EC of 7.6 and 2.58 dS m^{-1}, respectively. The concentration of N, available P, K, and organic matter were recorded 0.061%, 7.9 mg kg^{-1}, 76 mg kg^{-1}, and 1.01%, respectively. There were a total of 120 pots with three replicates of each treatment. Ten seeds of each line were sown in each pot by hand. Thinning was done after complete emergence and eight plants were maintained in each pot. Pots were checked regularly for water requirement and irrigated according to the requirement of plants. Weeds were removed manually from the pots throughout the experimentation period. The seedlings were cultivated in the greenhouse for 10 weeks at the temperature of 25–30 °C with natural light conditions (14 h of light and 10 h of dark) and there was no rainfall during the experimentation.

Measurement of emergence attributes

Plants were counted on daily basis after emergence attributes. Counting for emerged seedlings was stopped when a constant number was encountered for continuous three days. After collecting the data of emergence parameters, thinning was done, and seven seedlings were maintained for destructive sampling and to collect the data of other traits. Time taken to 50% emergence of seedlings (E50) (Eq. 1) was calculated according to the following formulae of Farooq et al. [26].

$$\mathrm{E50} = \mathrm{ti} + [(\mathrm{N}/2 - \mathrm{ni})/\mathrm{nj} - \mathrm{ni}] \times (\mathrm{tj} - \mathrm{ti}) \quad (1)$$

Where N is the final emergence count and ni, nj are the cumulative number of seedlings emerged on adjacent days ti and tj respectively.

Mean emergence time (MET) (Eq. 2) was calculated according to the equation of Ellis and Roberts [27].

$$\mathrm{MET} = \sum (\mathrm{Dn}) / \sum \mathrm{n} \quad (2)$$

Where Dn is the number of seeds which emerged on day D, and n is the number of days counted from the beginning of emergence.

Emergence index (EI) (Eq. 3) was calculated as described in the Association of Official Seed Analysts manual [28].

$$\mathrm{EI} = \left(\frac{\text{number of emerged seedling(s)}}{\text{days of first count}}\right) + \cdots + \left(\frac{\text{number of emerged seedlings}}{\text{days of final count}}\right) \quad (3)$$

Final emergence percentage (FEP) (Eq. 4) was calculated by dividing the number of emerged seeds with total number of seeds sown and multiplied with 100 to convert it into percentage.

$$\mathrm{FEP} = \frac{\text{total number of emerged seedlings}}{\text{total number of seeds sown}} \times 100 \quad (4)$$

Measurement of growth parameters

To record the data of growth parameters, two seedlings were harvested twice, with an interval of 15 days, from each pot. First and second harvestings were done age of four and six weeks of seedlings respectively. Crop growth rate (CGR) and net assimilation rate (NAR) were recorded at two critical growth stages: four weeks (vegetative) and six weeks (pre-reproductive stage). CGR (Eq. 5) and NAR (Eq. 6) were determined according to the procedures of Hunt [29].

$$\mathrm{CGR} = (\mathrm{W2} - \mathrm{W1})/(\mathrm{T2} - \mathrm{T1}) \quad (5)$$

Where W_1=Total dry matter at the first harvest, W_2=Total dry matter at the second harvest, T_1=Date of observation of first dry matter, T_2=Date of observation of second dry matter.

$$\mathrm{NAR} = \text{Final TDM}/\text{Final LAD} \quad (6)$$

Where TDM=Final total dry matter at harvesting and LAD=Final leaf area duration at harvesting [30].

The plants were harvested at the age of 75 days. Plant height and panicle length were measured at the time of harvesting. Three plants, from each pot, were selected randomly and their heights and panicle lengths were measured with a meter rod. Plant biomass was recorded after harvesting. Three plants were uprooted from each experimental unit and their fresh weight was measured. Mean value for selected plants was taken from each plot and treatment means were also observed. Panicle was detached from each plant and weight by electric balance to record the panicle weight. Grain yield was recorded

after threshing the panicle. Harvest index was calculated by following formula:

$$\text{Harvest index } (\%) = \frac{\text{Grain yield}}{\text{Biological yield}} \times 100$$

Estimation of photosynthetic pigments

For analysis of chlorophyll *a*, *b*, total chlorophyll, and carotenoids contents, fully expanded young leaves were sampled at vegetative stage of plants (6 weeks after emergence). Arnon's [31] method was followed for chlorophyll *a* (Eq. 7), chlorophyll *b* (Eq. 8), and carotenoids (Eq. 9) estimation. From each experimental treatment 0.5 g of fresh leaves were taken. These samples were finely grinded in 5 ml of 80% methanol (Merck KGaA, Darmstadt, Germany) by using pestle and mortal. The solution was centrifuged and filtered cautiously. After which, with the assistance of UV-VIS Spectrophotometer, model Hitachi-U-2001 (Hitachi, Tokyo, Japan) the absorbance at wavelengths of 645 nm, 663 nm and 480 nm was recorded. The following formulas were under consideration to estimate the chlorophyll *a*, *b*, and carotenoid contents (Eqs. 7–9).

$$\text{Chlorophyll } a \text{ (mg g}^{-1}) = [12.7\,(\text{OD663}) - 2.69\,(\text{OD645})] \times \text{V} \div 1000 \times \text{W} \quad (7)$$

$$\text{Chlorophyll } b \text{ (mg g}^{-1}) = [22.9\,(\text{OD645}) - 4.68\,(\text{OD663})] \times \text{V} \div 1000 \times \text{W} \quad (8)$$

$$\text{Carotenoid (mg g} - 1) = \left[\begin{array}{l}(\text{OD } 480) + 0.114\ (\text{OD } 663) \\ -\ 0.638\ (\text{OD } 645)\end{array}\right] \times \text{V} \div 1000 \times \text{W} \quad (9)$$

Where OD is optical density, W is fresh weight (mg), and V is the volume of 80% methanol used in the extract.

Total chlorophyll contents were recorded by sum of chlorophyll a and b contents.

Statistical analysis

The experiment was conducted according to a completely randomized design (CRD), with the factorial arrangement primarily due to two factors: (1) foxtail millet lines and (2) the NPK treatments. Data recorded for emergence, growth, biochemical, and yield attributes were examined by the two-way analysis of variance (ANOVA) procedure by considering the foxtail millet lines and the NPK treatments as factors. The Tukey honestly significant difference (HSD) test was used to compare the differences among the means' values [32]. A statistical computer package called "Statistix 8.1" by Analytical Software, Tallahassee, Florida, USA, was used for ANOVA. The statistical program "RStudio (v2023.06.1–524) by Boston, Massachusetts, USA" was used for recording Pearson's correlation coefficient between attributes.

