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RESEARCH ARTICLE

Optimizing plant spacing and seedling age for enhanced growth and yield of transplanted sorghum (*Sorghum bicolor*) under aberrant weather conditions

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Abstract

Transplanting sorghum seedlings into agricultural fields at the commencement of the rainy season can significantly enhance stand uniformity, mitigate replanting expenditures and reduce the duration of the crop's presence in the field, thereby facilitating earlier harvests and bolstering food security. Moreover, these seedlings were cultivated within controlled environments in nurseries, utilizing minimal water resources. This study evaluated the effects of seedling age and plant spacing on survival, yield and shoot fly incidence in transplanted sorghum to support evidence-based cultivation practices. A field experiment was conducted in the Agricultural Research Station, Kovilpatti, Tamil Nadu using a split-plot design with three replicates. Main plots compared three spacing (45 × 15 cm, 45 × 30 cm, 45 × 45 cm) and subplots evaluated seedling age at transplanting (15, 18 and 21-days transplants) versus direct sowing (control). Direct-sown seeds had the highest survival (96 %), followed by 18-day transplants (78 %). Shoot fly incidence didn't differ significantly across treatments. The combination of 18-day seedlings at 45 × 15 cm spacing yielded the highest grain production (3506 kg ha^{-1}), revenue (₹87211) and benefit-cost ratio (2.88). Direct sowing at the same spacing produced the highest stover yield (11900 kg ha^{-1}). Transplanting 18-day transplants at 45 × 15 cm spacing optimizes grain yield and profitability without increasing pest incidence. This approach offers a viable alternative to direct sowing, particularly in environments where earlier harvests are critical. The Pearson correlation analysis identified strong positive associations among grain yield, seed weight and plant height.

Keywords: plant spacing; seedling age; *Sorghum bicolor*; yield and economics

Introduction

Sorghum (*Sorghum bicolor* (L.) Moench) is the world's fourth most important cereal grain, cultivated on approximately 39.9 million hectares, producing around 58.7 million tonnes globally (1). It is a staple food for millions in Africa and Asia, contributing approximately 55 % of grain to human consumption and 33 % to animal feed. In India, sorghum covers 6.16 million hectares with 5.45 million tonnes produced. However, global production dropped from 41.79 million tonnes in 2011-13 to 39.8 million tonnes in 2023. In the arid and semi-arid regions of India, including Tamil Nadu, approximately 20-25 % of sorghum is sown during the summer season. This period is notably characterized by erratic rainfall patterns, water scarcity and brief rainy seasons, which collectively contribute to inconsistent germination rates, irregular stands, elevated replanting costs and the potential for complete crop failure.

Considering these circumstances, transplanting emerges as a viable strategy to navigate the unpredictable environmental conditions. In semi-arid regions, enhancing crop stands can be effectuated by replenishing gaps with seedlings sourced from overcrowded segments of the field. They utilized the surplus from overcrowded thinning to expand their planting areas. More than 95 % of farmers are gap filling their sorghum field by transplanting seedlings (2). Transplanting is predominantly practiced in regions characterized by a truncated growing season, as the establishment of seedlings in nursery facilitates an expedited harvest. This methodology possesses the potential to substantially augment yields, thereby contributing an additional dimension to food security. Beyond the provision of food security, it is imperative to equip individuals with a diverse array of agricultural techniques that facilitate the mitigation of risk associated with potential harvest losses.

Nursery-based transplanting using minimal water allows for early establishment, better stand uniformity, gap filling and quicker harvests (3). Studies in millet, maize, pearl millet and sorghum indicate that transplanting can improve yields and stability compared to direct sowing of sorghum and bajra (4–6) and maize (7,8) though results vary by crop, environment and seedling age. Optimal plant spacing influences light interception, weed suppression and overall yield. Suggested sorghum spacing ranges from 30-45 cm, depending on rainfall and irrigation levels. Seedling age at transplanting significantly affects establishment and yield; younger seedlings (7-10 days) are often preferred, although older seedlings (20-25 days) may still perform well in some cereals. Despite promising anecdotal and experimental evidence, the combined effects of seedling age and spacing on transplanted sorghum in semi-arid irrigated systems require systematic evaluation. This study investigates how seedling age (15, 18, 21 days) and plant spacing (45×15, 45×30, 45×45 cm) influence establishment, grain and stover yields and shoot fly incidence compared to direct sowing.

Materials and Methods

Experimental site

The study was conducted at the Agricultural Research Station in Kovilpatti during the summer and winter of 2021 (Fig. 1). The area is classified as semi-arid, with an average annual rainfall of 737 mm (340 mm during the northeast monsoon), mean daytime temperatures of 35 °C and night-time temperatures around 22 °C. The soils are very deep vertisols (Typic Haplusterts) with sub-angular blocky structure.

Weather conditions

Summer season (first cropping season)

Total rainfall was 75.4 mm over six days; temperatures ranged from 25.2 - 39.3 °C, with mean sunshine duration of 8.2 hr (Fig. 2a).

Winter season (second cropping season)

Total rainfall reached 417.6 mm across 28 rainy days, including a heavy 102 mm event, followed by a week of persistent rainfall. This led to high soil moisture and humidity, correlating with increased fall armyworm incidence (Fig. 2b).

Experimental design

We used a split-plot design with three replications. A split-plot design is employed to enhance the accuracy of evaluating the impacts of factors assigned to subplots, as these smaller units exhibit less variability. By distinguishing between whole plot and subplot errors, split-plot designs facilitate improved error management. This statistical differentiation frequently leads to more accurate estimates of treatment effects. Main plots tested three row spacing (45 × 15 cm, 45 × 30 cm, 45 × 45 cm) and sub-plots evaluated seedling ages (15, 18 and 21 days) in comparison to direct-sown seeds (control).

The sorghum variety K12 (also known as TKSV 0809) is photo -insensitive, hence, it can be grown in Tamil Nadu throughout the year. It produces yellowish-white grains on medium, semi-compact ear heads after maturing in 105-110 days. K12 is regarded as a dual -purpose variety with plant height of 225-240 cm, that can be used to produce both grain and fodder. Hardened seeds were treated with fungicide and biofertilizer and sown in the raised nursery with the recommended management practices. Seedlings of 15-21 days old were transplanted in different spacing as per the treatment schedule. Direct sorghum seeding was done in the main field on the same day as the seed sowing in the nursery. Fertilizer @ 90 kg N, 45 kg P_2O_5, 45 kg K_2O ha^{-1} was applied as per the recommended split doses in the form of urea, Di ammonium Phosphate and muriate of potash respectively. Pest and disease management practices were taken timely.

Crop growth parameters

Days to 50 % panicle emergence

The total number of days from the commencement of sowing or transplanting to the time at which 50 % of the panicle of the plant is observed to emerge from the sheath of the flag leaf (indicating that the panicle being either partially or fully extruded from the sheath) was meticulously documented.

Days to 50 % flowering

The accumulation of days from the commencement of sowing/ transplantation to the point at which 50 % of the plant's panicle bearing flowers were recorded.