Results

Emergence attributes

The significant level of various emergence, growth, yield, and biochemical parameters of eight genotypes of foxtail is presented in Table 1. The time to 50% emergence (E50) ranged from 4.33 days in V111 to 5.92 days in V19 (26%) (Fig. 1). Similarly, mean emergence time (MET) varied between 6.42 days (V111) to 7.15 days (V19) (Fig. 1). Regarding emergence index (EI), V107 exhibited the highest value of 8.72, indicating a relatively more rapid and synchronous emergence compared to other

Table 1 Mean sum of squares of emergence, growth, yield, and biochemical attributes of eight lines of foxtails cultivated under five NPK rates

SOV	DF	E50	MET	EI	FEP
Foxtail Millet Lines (L)	7	4.54381**	0.98218**	44.3175**	267.532**
Treatment (T)	4	0.71134NS	0.15594NS	8.0355NS	52.774NS
L × T	28	0.12905NS	0.03705NS	1.3684NS	59.971NS
SOV	DF	CGR	NAR	PH	PL
Foxtail Millet Lines (L)	7	0.42473**	0.08388**	1942.02**	42.2128**
Treatment (T)	4	11.1231**	1.15546**	954.27**	58.6445**
L × T	28	0.12088**	0.03191**	135.94**	21.3078**
SOV	DF	PW	GY	PB	HI
Foxtail Millet Lines (L)	7	2.48493**	2.31737**	9.71628**	214.694 **
Treatment (T)	4	1.30783**	7.00523**	4.45735**	881.866 **
L × T	28	0.84307**	1.48078**	2.43559**	131.273 **
SOV	DF	Chlo *a*	Chlo *b*	Total Chlo	Caro
Foxtail Millet Lines (L)	7	0.00196**	0.72453**	0.08600**	1123.02**
Treatment (T)	4	0.01708**	0.01479**	0.03956**	18.169**
L × T	28	0.00338**	0.06079**	0.07297**	81.127**

Source of variance (SOV); degree of freedom (DF); time taken to 50% emergence of seedlings (E50); mean emergence time (MET); emergence index (EI); final emergence percentage (FEP); crop growth rate (CGR); net assimilation rate (NAR); plant height (PH); panicle length (PL); panicle weight (PW); grain yield (GY); harvest index (HI); chlorophyll (Chlo); carotenoids (Caro); interaction of foxtail millet lines and treatments (L × T); ** = significant at $p \leq 0.01$, NS = non-significant at $p > 0.05$

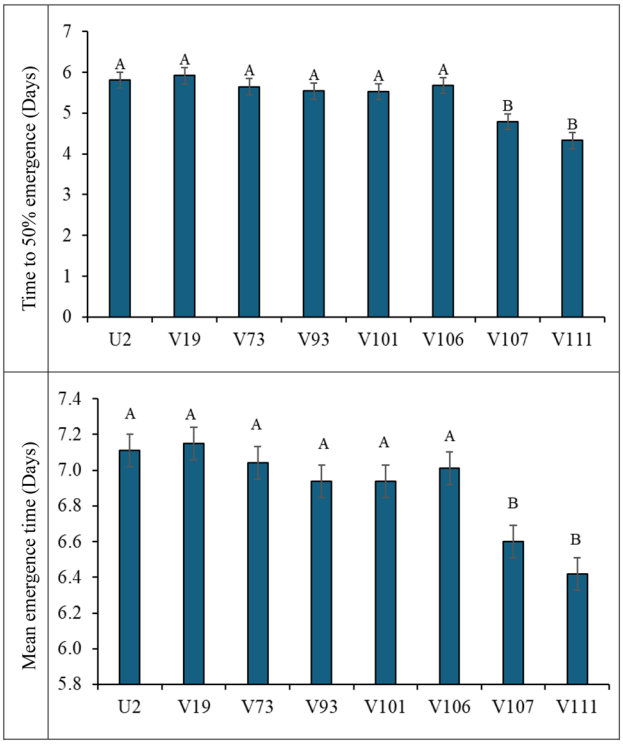

Fig. 1 Performance of various foxtail lines regarding time to 50% emergence and mean emergence time. Bars followed by different alphabets (A, B, etc.) are significantly different by the HSD $p \leq 0.05$ test

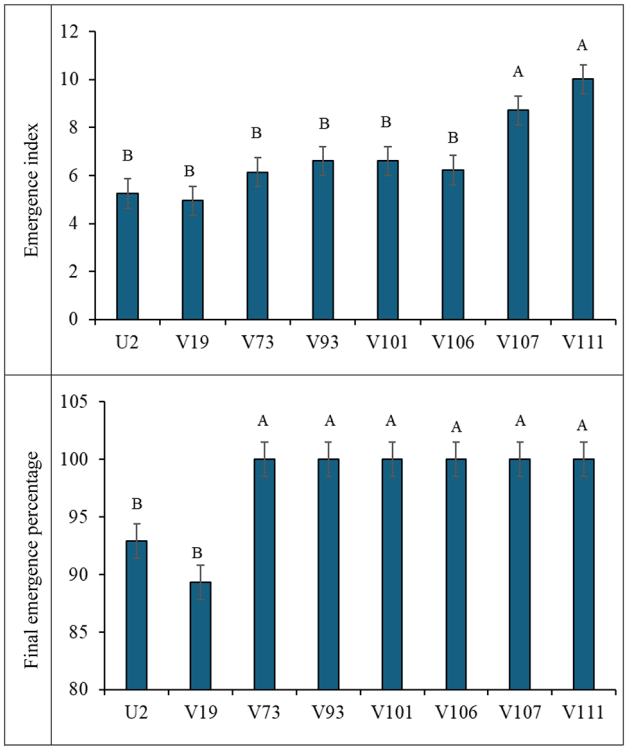

Fig. 2 Performance of various foxtail lines regarding emergence index and final emergence percentage. Bars followed by different alphabets (A, B, etc.) are significantly different by the HSD $p \leq 0.05$ test

genotypes (Fig. 2). On the other hand, V19 had the lowest EI of 4.95. Furthermore, all genotypes, except U2 and V19, achieved a complete final emergence percentage (FEP) of 100, indicating successful establishment (Fig. 2).