Days to physiological maturity

The total number of days from the commencement of sowing or transplanting to the point at which the grain reaches its maximum dry weight, thereby halting further growth or dry matter accumulation and entering the hard stage, was precisely recorded. The maturation of the panicle was assessed when the basal portion (point of attachment to the panicle stem) of the grain reached the black layer (9).

Leaf Area Index (LAI)

From five randomly chosen plants within each treatment plot, measurements were conducted for leaf length, width and the total number of leaves per plant on the third physiologically active leaf from the apex of the sorghum plant during the flowering stage. Based on these measurements, the LAI was computed utilizing the methodology established by (10).

$$LAI = \frac{L \times W \times K \times N}{S}$$

Where,

L = Length of the leaf from top (cm)

W = Maximum width of the leaf blade (cm)

K = A constant factor of 0.75

N = Number of leaves per plant

S = Land area occupied (cm^2)

Data concerning the survival percentage as well as shoot fly incidence was carefully recorded. A total of ten plants, strategically positioned at the center of each plot, were selected for continuous sampling throughout the growing season, with the average values utilized for subsequent analyses. From the selected plants, measurements of plant height LAI and the number of grains per panicle and the weight of 1000 seeds were collected replication-wise in a systematic manner.

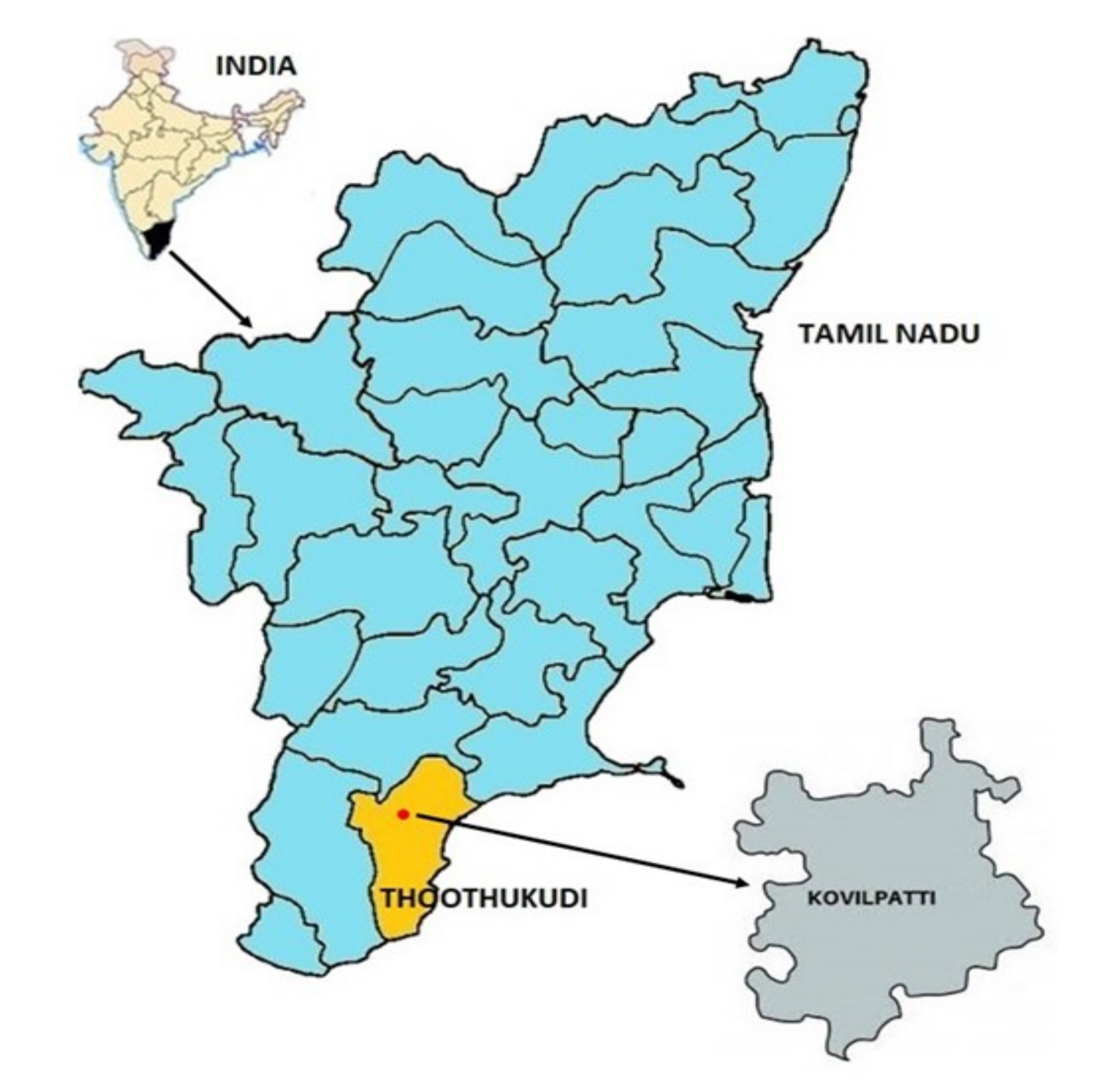

Fig. 1. Location of the study area.

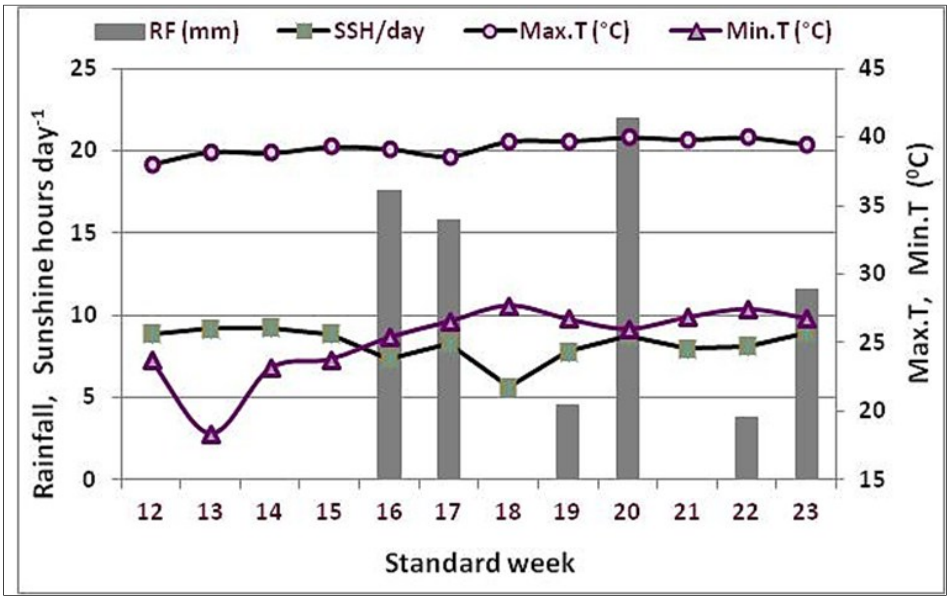

Fig. 2a. Weather prevailed during the 1st cropping period.

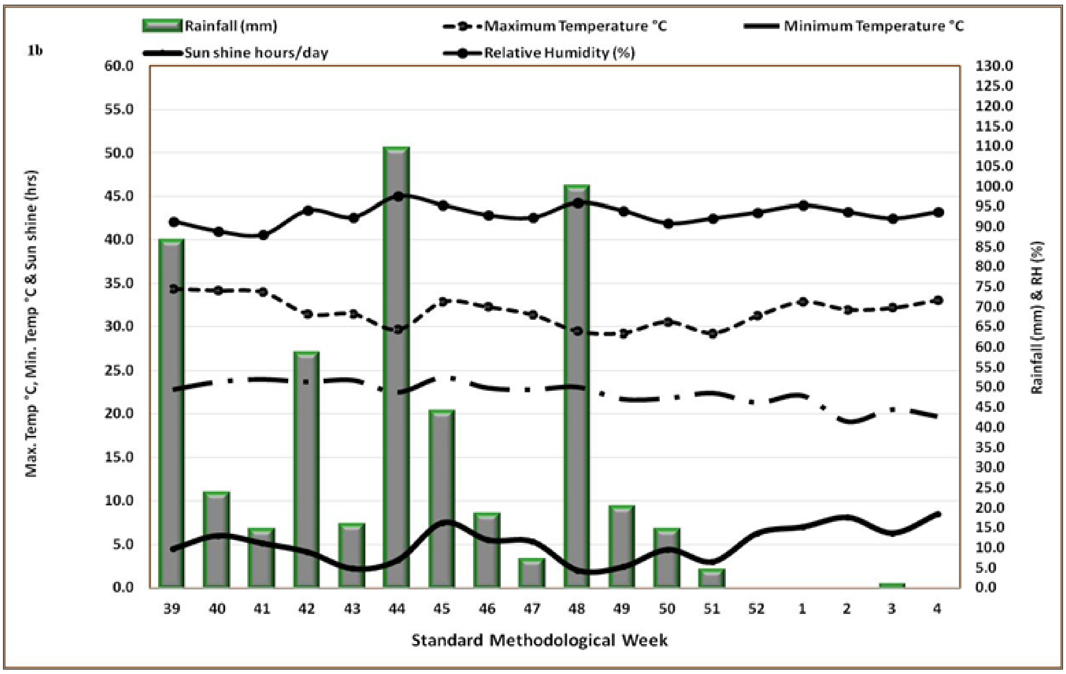

Fig. 2b. Weather prevailed during the 2nd cropping period.

Yield and biomass collection

Panicles from net plot areas were sun-dried, threshed, cleaned and weighed at 14 % moisture. Stover was cut for 3 days postharvest and weighed. Yields were expressed in kg ha^{-1}.

Economic analysis

Cost components from sowing to harvest were recorded for each treatment. Gross returns (grain + stover) were calculated using farm gate prices. Net returns and benefit-cost ratio (B:C) were computed:

- Net returns (₹/ha) = Gross returns - variable cost
- B:C ratio = Gross returns ÷ cultivation cost

Statistical analysis

Growth duration parameters are presented as means; all other data were analyzed using ANOVA (11), with significance at P ≤0.05. The Least Significant Difference (LSD) test applied for the purpose of conducting multiple comparisons. Pearson's correlation and Principal Component Analysis (PCA) are two prominent statistical methodologies employed to investigate the interrelations among variables. The Pearson correlation coefficient serves to quantify both the magnitude and directionality of linear associations between pairs of continuous variables. It evaluates the intensity of linear relationships such as strong, weak or the absence of correlation between two continuous variables. PCA facilitates the reduction of dimensionality within a dataset comprising multiple variables by identifying a novel set of uncorrelated variables. This technique effectively simplifies intricate datasets characterized by numerous correlated variables, thereby decreasing the total number of variables for subsequent visualization or further analytical endeavors. Both Pearson's correlation and PCA were executed utilizing R Studio software.

Results

Different phenophases of sorghum

Days to 50% panicle emergence, flowering and physiological maturity were similar across spacing but varied significantly with seedling age. The seedling ages and the method of direct sowing have a pronounced effect on the field duration of sorghum. The direct sowing of the sorghum variety K 12 required the maximum duration for panicle emergence, 50 % flowering and physiological maturity. These durations exhibited a progressive reduction when adopting transplanted sorghum (Table 1). The main field durations recorded were 88, 85, 87 and 95 days for the transplantation of seedlings aged 15, 18 and 21-days, respectively, as well as for direct sowing. Collectively, transplanting reduced the main field duration compared to direct sowing by 7 days for 15-day old seedlings, 8-days for 21-day old seedlings and 10-days for 18-day old seedlings.

Table 1. Mean values of days to panicle emergence, 50 % flowering and physiological maturity

Interaction		Days to 50 % panicle emergence	Days to 50 % flowering	Days to physiological maturity
Spacing x	**Seedling age**			
45 x 15 cm	15 days old seedling	49	56	88
	18 days old seedling	46	53	85
	21 days old seedling	48	55	87
	Direct sowing	56	63	95
45 x 30 cm	15 days old seedling	49	55	88
	18 days old seedling	46	53	85
	21 days old seedling	48	55	87
	Direct sowing	56	63	95
45 x 45 cm	15 days old seedling	48	55	88
	18 days old seedling	46	53	85
	21 days old seedling	47	55	87
	Direct sowing	56	63	95

Survival percentage and shoot fly incidence

Transplantation of seedlings with varying spacing did not exhibit a statistically significant effect on stand establishment or survival percentage during both summer and winter seasons. The seedling age significantly influenced the survival percentage across both seasons. Among the various ages of seedlings, the highest survival percentage was observed in direct sowing within the main field (96 %), followed by the transplantation of 18-day old seedlings (78 %). Both older and excessively young seedlings were associated with suboptimal establishment. No significant differences were identified in shoot fly incidence across the various spacing and ages of seedlings evaluated (overall mean ~8 -9 %) (Table 2).

Plant height and LAI

Plant height was not significantly affected by treatments (Fig. 3). LAI was significantly influenced by both spacing and seedling age with the CD value of 0.72 and 0.46 for spacing and seedling age respectively (Fig. 4). Single plant LAI was highest at 45×45 cm (5.78) and among seedling ages, 18-day seedlings achieved the maximum LAI (5.48).