Growth and yield parameters

The highest crop growth rate (CGR) is observed in treatment 5 (3.13), followed by T4 (2.95), T3 (2.57), T2 (2.07), and T1 (1.46), respectively (Table 2). It indicates that higher amounts of fertilizer generally lead to higher CGR. The lines with the highest CGR are V111 and V107. The NAR indicates the amount of carbon that is being assimilated by the plant per unit area and time. When looking at the NAR (Table 3), the highest NAR (3.13) is observed in T5, followed by T4 (2.77), T3 (2.63), T2 (2.63), and T1 (2.62). This suggests that higher amounts of fertilizer generally lead to higher rates of carbon assimilation by the plants. The lines with the highest NAR are V107 and V111. Overall, it appears that the treatment with the highest amount of fertilizer (T5) is the most effective at promoting both CGR and NAR. The lines V107 and V111 appear to be particularly responsive to fertilizer treatment in terms of both CGR and NAR.

The PH of eight different lines of foxtail under five different treatments of fertilizer application is presented in Table 4. The impact of different treatments on PH is statistically significant ($p<0.05$) for most of the lines, as indicated by different alphabets. For example, for line V73, treatments T1, T2, T3, and T4 have significantly different effects on PH. Among these treatments, T3 resulted in the highest PH (84.19 cm) for this line, while T5 had the lowest mean PH (72.06 cm). Overall, the highest mean PH (92.92 cm) was observed in line U2, while the lowest mean PH (57.68 cm) was observed in line V106 (Table 4).

The PL of different lines of foxtail under five different treatments of fertilizer application is presented in Table 5. The impact of different treatments on PL is also significant for most of the lines, as indicated by different alphabets. For example, for line V19, treatments T3, T4, and T5 have significantly different effects on PL. Among these treatments, T3 resulted in the highest mean PL (14.30 cm) for this line, while T5 had the lowest mean PL (6.33 cm). Overall, the highest mean PL (11.34 cm) was observed in line U2, while the lowest mean PL (5.89 cm) was observed in line V106. Among the different treatments, T3 generally resulted in the highest mean values for PL, while T5 had the lowest mean values.

The mean values for PW are also provided for each line and each treatment (Table 6). The impact of different treatments on PW is statistically significant ($p<0.05$) for most of the lines, as indicated by different alphabets. For instance, for line V73, treatments T3 and T4 have significantly different effects on PW. Treatment T4 resulted in

Table 2 Impact of various ratios of NPK on crop growth rate (CGR) (g plant^{-1} day^{-1}) of eight lines of foxtail millet (*Setaria italica* L.)

Treatments	Foxtail Millet Lines (L)								
	U2	V19	V73	V93	V101	V106	V107	V111	Mean (T)
T1	0.73 x	1.13 w	1.53 u	1.60 t	1.50 u	1.90 r	1.46 v	1.86 s	1.46 E
T2	1.63 t	2.03 p	2.10 o	2.00 pq	2.40 m	1.97 q	2.36 n	2.13 o	2.07 D
T3	2.43 m	2.50 l	2.40 m	2.80 j	2.36 n	2.76 k	2.53 l	2.83 ij	2.57 C
T4	2.90 h	2.80 j	3.00 g	2.76 k	3.06 ef	2.93 h	3.09 de	3.12 d	2.95 B
T5	3.00 g	2.90 h	3.300 b	2.86 i	3.26 c	3.03 fg	3.33 b	3.40 a	3.13 A
Mean (L)	2.13 G	2.27 F	2.46 D	2.40 E	2.51 C	2.51 C	2.55 B	2.66 A	
Tukey's HSD	L = 3.808E-03, T = 2.700E-03, L × T = 0.011								

Means followed by different alphabets are significantly different by the HSD $p \leq 0.05$ test (lowercase alphabets depict the differences between the interaction of Foxtail Millet Lines (L) and treatments (T); uppercase alphabets depict the differences between Foxtail Millet Lines (L) means and treatments (T) means

Table 3 Impact of various ratios of NPK on net assimilation rate (NAR) (g plant^{-1} day^{-1}) of eight lines of foxtail millet (*Setaria italica* L.)

Treatments	Foxtail Millet Lines (L)								
	U2	V19	V73	V93	V101	V106	V107	V111	Mean (T)
T1	2.63 j	2.63 j	2.63 j	2.60 k	2.63 j	2.63 j	2.63 j	2.63 j	2.62 D
T2	2.63 j	2.63 j	2.63 j	2.63 j	2.63 j	2.63 j	2.63 j	2.63 j	2.63 C
T3	2.63 j	2.63 j	2.63 j	2.63 j	2.63 j	2.63 j	2.63 j	2.63 j	2.63 C
T4	2.63 j	2.63 j	2.90 h	2.63 j	2.86 i	2.63 j	2.93 g	3.00 f	2.77 B
T5	3.00 f	2.90 h	3.30 c	2.86 i	3.26 d	3.03 e	3.33 b	3.40 a	3.13 A
Mean (L)	2.70 F	2.68 G	2.81 C	2.67 H	2.80 D	2.71 E	2.83 B	2.85 A	
Tukey's HSD	L = 3.80E-03, T = 2.70E-03, L × T = 0.011								

Means followed by different alphabets are significantly different by the HSD $p \leq 0.05$ test (lowercase alphabets depict the differences between the interaction of Foxtail Millet Lines (L) and treatments (T); uppercase alphabets depict the differences between Foxtail Millet Lines (L) means and treatments (T) means

Table 4 Impact of various ratios of NPK on plant height (PH) (cm) of eight lines of foxtail millet (*Setaria italica* L.)

Treatments	Foxtail Millet Lines (L)								
	U2	V19	V73	V93	V101	V106	V107	V111	Mean (T)
T1	88.83 e-h	74.40 m	66.60 o-q	82.73 i-l	64.93 pq	55.23 st	72.30 m-o	80.53 kl	73.19 C
T2	92.57 d-g	87.47 g-j	87.63 g-j	85.13 h-k	110.43 a	50.27 tu	82.43 j-l	88.07 f-j	85.50 A
T3	99.10 bc	99.13 bc	88.97 e-h	97.70 cd	104.70 b	51.63 t	67.87 n-p	64.47 pq	84.19 A
T4	95.77 cd	88.43 f-i	94.27 c-e	85.23 h-k	58.43 rs	73.20 mn	74.40 m	85.97 h-k	81.96 B
T5	88.37 f-i	45.87 u	77.10 km	96.53 cd	93.47 c-f	58.07 rs	55.97 r-t	61.17 qr	72.06 C
Mean (L)	92.92 A	79.06 E	82.91 D	89.46 B	86.39 C	57.68 H	70.59 G	76.04 F	
Tukey's HSD	L = 1.9663, T = 1.3941, L × T = 5.7061								

Means followed by different alphabets are significantly different by the HSD $p \leq 0.05$ test (lowercase alphabets depict the differences between the interaction of Foxtail Millet Lines (L) and treatments (T); uppercase alphabets depict the differences between Foxtail Millet Lines (L) means and treatments (T) means

Table 5 Impact of various ratios of NPK on panicle length (PL) (cm) of eight lines of foxtail millet (*Setaria italica* L.)