Table 2. Influence of spacing and seedling age on survival percentage and shoot fly incidence

Treatments	Survival %	Shoot fly incidence (%)
Main plot: Spacing		
S_1: 45× 15 cm	81	8.5
S_2: 45 × 30 cm	70	8.5
S_3: 45 × 45 cm	74	8.5
Standard Error (SEd)	**5**	**0.4**
Critical Difference (CD) (5 %)	**NS**	**NS**
Sub plot: Seedling ages		
T_1: Transplanting of 15 days seedling	64	8.7
T_2: Transplanting of 18 days seedling	78	8.3
T_3: Transplanting of 21 days seedling	61	9.0
T_4: Direct sowing as control	96	8.0
SEd	**7**	**0.4**
CD (5 %)	**14**	**NS**
Main at Sub SEd	**12**	**0.8**
Main at Sub CD (5 %)	**NS**	**NS**
Sub at Main SEd	**12**	**0.8**
Sub at Main CD (5 %)	**NS**	**NS**

Number of grains per panicle

Highest values were recorded at wider spacing (45×45 cm: 2147 grains) and 18-day seedlings (2023 grains) which was comparable to the direct sowing of sorghum seeds at the same spacing in the main field which yielded 1950 seeds per panicle (Fig. 5).

1000- seed weight

Not significantly affected overall; however, closer spacing (45 × 15 cm) and 18-day seedlings yielded slightly higher values (23.3 g and 23.1 g respectively) (Fig. 6).

Grain and stover yield

A significantly enhanced grain yield of sorghum was observed at closer spacing of 45 × 15 cm, achieving a yield of 2697 kg ha^{-1} whereas, among the different seedling ages tested, the transplantation of 18-day old seedlings registered a significantly higher grain yield of 2512 kg ha^{-1} (Fig. 7). Closest spacing (45 × 15 cm) and 18-day seedlings significantly increased yields. The highest grain output (3506 kg ha^{-1}) resulted from 18-day seedlings grown at 45 × 15 cm spacing.

In a similar manner, a significantly higher stover yield of sorghum was registered at the closer spacing of 45 × 15 cm which yielding 11100 kg ha^{-1} and the direct sowing of sorghum grain in the main field achieved a significantly higher stover yield of 9700 kg ha^{-1} (Fig. 8). The interaction effect indicated that the highest stover yield of 11900 kg ha^{-1} was attained by the direct sowing of sorghum seeds in the main field at a spacing of 45 × 15 cm.

Pearson correlation heatmap analysis

Pearson correlation heatmap shows the Pearson correlation coefficients among key agronomic traits (Fig. 9). Grain yield is strongly correlated with stover yield (r = 0.94) and plant height (r = 0.79), indicating that taller plants tend to have both higher grain and biomass production. The selected sorghum variety K12 is a taller variety with the plant height of 240 cm. Seed weight also shows strong positive correlations with plant height (r = 0.71) and grain yield (r = 0.72). LAI is negatively correlated with most traits, especially plant height (r = -0.65) and stover yield (r = -0.55), suggesting that higher LAI may not contribute positively to yield in this context may be due to various factors, such as increased self-shading, diminished light penetration and possible water stress.

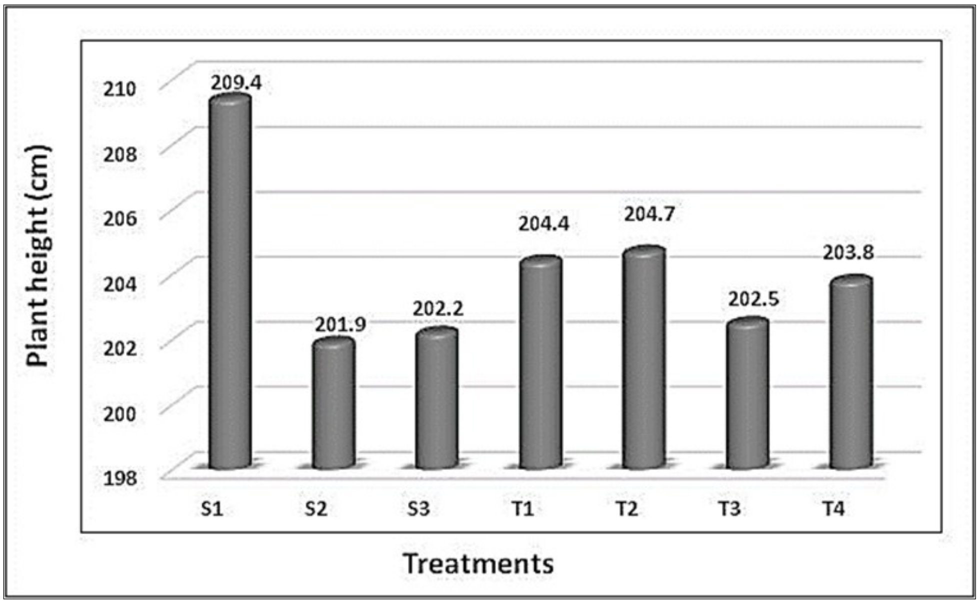

Fig. 3. Effect of treatments on plant height (cm) of sorghum.

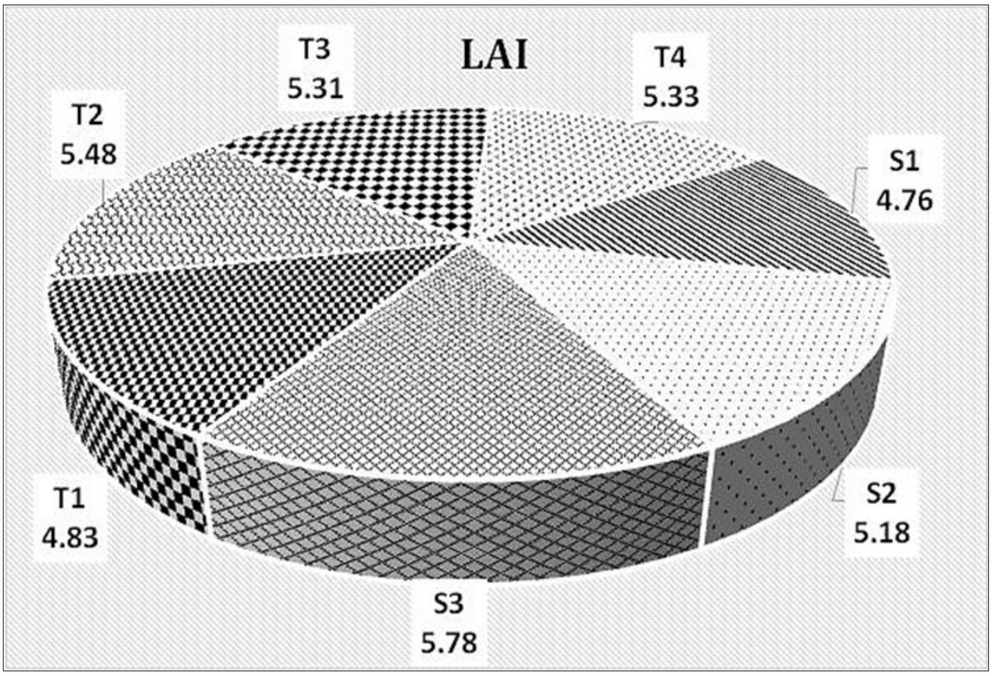

Fig. 4. Effect of treatments on LAI of sorghum.

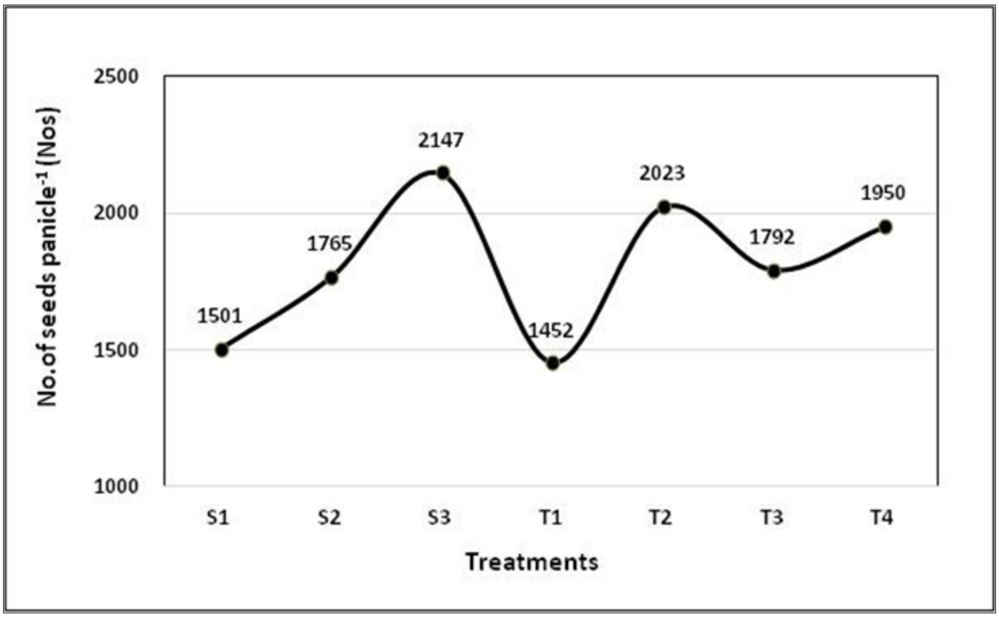

Fig. 5. Effect of treatments on number of seeds per panicle.

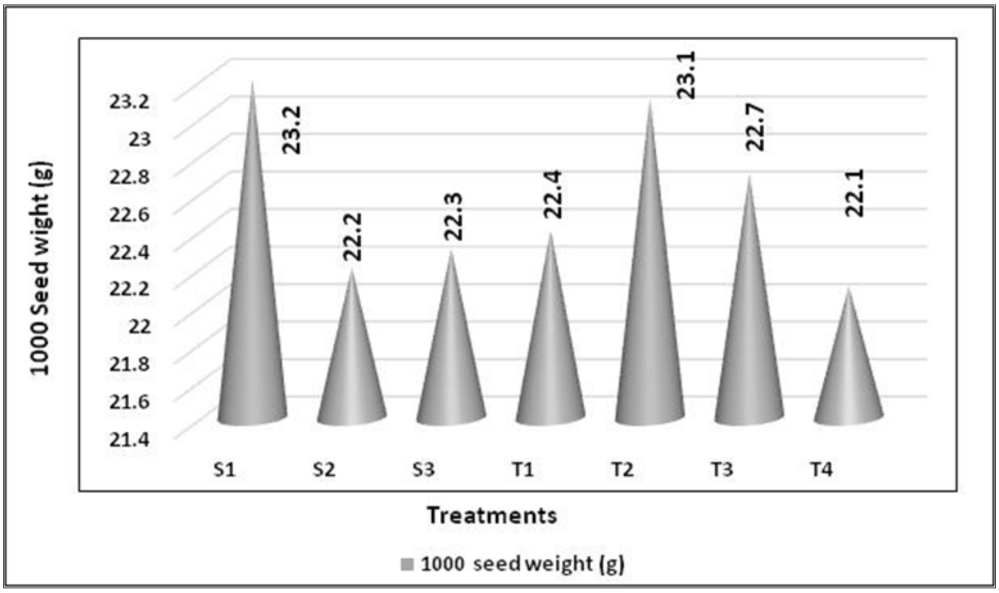

Fig. 6. Effect of treatments on 1000 seed weight of sorghum.

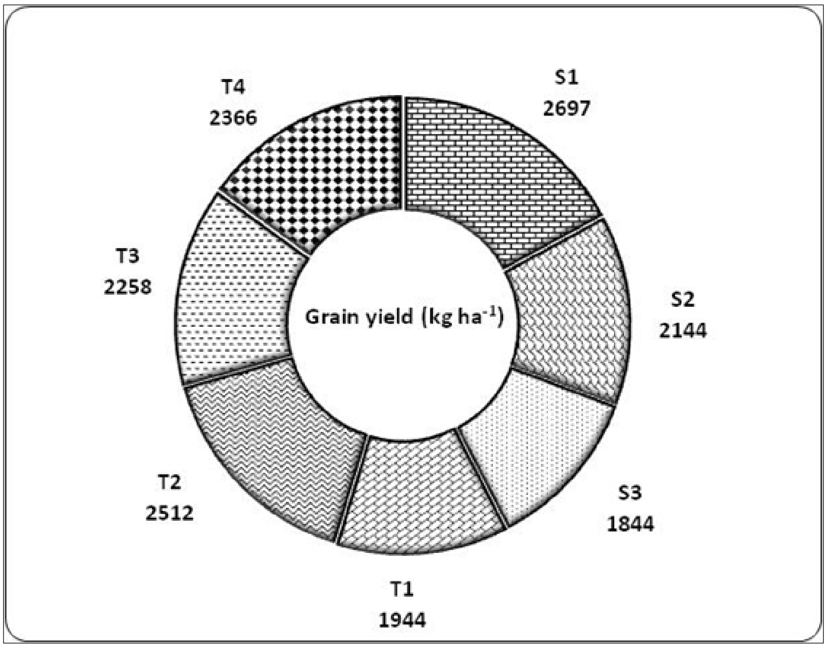

Fig. 7. Effect of treatments on grain yield (kg ha^{-1}) of sorghum.