Treatments	Foxtail Millet Lines (L)								
	U2	V19	V73	V93	V101	V106	V107	V111	Mean (T)
T1	9.03 ij	11.03 e-h	8.00 jk	7.06 kl	6.66 kl	4.36 n-p	5.96 l-o	7.16 kl	7.41 D
T2	11.60 c-h	12.10 c-g	7.47 j-l	6.19 k-n	11.13 c-h	4.00 p	7.23 j-l	12.40 c-f	9.01 C
T3	12.66 b-e	14.30 a	12.83 b-e	10.46 g-i	15.56 a	4.23 op	12.36 c-f	10.66 f-i	11.63 A
T4	10.40 g-i	10.63 f-i	10.40 g-i	9.93 hi	4.83 m-p	12.63 b-e	12.90 b-d	10.40 g-i	10.26 B
T5	13.00 bc	6.33 k-m	6.23 k-m	11.96 c-g	10.52 g-i	4.21 op	11.16 c-h	11.16 c-h	9.32 C
Mean (L)	11.34 A	10.88 AB	8.98 E	9.12 DE	9.74 CD	5.89 F	9.92 C	10.36 BC	
Tukey's HSD	L = 0.6299, T = 0.4466, L × T = 1.8279								

Means followed by different alphabets are significantly different by the HSD $p \leq 0.05$ test (lowercase alphabets depict the differences between the interaction of Foxtail Millet Lines (L) and treatments (T); uppercase alphabets depict the differences between Foxtail Millet Lines (L) means and treatments (T) means

the highest mean PW (3.33 g) for this line, while treatment T1 had the lowest mean PW (1.25 g). Overall, the highest mean PW (2.35 g) was observed in line V106, while the lowest mean PW (2.23 g) was observed in line V19. Among the different treatments, T4 generally resulted in the highest mean values for PW, while T1 had the lowest mean values (Table 6).

Table 6 Impact of various ratios of NPK on panicle weight (PW) (g) of eight lines of foxtail millet (*Setaria italica* L.)

Treatments	Foxtail Millet Lines (L)								
	U2	V19	V73	V93	V101	V106	V107	V111	Mean (T)
T1	1.61 op	2.38 h-m	1.25 p	2.35 h-n	1.33 p	1.96 mno	1.97 mno	2.06 l-o	1.86 D
T2	1.57 op	2.62 f-k	1.28 p	1.15 p	2.84 d-h	1.94 mno	1.86 no	2.97 c-g	2.03 C
T3	2.54 g-l	2.81 e-h	2.77 e-i	3.63 ab	2.74 e-j	2.25 j-n	2.65 e-j	2.95 c-g	2.79 A
T4	3.14 b-e	2.49 g-l	3.04 c-f	2.77 e-i	3.35 abc	2.64 f-j	3.33 a-d	2.24 j-n	2.87 A
T5	2.29 i-n	1.13 p	2.12 l-n	3.65 a	2.13 k-n	3.39 abc	2.77 e-i	1.59 op	2.38 B
Mean (L)	2.23 DE	2.28 CDE	2.09 E	2.71 A	2.48 BC	2.43 BC	2.52 AB	2.35 BCD	
Tukey's HSD	L = 0.1136, T = 0.0805, L × T = 0.3295								

Means followed by different alphabets are significantly different by the HSD $p \leq 0.05$ test (lowercase alphabets depict the differences between the interaction of Foxtail Millet Lines (L) and treatments (T); uppercase alphabets depict the differences between Foxtail Millet Lines (L) means and treatments (T) means

Table 7 Impact of various ratios of NPK on grain yield (GY) (g) of eight lines of foxtail (*Setaria italica* L.)

Treatments	Foxtail Millet Lines (L)								
	U2	V19	V73	V93	V101	V106	V107	V111	Mean (T)
T1	0.94 t	1.60 lm	0.74 u	1.64 jkl	0.69 uv	1.23 qr	1.21 qr	1.74 ij	1.23 E
T2	1.21 qr	1.45 no	0.77 u	0.67 v	1.72 ijk	1.38 o	1.27 pq	2.03 g	1.30 D
T3	1.52 mn	2.12 efg	1.23 qr	2.82 a	1.67 i-l	1.36 op	1.60 lm	1.41 o	1.72 B
T4	2.36 c	1.05 s	2.03 g	1.16 r	2.23 d	2.15 def	2.04 fg	1.62 klm	1.83 A
T5	1.43 o	0.62 v	1.84 h	2.15 de	1.75 hi	2.67 b	1.37 o	0.98 st	1.61 C
Mean (L)	1.49 E	1.37 F	1.32 F	1.68 B	1.61 C	1.76 A	1.50 E	1.56 D	
Tukey's HSD	L = 0.0487, T = 0.0345, L × T = 0.1413								

Means followed by different alphabets are significantly different by the HSD $p \leq 0.05$ test (lowercase alphabets depict the differences between the interaction of Foxtail Millet Lines (L) and treatments (T); uppercase alphabets depict the differences between Foxtail Millet Lines (L) means and treatments (T) means

Table 8 Impact of various ratios of NPK on plant biomass (PB) (g) of eight lines of foxtail (*Setaria italica* L.)