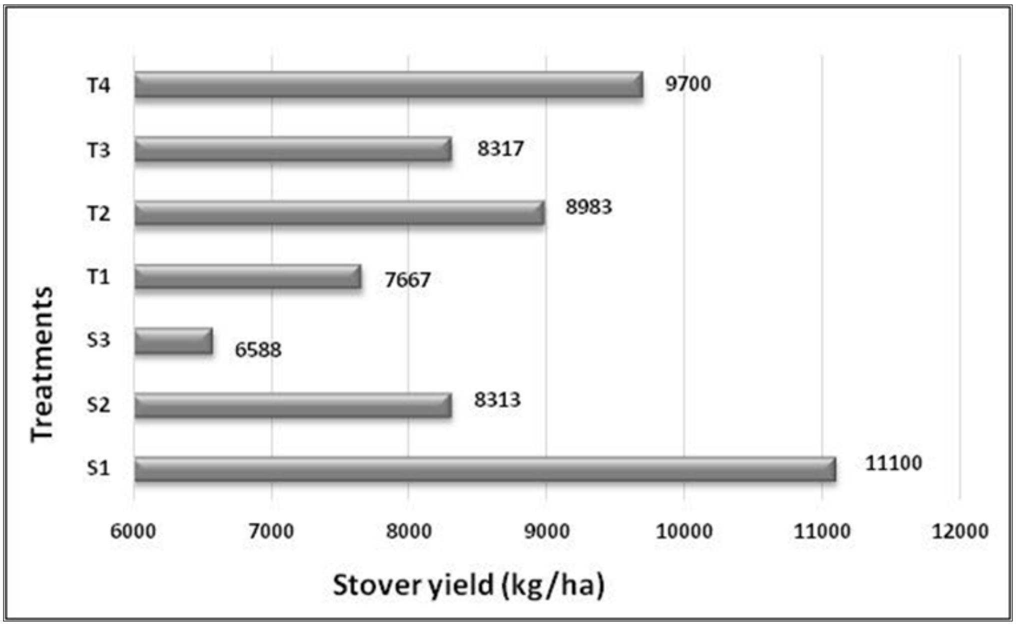

Fig. 8. Effect of treatments on stover yield (kg ha^{-1}) of sorghum.

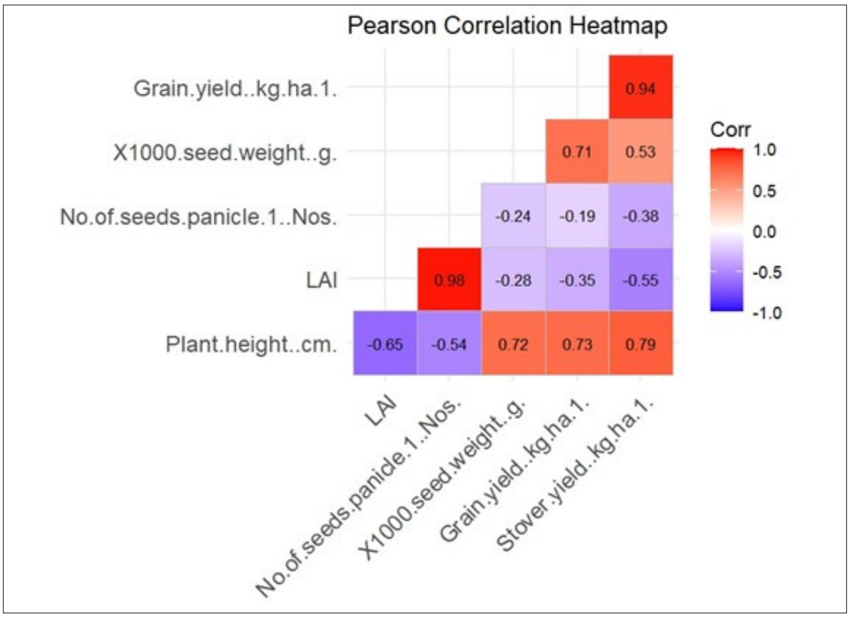

Fig. 9. Pearson correlation heat map.

Although a higher LAI typically indicates more leaf area available for photosynthesis, an excessive amount of leaf area can obstruct light from reaching lower leaves, reducing overall photosynthetic effectiveness. Furthermore, a larger leaf area can elevate water requirements, which may result in drought stress, particularly in environments with limited water supply, adversely affecting yield. Interestingly, seeds per panicle has a strong positive correlation with LAI (r = 0.98) but negative correlations with all yield-related traits.

Implication

Grain yield is most strongly associated with plant height and seed weight, suggesting these are key determinants. LAI and seeds per panicle may not be reliable yield indicators in this dataset.

PCA

This PCA biplot (Fig. 10) maps both variables and treatments onto the PC1-PC2 space. Traits like seed weight, grain yield and stover yield align closely along PC1, indicating they contribute strongly to the first principal component. LAI and seeds per panicle align more with PC2, suggesting they represent a different dimension of variability.

Implication

PC1 primarily reflects yield-related variation (grain, seed, biomass), while PC2 reflects vegetative characteristics like LAI and seed number. Treatments spread across the quadrants show clear differentiation based on trait profiles.

PCA - trait contribution plot

This plot (Fig. 11) shows how each trait contributes to the principal components:

The correlation analysis identified strong positive associations among grain yield, seed weight and plant height, while LAI and seeds per panicle showed negative or weak correlations with yield traits. PCA results revealed that the first two components accounted for 88.5 % of the total variance, with PC1 capturing yield-related variation and PC2 reflecting vegetative traits like LAI. Biplot and trait contribution plots further confirmed this dichotomy, enabling effective clustering of treatments. These results highlight plant height, seed weight and grain yield as key traits for varietal or treatment selection, while also emphasizing the utility of PCA in trait-based classification

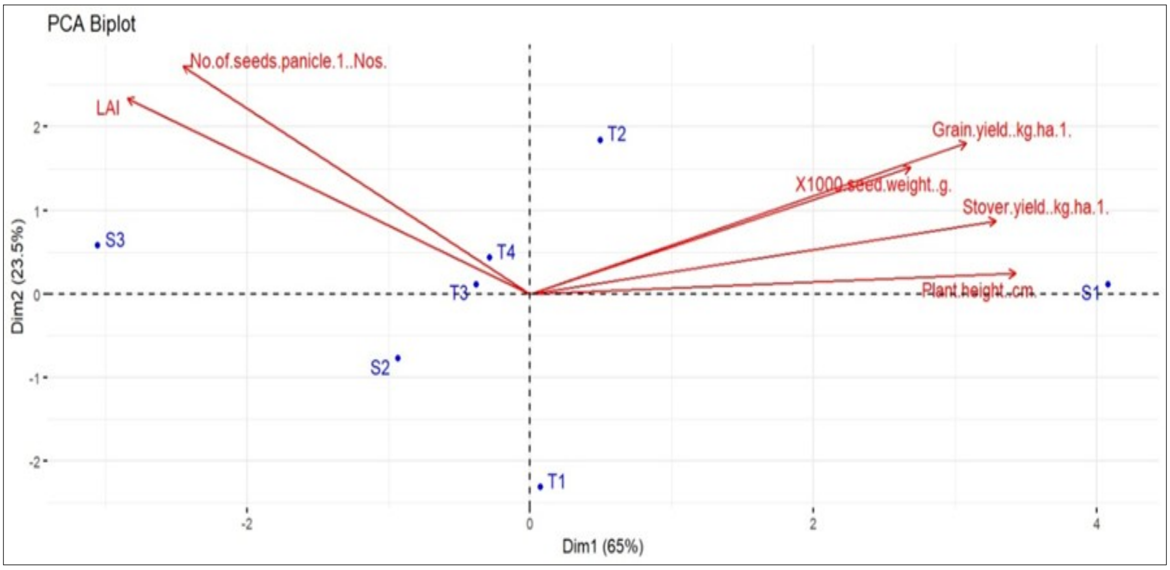

Fig. 10. PCA biplot analysis

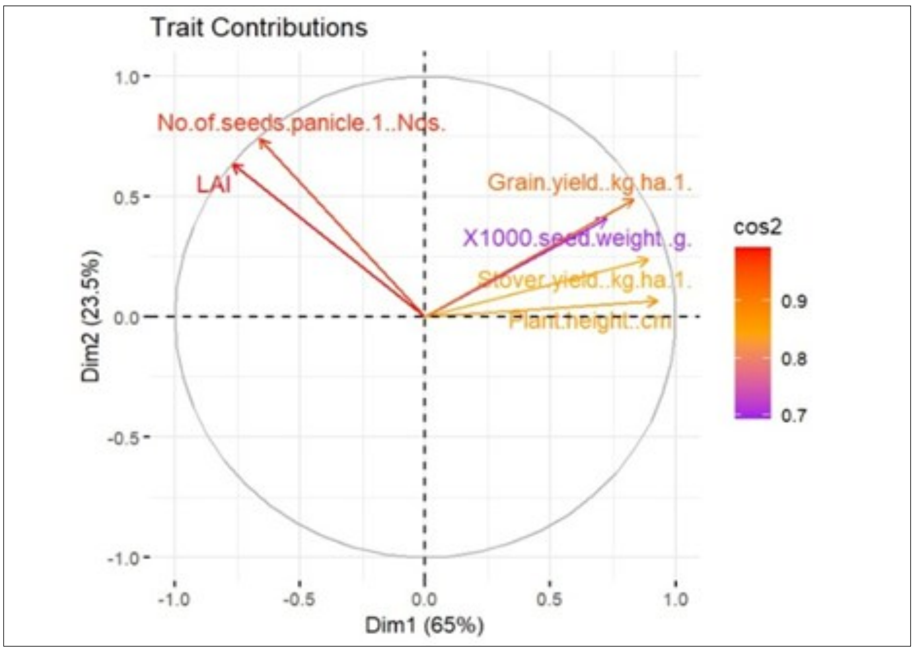

Fig. 11. PCA trait contribution.

Economics of sorghum cultivation

The economic analysis showed that, the higher cost of cultivation was associated with the transplanting of 15 days old seedlings at closer spacing which amounting to ₹31486 whereas, superior total income (₹87211), net profit (₹56952) and benefit-cost ratio (B:C value of 2.88) were observed from the transplanting of 18 days old seedlings at a closer spacing of 45 x 15 cm (Table 3). This was followed by the direct sowing of seeds at 45 x 15 cm spacing. Conversely, the lower gross return (₹44713 ha^{-1}), net profit (₹16302) and B:C value (1.57) were associated with the transplantation of 15 -day old seedlings at wider spacing of 45 x 45 cm.

Discussion

Phenophases of sorghum

The duration of the growing season has considerable agronomic importance in semi-arid regions, where the growing season in the study location is approximately 72 days. The establishment of nurseries facilitates crop growth for an extended period of 21 days without reliance on rainfall due to the availability of stored water, thus allowing crops to occupy the main field for a reduced duration (post-transplanting duration) in comparison to directly sown crops. This practice effectively minimizes the duration of the crops in main field. Consequently, this results in reduced reliance on rainfall, allowing the crops' growing periods to align more effectively within the shorter duration of the main field. Nursery-raised seedlings extend effective growing days before transplanting, thus shortening the crop's field exposure. This aligns with findings that transplant older seedlings accelerates maturity (12–14).

Survival percentage of transplanted sorghum

The seedling age represents a critical factor in the establishment process. Direct sowing facilitated superior crop establishment comparative to transplanted crops, as the latter experienced the adverse effects associated with transplant shock. In the perspective of transplants, a delay in the sowing date leads to reduced stand counts. Highest survival and yield metrics were observed with 18-day transplants. In contrast, 21-day seedlings likely suffered higher transpiration, while 15-day transplants underdeveloped both scenarios compromising establishment success (Table 2). Older seedlings, having more established root systems, might suffer greater root damage when uprooted, which can lead to transplant shock. Transplanting can create a short-term discrepancy between water absorption and transpiration, resulting in wilting and possibly hindering recovery. The underdeveloped roots of younger seedlings result in a brief imbalance in water absorption and transpiration.

Table 3. Effect of spacing and seedling age on economics of sorghum

Treatments	Cost of cultivation (₹ ha^{-1})	Gross returns (₹ ha^{-1})	Net returns (₹ ha^{-1})	B:C ratio
S_1T_1	31486	55959	24473	1.78
S_1T_2	30259	87211	56952	2.88
S_1T_3	30686	59255	28569	1.93
S_1T_4	27996	79949	51953	2.86
S_2T_1	29266	50490	21224	1.73
S_2T_2	28252	56533	28281	2.00
S_2T_3	28066	57071	29005	2.03
S_2T_4	26921	57271	30350	2.13
S_3T_1	28411	44713	16302	1.57
S_3T_2	27193	47349	20156	1.74
S_3T_3	27611	46595	18984	1.69
S_3T_4	26029	48413	22384	1.86

Similar trends have been documented in sorghum and rice cultivars (6,15).

Growth attributes of sorghum

Among the various spacing assessed, the highest recorded plant height of 207.4 cm was associated with the closer spacing (45 × 15 cm), which may be attributable to the synergistic effects of intra-specific competition for light, stimulation of apical dominance and the reallocation of resources (16), development of narrow leaves, elongated stems and relatively less substantial root systems (17).

A higher single plant LAI of 5.78 was observed with a wider spacing configuration of 45 × 45 cm. The density of plant plays an essential role in the crop's early stages, as it influences the available leaf area necessary for effective solar radiation interception, which is fundamentally connected to the rate of photosynthesis (18). The increased plant spacing diminishes resource competition among the plants, thereby facilitating an increase in both leaf number and leaf development. Among the various ages of seedlings, those that were 18 days old demonstrated a significantly higher LAI (5.48), which might be due to their rapid establishment, more efficient utilization of light, nutrients and space, as well as an increase in the photosynthetic rate.

Yield parameters

The number of seeds per panicle constitutes 70 % of the yield of sorghum grain thereby serving a crucial role in the determination of yield (19). The adoption of wider spacing resulted in a 30 % enhancement in the number of seeds per panicle. When compared to the recommended plant density, grain sorghum exhibited an increase in the number of seeds per panicle at densities lower than those suggested (20). This phenomenon may be explainable by the observation that wider row spacing of 45 x 45 cm allows for a greater number of allocation of seeds to each row. Comparable outcomes have been documented in other studies and in various crops (21). Among seedlings of various ages, those at 18 days exhibited an enhancement of 28 %, 11 % and 4 % in the number of seeds per panicle compared to 15 day and 21-day old seedlings, as well as direct seeding respectively. The ontogeny of sorghum is delineated into three distinct developmental phases: the emergence to flower commencement phase (GS1), which establishes the timeline for flowering; the flower beginning to anthesis phase (GS2), which determines the number of seed per panicle and the anthesis to physiological maturity phase (GS3), which influences seed weight (22).