Treatments	Foxtail Millet Lines (L)								
	U2	V19	V73	V93	V101	V106	V107	V111	Mean (T)
T1	11.82 d-g	11.93 c	11.76 f-i	11.71 ij	11.53 m	11.46 n-p	11.32 q	11.53 mn	11.63 E
T2	11.83 d	11.83 de	11.93 c	11.64 k	11.52 m-o	11.46 op	11.74 i	11.92 c	11.68 D
T3	11.67 jk	11.53 m-o	11.61 kl	11.75 hi	12.48 b	11.93 c	11.44 p	11.64 k	11.75 B
T4	11.74 i	11.65 jk	11.82 d-f	11.66 jk	11.75 hi	11.81 d-h	11.33 q	11.84 d	11.701 C
T5	11.76 e-i	11.65 jk	11.64 k	11.81 d-h	12.59 a	11.75 hi	11.75 g-i	11.55 lm	11.87 A
Mean (L)	11.76 B	11.72 C	11.75 B	11.71 C	11.97 A	11.68 D	11.51 E	11.69 CD	
Tukey's HSD	L = 0.1625, T = 0.1152, L × T = 0.4717								

Means followed by different alphabets are significantly different by the HSD $p \leq 0.05$ test (lowercase alphabets depict the differences between the interaction of Foxtail Millet Lines (L) and treatments (T); uppercase alphabets depict the differences between Foxtail Millet Lines (L) means and treatments (T) means

The impact of different treatments on GY per panicle is also significant for most of the lines, as indicated by different alphabets (Table 7). For example, for line V19, treatments T2 and T3 have significantly different effects on GY per panicle. Treatment T3 resulted in the highest mean GY per panicle (2.12 g) for this line, while treatment T5 had the lowest mean GY per panicle (0.62 g). Overall, the highest mean GY per panicle (1.56 g) was observed in line V106, while the lowest mean GY per panicle (1.37 g) was observed in line V19. Among the different treatments, T4 generally resulted in the highest mean values for GY per panicle, while T1 had the lowest mean values (Table 7).

The impact of different treatments on plant biomass (PB) is statistically significant ($p < 0.05$) for most of the lines, as indicated by different alphabets. For instance, for line V101, treatments T3 and T5 have significantly different effects on PB (Table 8). Treatment T5 resulted in the highest mean PB (12.59) for this line, while treatment T4 had the lowest mean PB (11.75). Overall, the highest mean PB (11.97) was observed in line V106, while the lowest mean PB (11.51) was observed in line V107. Among the different treatments, T5 generally resulted in the highest mean values for PB, while T4 had the lowest mean values (Table 8).

The impact of different treatments on HI is also significant for most of the lines, as indicated by different alphabets (Table 9). For example, for line V111, treatments T2 and T5 have significantly different effects on the HI. Treatment T5 resulted in the highest mean HI (54.55%) for this line, while treatment T4 had the lowest mean HI (19.24%). Overall, the highest mean HI (33.55%) was observed in line V106, while the lowest mean HI (25.43%) was observed in line V107. Among the different

Table 9 Impact of various ratios of NPK on harvest index (HI) (%) of eight lines of foxtail (*Setaria italica* L.)

Treatments	Foxtail Millet Lines (L)								
	U2	V19	V73	V93	V101	V106	V107	V111	Mean (T)
T1	37.41 a-f	41.55 a-c	39.81 a-d	34.03 b-j	30.08 b-j	34.01 b-j	33.73 b-j	35.62 b-i	25.58 B
T2	38.01 a-f	36.83 a-g	36.42 a-h	37.78 a-f	28.12 c-j	46.42 ab	33.64 b-j	27.44 c-j	35.58 A
T3	28.64 b-j	37.01 a-g	27.64 c-j	16.53 j	17.55 ij	26.70 c-j	20.08 f-j	30.91 b-j	25.65 B
T4	19.11 g-j	33.43 b-j	18.64 h-j	26.06 c-j	22.92 d-j	25.20 c-j	18.04 ij	19.24 g-j	33.78 A
T5	26.17 c-j	38.47 a-e	33.03 b-j	36.48 a-h	34.19 b-j	20.60 e-j	21.64 e-j	54.55 a	37.78 A
Mean (L)	29.89 BC	37.46 A	31.11 BC	29.78 BC	26.57 C	30.59 BC	25.43 C	33.55 AB	
Tukey's HSD	L = 2.063, T = 9.561, L × T = 4.603								

Means followed by different alphabets are significantly different by the HSD $p \leq 0.05$ test (lowercase alphabets depict the differences between the interaction of Foxtail Millet Lines (L) and treatments (T); uppercase alphabets depict the differences between Foxtail Millet Lines (L) means and treatments (T) means

Table 10 Impact of various ratios of NPK on chlorophyll *a*, *b*, and total chlorophyll contents (mg g^{-1} on fresh weight basis) of eight lines of foxtail (*Setaria italica* L.)

Treatments	Chlorophyll*a*contents								
	U2	V19	V73	V93	V101	V106	V107	V111	Mean (T)
T1	0.07 bc	0.07 bc	0.07 bc	0.06 bc	0.05 c	0.05 c	0.05 c	0.05 c	0.06 B
T2	0.06 c	0.07 bc	0.07 bc	0.07 bc	0.06 bc	0.06 bc	0.06 bc	0.07 bc	0.06 B
T3	0.07 bc	0.06 c	0.06 bc	0.06 bc	0.06 bc	0.06 bc	0.06 bc	0.05 c	0.06 B
T4	0.06 c	0.06 c	0.06 bc	0.06 bc	0.06 bc	0.06 bc	0.06 bc	0.05 c	0.06 B
T5	0.06 c	0.06 c	0.06 bc	0.06 bc	0.11 bc	0.20 a	0.21 a	0.20 a	0.12 A
Mean (L)	0.06 D	0.06 CD	0.07 CD	0.06 CD	0.07 B-D	0.09 AB	0.09 A	0.08 A-C	
Tukey's HSD	L = 0.0174, T = 0.0124, L × T = 0.0506								
Chlorophyll*b*contents									
	U2	V19	V73	V93	V101	V106	V107	V111	Mean (T)
T1	0.59 cde	0.48 fgh	0.42 g-j	0.68 bc	0.46 f-i	0.54 def	0.19 o	0.38 i-l	0.46 B
T2	0.35 j-m	0.80 a	0.73 ab	0.61 cd	0.42 g-j	0.26 m-o	0.36 jkl	0.55 def	0.51 A
T3	0.31 lmn	0.33 j-n	0.30 lmn	0.60 cde	0.71 ab	0.34 j-m	0.35 j-m	0.59 cde	0.44 C
T4	0.47 f-i	0.67 bc	0.60 cde	0.54 def	0.48 fgh	0.42 g-j	0.24 no	0.36 jkl	0.47 B
T5	0.51 efg	0.59 cde	0.32 k-n	0.49 fgh	0.41 h-k	0.65 bc	0.46 f-i	0.42 g-j	0.48 B
Mean (L)	0.44 C	0.57 A	0.47 BC	0.58 A	0.49 B	0.44 C	0.32 D	0.46 C	
Tukey's HSD	L = 0.03, T = 0.02, L × T = 0.09								
Total chlorophyll contents									
	U2	V19	V73	V93	V101	V106	V107	V111	Mean (T)
T1	0.66 fg	0.55 lmn	0.49 op	0.74 d	0.51 nop	0.59 i-l	0.24 u	0.43 q	0.52 C
T2	0.41 qr	0.87 a	0.80 bc	0.68 ef	0.48 p	0.32 st	0.42 q	0.62 g-j	0.57 B
T3	0.37 rs	0.39 qr	0.36 rs	0.66 fg	0.77 cd	0.40 qr	0.41 qr	0.64 f-i	0.50 D
T4	0.53 m-p	0.73 de	0.38 qr	0.60 h-k	0.54 l-o	0.48 p	0.30 t	0.41 qr	0.53 C
T5	0.57 j-m	0.65 fgh	0.38 qr	0.55 k-n	0.52 m-p	0.85 ab	0.67 f	0.62 g-j	0.60 A
Mean (L)	0.50 D	0.64 A	0.54 C	0.65 A	0.57 B	0.53 C	0.41 E	0.54 C	
Tukey's HSD	L = 0.017, T = 0.012, L × T = 0.050								