This information implies that the phenomenon of transplanting shock may have disrupted the GS2 phase in both older and very young seedlings. Comparable findings of previous studies in their investigation of two sorghum varieties, where the reduced number of seeds per panicle in older seedlings was attributed to the disruption of the GS2 phase (5). The seedling age correlates negatively with the grain yield per panicle in sorghum. Number of seeds per panicle decreases with increasing seedling age, consistent with previous findings (6,15).

Grain and stover yield

The sowing or transplanting of sorghum seeds or seedlings utilizing a spacing of 45 x 15 cm yielded grain outputs that were 21 and 32 % superior, alongside stover yields that were 25 and 41 % greater than those achieved with sowing or transplanting in 45 x 30 cm and 45 x 45 cm spacing respectively primarily through the increased number of panicles and the number of plants per unit area. Row spacing exerts a significant influence on the yield potential of crops (23).

Although optimal plant densities for grain sorghum shows variation across different geographical regions, prior studies have pointed out that both grain and stover yield typically increased with increasing plant density (24). Under conditions characterized by adequate soil moisture, increased corn plant population (54360 plants/ha) yielded superior results compared to lower population (39540 plants/ha), with 50 cm rows spacing achieving greater yields than 100 cm spacing (25).

The reduction of inter-row spacing contributes to improved weed management by rising increased competition among crops and diminishing light penetration to the soil (26,27). The competition between weeds and grain sorghum is strengthened by open canopy structures (28), whereas narrow row planting confers a competitive advantage to grain sorghum over weeds (26). Configurations with a row spacing of 45 cm can lead to enhanced grain sorghum yields and a decrease in weed populations (25-54 %) when contrasted with row spacings of 60-90 cm (29). Less than 76 cm of plant inter row spacing would enhance grain yield in the regions having maximum yield potential and minimal risk of yield reduction in the region having less yield potential (30). Closer spacing has been associated with increased pod yield in soybean (31,32).

Regarding seedling age, seedlings that were 18 days old demonstrated a yield advantage of 22 %, 10 % and 6 % over seedlings that were 15 and 21 days old, as well as those sown directly. The transplantation of 18-day old seedlings tends to facilitate more rapid establishment and growth, which may contribute to enhanced yield compared to both older and younger seedlings. Delays in transplanting can adversely affect rice growth and grain yield, primarily resulting from reduced tiller production, a shortened vegetative phase and reduced dry matter production (33). When rice plants subjected to delayed transplanting, noted a significant reduction in above-ground dry matter production, primarily due to inhibited photosynthetic capacity when compared to timely transplanting of rice seedlings (34). Comparatively, a lower grain yield of 1944 kg ha^{-1} was recorded by transplanting of 15-day old seedlings (35-38).

With respect to stover yield, direct sowing of seeds in the main field produced higher stover yield of 21, 7 and 14 % over 15 days, 18 days and 21-day old seedlings respectively. Sorghum that is sown directly tends to produce higher biomass yields than sorghum that is transplanted, as it avoids the shock from transplantation and can spend a longer period growing in the field. Transplanting can hinder root growth and postpone initial growth phases, which adversely affects the total biomass accumulation. The leaves may droop and become wilted because the plant struggles to take up sufficient water to match transpiration levels. The leaves can show signs of yellowing or bronzing, particularly at the edges and between the veins, ultimately turning brown and drying out.

Economics

The higher cultivation expenditure (₹31486 ha^{-1}) was observed when transplanting younger seedlings aged 15 days under a narrower spacing arrangement (45 cm × 15 cm). The younger seedlings, being 15 days old, necessitated an increased labour input (20 labours ha^{-1}) for both transplanting and gap-filling due to their inadequate establishment. Likewise, the closer spacing demanded a greater quantity of seeds and seedlings as well as labour resources for transplanting due to the higher plant population per unit area when compared to wider spacing (45 x 45 cm). Consistent findings of an augmented cost of cultivation were associated with denser spacing (38,39).

Conversely, the reduced cultivation cost (₹26029 ha^{-1}) was noted with direct sowing of seeds in main field adopted wider spacing (45 cm × 45 cm). Owing to superior establishment in direct sowing, the labour required for sowing and gap-filling was diminished (6 labour ha^{-1}) in comparison to the transplanting of 18- and 21-days seedling required 10 and 11 labour ha^{-1} respectively. This phenomenon may have contributed to the lower cost of cultivation associated with direct seeding employing wider spacing.

The transplantation of seedling aged 18 days at a closer spacing of 45 cm × 15 cm (S_1T_2) registered a superior gross return of ₹87211 ha^{-1} in comparison to rest of the treatments even this treatment combination required 17 labour ha^{-1} for transplanting and gap filling. Seedlings that were 18 days old and transplanted at closer spacing demonstrated enhanced plant growth and yield characteristics. This phenomenon may have contributed to an increase in both grain yield and straw yield, thereby culminating in a higher gross return. Conversely, when 15 days old seedlings were transplanted at a wider spacing of 45 cm × 45 cm resulted in a numerically diminished total income of ₹44713 ha^{-1}. Inadequate establishment and development of younger seedlings, combined with a reduced plant population due to wider spacing leads to lower yield that could have adversely impacted on gross return (39,40).

A comparatively enhanced net return of ₹56952 ha^{-1}was achieved when 18-day old seedlings were transplanted at a narrow spacing of 45 cm × 15 cm. The combination of increased gross returns coupled with lowered cultivation costs resulted in an augmented net return. Spacing of 30 cm × 10 cm yielded a superior net return in contrast to wider spacing (39,40). The computed benefit-cost ratio was notably higher (2.88) for the transplantation of 18 days old seedlings at the narrow spacing of 45 cm × 15 cm. A relatively reduced net return of ₹16302 ha^{-1} and B:C ratio of 1.57 were observed in 15 days old seedlings transplanted under wider spacing of 45 cm × 45 cm.

Conclusion

This study demonstrates that transplanting sorghum seedlings significantly reduces field duration, improves stand establishment, enhances yield and boosts profitability especially when 18-day old seedlings are transplanted at 45 × 15 cm spacing. Notably, grain yield improved by 32 % and the benefit-cost ratio reached 2.88, while shoot fly incidence remained unaffected. Plant height, seed weight and grain yield as key traits for varietal or treatment selection. The Pearson correlation analysis identified strong positive associations among grain yield, seed weight and plant height.

Farmers in semi-arid zones, transplanting 18-day seedlings at close spacing offers a strategic approach to maximize yield and profit while coping with erratic rainfall-without altering pest risk. Studies on finding suitable nursery technologies along with mechanized transplanting for improving survival percentage of transplants could improve scalability. Training and demonstration are needed for popularization of this technology.

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Authors' contributions

SS participated in the design of the study and conducted experiment, studied agronomic parameters, DKK performed PCA and correlation analysis, KMP corrected the manuscript, conceived the study and participated in its design and coordination. JS performed shoot fly incidence study, VB performed growth parameters study. SA and SD performed statistical analysis, SS and DKK drafted the manuscript. SJ and TJ corrected the manuscript, conceived the study and participated in its design and coordination. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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