Means followed by different alphabets are significantly different by the HSD $p \leq 0.05$ test (lowercase alphabets depict the differences between the interaction of Foxtail Millet Lines (L) and treatments (T); uppercase alphabets depict the differences between Foxtail Millet Lines (L) means and treatments (T) means

treatments, T5 generally resulted in the highest mean value of HI, while T4 had the lowest mean value of HI (Table 9).

Biochemical traits

The different treatments have a significant effect on chlorophyll *a* content in foxtail plants. The mean values for chlorophyll *a* content range from 0.06 to 0.12 (Table 10). Similarly, the impact of different treatments on chlorophyll *b* content is also statistically significant. The mean values for chlorophyll *b* content range from 0.44 to 0.51. Overall, the mean chlorophyll *a* content is lower than the mean chlorophyll *b* content across all lines and treatments. Line V106 and V107 has the highest mean chlorophyll *a*, V93 and V19 exhibited highest chlorophyll *b* contents, while line V107 and U2 has the lowest mean values for both chlorophyll *a* and chlorophyll *b*. The impact of different treatments on total chlorophyll contents is statistically significant. For example, in treatment T2, line V19 has significantly higher total chlorophyll content compared to lines V73, V93, V106, V107, and V111. The mean values for total chlorophyll content

range from 0.50 to 0.60. This suggests that the different treatments had a significant effect on total chlorophyll content in foxtail plants (Table 10).

The impact of different treatments on carotenoid contents is statistically significant, as indicated by different alphabets for some treatments and lines. For example, in treatment T2, line V19 has significantly higher carotenoid contents compared to lines V73, V93, V101, V106, V107, and V111. The mean values for carotenoid content range from 14.58 to 16.58. This indicates that the different treatments had a significant effect on carotenoid contents in foxtail plants. Line V93 and V19 has the highest mean carotenoid contents, while line V107 has the lowest mean values for carotenoids. The differences in carotenoid contents among the lines and treatments are statistically significant. In conclusion, the different treatments of fertilizer application had a significant impact on carotenoid contents in foxtail plants, as indicated by the significant differences among the treatments (Table 11).

Pearson's correlations of various emergence, growth, yield, and photosynthesis traits of foxtail millet lines are presented in Fig. 3. Positive correlations of GY with chlorophyll contents, photosynthetic attributes, PH, and PB of foxtail millet plants. MET and EI have a very strong positive correlation of 0.99. There is also a very strong correlation between FEP with CGR (0.79) and NAR (0.83). PW is very positively linked with GY (0.73). There is a perfect correlation between the CGR and the NAR. GY and chlorophyll are linked positively with each other. A very strong correlation is observed between total chlorophyll contents and carotenoids.

Discussion

Crop production is now facing some challenges because of climate change. Sustainable production in the agricultural industry requires a change or the inclusion of new and alternative crops. Foxtail millet is an emerging crop that can withstand harsh environmental conditions. Seed germination, which marks the start of the crop life cycle and is linked to seed emergence, growth, and plant development, affects grain yield. Crop growth is the inevitable expansion in the size and mass of plants. The CGR is measured to determine how well applied fertilizers affect crop size, height, and weight. The CGR of foxtail varieties increased with increasing the concentrations of NPK applied. This increase demonstrated that NPK at the highest dose significantly affects the pace of plant and crop growth. Our findings are in line with those of Kalaghatagi et al. [33], who claimed that applying NPK in combination with micronutrients increased crop growth rate. The net assimilation rate (NAR) is the increase in the plant's dry weight per unit leaf area and unit time. It is the measure of plant biomass, leaf dry weight, and simply crop growth. N plays an important role in the growth and development of plants since it is a necessary component of amino acids and aids the plants in photosynthesis; therefore, more N will improve the NAR. The increase in NAR was caused by the application of N, P, and K. Our findings concur with those of Farooqi et al. [34], who demonstrated that N played a role in the formation of new cells and increased the photosynthetic activity that ultimately increased the NAR of crops. Application of various nutrients, either foliar spray or soil amendment, significantly improved the growth, yield, and quality of produce [35–37]. Line V107 showed the highest crop growth rate (CGR) and net assimilation rate (NAR) under higher NPK doses, possibly due to its genetic predisposition for more efficient carbon assimilation Guan et al. [18]. These lines demonstrate superior nutrient utilization compared to others, which could be explored for breeding programs aimed at improving nutrient efficiency under varying fertilization regimes.

Plant height is also very important in terms of the yield of the crops. The findings were comparable to those of an experiment conducted on millet by Ngala and Musa [38], in which maximum plant height was recorded by application of NPK at 30:15:15 kg ha^{-1} of NPK along with farmyard manure at 2.5 metric tonnes ha^{-1}. Panicle length is one aspect of panicle architecture and is usually measured as a yield related trait. Increased NPK application promotes growth and yield in foxtail millet by improving nutrient availability, which is vital for photosynthesis

Table 11 Impact of various ratios of NPK on carotenoids (mg g^{-1} on fresh weight basis) of eight lines of foxtail (*Setaria italica* L.)

Treatments	Foxtail Millet Lines (L)								
	U2	V19	V73	V93	V101	V106	V107	V111	Mean (T)
T1	20.20 fgh	16.51 no	15.24 p	24.21 c	16.15 o	19.33 i	7.76 z	13.24 r	16.58 A
T2	9.22 xy	27.84 a	25.09 b	20.32 efg	12.95 r	10.57 vw	5.20 A	17.96 k	16.14 B
T3	9.55 x	10.31 w	9.00 y	20.60 e	25.00 b	11.30 t	11.02 tu	19.90 h	14.58 D
T4	14.93 p	20.40 ef	20.42 ef	18.63 j	16.85 mn	12.36 s	7.80 z	10.40 w	15.22 C
T5	17.55 l	19.98 gh	10.88 uv	17.15 m	13.67 q	22.69 d	15.14 p	14.96 p	16.50 A
Mean (L)	14.29 F	19.00 B	16.12 D	20.18 A	16.92 C	15.25 E	9.38 G	15.29 E	
Tukey's HSD	L = 0.128, T = 0.091, L × T = 0.373								

Means followed by different alphabets are significantly different by the HSD $p \leq 0.05$ test (lowercase alphabets depict the differences between the interaction of Foxtail Millet Lines (L) and treatments (T); uppercase alphabets depict the differences between Foxtail Millet Lines (L) means and treatments (T) means

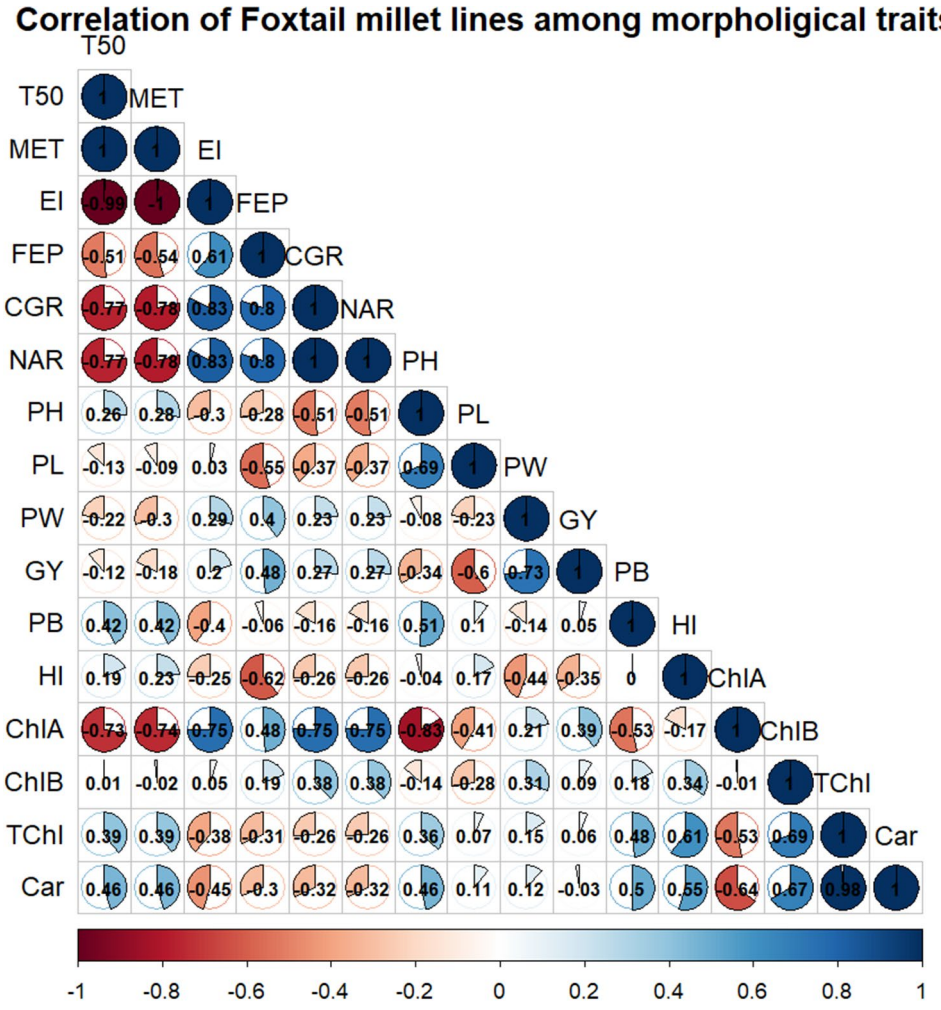

Fig. 3 Pearson correlation between different attributes of foxtail millet

and metabolic functions. Nitrogen stimulates vegetative growth [39], P supports root development and energy transfer [40], while K enhances water regulation and disease resistance [41]. This synergy results in improved plant height, panicle length, and grain yield. Previous findings by Kalaghatagi et al. [33] and Hasan et al. [42] have demonstrated similar outcomes in foxtail millet and other crops where balanced NPK application improved both growth and yield components. Our results in the case of PL are like Nandini et al. [43], who reported an increase in PL due to application of N fertilization to foxtail millet. In another study, it was illustrated that macro-nutrients such as NPK had vital role in enhancing the photo assimilates in the plant and consequently increasing the PL [44]. A high dose of NPK significantly enhanced the growth and yield attributes, including panicle weight, plant height, total biomass, and grain yield in pearl millet [45].

Panicle weight is an important component of yield that is a direct indicator of grain and biological yield. Although it is a hereditary trait, nutritional management may have an impact. The weight of the foxtail millet panicle was positively impacted by the NPK application. However, certain foxtail millet lines responded significantly better than others to various NPK doses. The findings of the current study, which show a considerable increase in panicle weight, are consistent with those of Jali et al. [8], who found that the application of essential nutrients such as NPK was associated with increased panicle length and panicle weight. An increase in grain yield of foxtail millet was advocated by many researchers. Bameri et al. [46] reported an increase in the grain yield of foxtail millet by the application of combined NPK and microelements. Similarly, Kalaghatagi et al. [33] also reported that N is the key nutrient that is required for the millets to increase their growth and yield. Hasan et al. [42] reported that the application of NPK increased the grain yield of foxtail millet. Moreover, Nandini et al. [43] observed that the application of 125% of N led to improved yield-related characteristics, including the

number of effective tillers, panicle length, panicle weight, and test weight of foxtail millet.

Since N is a crucial component of amino acids and helps plants with photosynthesis, it plays a crucial role in the growth and development of crops. Consequently, greater N will increase plant biomass. The increase in plant biomass was mainly because of NPK supplementation in the crop. The outcomes made it obvious that all the foxtail millet lines responded well to fertilizer application. The results of this study are consistent with those of Kalaghatagi et al. [33] and Hasan et al. [42]. The results of Nadeem et al. [46] showed that macronutrients, like N, are crucial for the millet crop because they raise plant height, leaf area, biomass, harvest index, and grain production. The harvest index of some foxtail varieties used was reduced with an increase in concentration of NPK applied. This decrease in harvest index followed the law of diminishing returns, which states that an increasing amount of any nutrient will increase the yield, but up to an optimum concentration, an increase in dose above the optimum will lead to decrease in yield [47]. Imran et al. [48] stated that application of Nat higher rate increased the growth and yield attributes, including plant height, 1000-grain weight, and grain yield of maize. The presence of elements in plants is affected by both environmental factors and genetic mechanisms. Importantly, considerable advancements have been made in the identification of key transporters responsible for the accumulation of diverse elements [49, 50]. The expanding datasets derived from genome sequencing, re-sequencing, pan-genomics, and RNA-sequencing serve as valuable resources for investigating inherent variations in crucial genes related to mineral transport and accumulation in plants [51].

The crop growth rate and net assimilation rate were observed to be highest (Tables 3 and 4) with the highest dose of NPK, while growth parameters like plant height, spike length, and yield (Tables 5, 6 and 7) were decreased by the higher dose. These variations may be linked to the genetic makeup of the lines that are more responsive at the vegetative growth stage and some reproductive growth stage. The lines with low vegetative growth attributes and high reproductive growth may a have higher capacity for assimilates' translocation from source to sink. Therefore, in this study, we investigated the effect of fertilizers on agronomic traits, yield, and yield components. Studies have shown that different NPK combinations have significant effects on the nutritional and growth characteristics of foxtail millet [18, 52]. In the present study, we found that there were significant differences in the effects of N, P, and K fertilizers and their interactions on the yield and quality in foxtail millet. Previous studies suggested that N fertilization was the most important factor in foxtail millet with respect to grain yield and aboveground produce [18]. Reasonable NPK ratios improved nutrient absorption, biomass accumulation, and crop yield; this phenomenon has also been observed in other crops including foxtail millet [18, 23]. In the present study, it was observed that a higher dose of NPK increased the growth attributes while yield components decreased and vice versa. This depicts that reasonable NPK-balanced fertilization promoted growth and development, whereas excessive fertilization inhibited it, and the current findings are supported by Xing et al. [24].

Chlorophyll is the green pigment that helps plants in photosynthesis. The chlorophyll contents of the foxtail varieties used increased with increasing the concentration of NPK applied. NPK plays a critical role in chlorophyll production, which is essential for photosynthesis. N, in particular, is a key component of chlorophyll molecules, and its availability directly influences the chlorophyll content. P and K also contribute by improving energy transfer and stomatal functioning, enhancing overall photosynthesis. Higher NPK levels (50:30:30 kg ha^{-1}) increased chlorophyll a and b concentrations by 23% and 15.8%, respectively. These increments in chlorophyll correlate strongly with increased photosynthetic activity, leading to higher biomass and grain yield. The relationship between NPK and chlorophyll content is consistent with findings from other studies where higher nitrogen levels led to increased photosynthetic efficiency and crop yields. Nadeem et al. [46] reported an increase in chlorophyll contents due to application of N fertilizer. The data demonstrates that different foxtail lines responded differently to applied NPK levels, although the higher amount of NPK (50:30:30) was most important in boosting all the foxtail lines' growth and yield metrics. When given NPK ratios, V111 among the varieties performed noticeably better. Line V106 showed the highest chlorophyll a and b contents under treatment T5, which could be attributed to better nutrient uptake and photosynthetic efficiency Loudari et al. [53]. Application of plant growth promoters also plays an important role in improving the concentration of chlorophyll contents [54]. According to Ciecko et al. [12], the application of N and Mg fertilizers significantly increased the concentration of chlorophyll contents in potatoes. They also reported that mineral fertilization enhanced the synthesis of chlorophyll pigments, which were responsible for higher yield as well. The discrepancy in pigment content may be due to overcrowding, as suggested, resulting in shading effects. Overcrowding likely caused increased plant height (Table 5) and competition for light, leading to higher carotenoid levels, which act as photo protective pigments. The high chlorophyll *b* content compared to chlorophyll *a* content, and elevated carotenoids indicate a shading effect likely caused by dense plant populations. This supports the observation of increased plant height and lower harvest index due to competition for light.

Lines like V106 and V107 excelled under high-input conditions (T5), other lines, such as V19, showed moderate performance under the T2 treatment. V19 had a consistent yield and chlorophyll content, suggesting that it can maintain a reasonable growth rate even under reduced nutrient input. This line could be a candidate for further breeding aimed at developing low-input varieties. Low-input agriculture is becoming increasingly important for sustainable farming, and exploring these responses is crucial for future research Sarkar et al. [55].

Conclusions

The current study was carried out to investigate the impact of various levels of NPK fertilizer on the growth, development, and yield of foxtail millet lines from USDA germplasm; U2, V19, V73, V93, V101, V106, V107, and V111. Application of NPK at the rate of 50:30:30 kg ha^{-1} produced maximum chlorophyll *a* (23%), *b* (15.8%), total chlorophyll contents (14.2%), plant fresh biomass (2.06%), and grain yield (23.6%) as compared to control treatment. A higher concentration of chlorophyll contents was found to be responsible for the higher biomass and yield, as a positive correlation was observed between the chlorophyll contents and biomass. The practical implications of this study include demonstrating the importance of optimizing NPK levels to enhance foxtail millet yield and quality. Since foxtail millet is a resilient crop, capable of thriving under marginal environments, the findings suggest that its cultivation can be promoted in nutrient-poor soils. Policy-wise, the study provides evidence for promoting foxtail millet as a climate-resilient crop, suitable for low-input sustainable agriculture, which aligns with global climate adaptation strategies. Furthermore, these findings are from the preliminary study of pot experiments. For efficient recommendation, field experiments are required regarding the optimal time, dose, and methods for nutrient application.

Recommendations and future thrusts

Future research should focus on conducting multi-season field trials to validate the findings from this preliminary pot experiment under variable environmental conditions. Additionally, it would be beneficial to explore the interaction of NPK with organic fertilizers or bio-based inputs to further optimize yield while promoting sustainable farming practices. Investigating genetic traits that make certain lines, such as V107 and V111, more responsive to NPK application can also provide valuable insights for breeding programs.

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Declarations

Ethics approval and consent to participate
We state that the methods used throughout the experiment were conducted in accordance with relevant guidelines and regulations.

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The authors declare no competing interests.

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