

COMPARATIVE EVALUATION OF GROWTH, PHENOLOGICAL TRAITS,
FRUIT CHARACTERISTICS, AND YIELD PERFORMANCE OF TOMATO
(*SOLANUM LYCOPERSICUM* L.) VARIETIES UNDER ARID AGRO-
CLIMATIC CONDITIONS OF UTHAL

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Abstract

Tomato (*Solanum lycopersicum* L.) is an economically important vegetable crop, and the identification of high-performing varieties adapted to local agro-climatic conditions is essential for improving productivity. This study evaluated the growth, phenological development, fruit characteristics, and yield performance of four tomato varieties under the agro-climatic conditions of Uthal, Balochistan, Pakistan, during the 2023-2024 growing season. The experiment was arranged in a randomized complete block design (RCBD) with three replications, using Almas, HT-362B, Investor, and CKD2 as treatments. Growth, flowering, fruit development, and yield-related traits were evaluated, including leaf number, plant height, branch number, stem diameter, flowering time, flower-cluster production, flowers per cluster and plant, fruit-setting and maturation periods, fruit number, fruit dimensions, average fruit weight, and yield per plant. Significant varietal differences were observed across the evaluated characteristics. CKD2 demonstrated superior overall performance, producing the highest number of flower clusters (10.62 plant⁻¹), flowers per cluster (5.68), flowers per plant (53.00), fruits per plant (41.00), average fruit weight (137.73 g), and yield (5.04 kg plant⁻¹). It also produced the longest fruits (78.12 mm) and greatest fruit diameter (65.59 mm). HT-362B also showed strong agronomic performance, producing 27.66 fruits plant⁻¹ and 2.72 kg plant⁻¹, while attaining relatively early fruit maturation (80.29 days). In contrast, Almas produced fewer fruits (22.33 plant⁻¹) and lower yield (2.07 kg plant⁻¹) and required the longest period for fruit maturation (87.36 days). Overall, the findings demonstrate pronounced varietal variation and identify CKD2 as the most promising variety for yield

performance under the conditions of Uthal. These findings provide a basis for varietal selection and improved tomato production in the region; however, multi-season and multi-location evaluations are recommended to confirm yield stability and broader adaptation.

1. Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most important vegetable crops grown in the world, and it is widely grown in a wide range of agro-ecological regions for fresh market and processing. Its importance depends on its high economic value, usage in culinary application, its nutritional composition, and its versatility in production systems. Tomato fruits are a source of essential nutrients, such as vitamins, minerals, carotenoids, polyphenols and other bioactive metabolites. Lycopene is one of these compounds, which is notable for its antioxidant activity as well as its role in the red coloration of ripe fruits (Bergougnoux, 2014; Dumas et al., 2003; Klee & Tieman, 2018). The nutritional and commercial value of tomato has thus become important targets of tomato production and breeding programmes for increased yield, fruit quality, adaptability, and stability.

Tomato has been subject to significant domestication and selection that has led to significant advancement in fruit size, plant architecture, productivity and other horticultural traits. Domestication and intensive breeding have also led to a significant decrease in the genetic diversity of cultivated tomato. Wild relatives of *Solanum* are thus still a valuable source of genetic variation for yield and fruit quality, disease resistance and tolerance, and environmental stress adaptation (Bai & Lindhout, 2007; Giovannoni, 2004; Foolad, 2007). The use of molecular approaches alongside traditional selection methods is a growing trend in tomato breeding to fully leverage the genetic diversity to produce plants with enhanced agronomic traits and environmental resilience (Campos et al., 2021; Li et al., 2025). Significant genetic variability in tomato germplasm is a significant scientific basis for assessing various cultivars in various production conditions.

The productivity of tomato is a complex quantitative trait which depends on the

interaction of different yield components such as plant growth, branching, flowering, fruit set, fruit number, fruit size and individual fruit weight. The yield of fruit thus does not depend on just a single morphological feature, but rather on the compound result of vegetative growth and reproductive allocation. The number and size of fruits may be genetically determined and have a significant effect on the final yield of the crop, and differences in flowering time and reproductive development can also affect the length and productivity of the fruit period (Ariizumi et al., 2013; Bertin, 2005; Klee & Giovannoni, 2011). Hence, screening of tomato varieties with respect to several growth, phenological, fruit and yield parameters gives a more reliable assessment of the varietal performance than just total yield.

Plant height, number of leaves, branches, and growth of stems are important vegetative growth characteristics which are good indicators of varietal vigor and canopy formation. A well-developed canopy is needed to create the photosynthetic surface area needed to produce assimilates and to facilitate and sustain the reproductive development that follows. Greater vegetative growth, however, does not always translate to more fruit yield because tomato plants need to have a proper balance between vegetative and reproductive sinks. Variations in plant architecture can affect light interception, assimilate distribution, flowering, fruit development and yield (Heuvelink, 1995; Picken et al., 1986; Prudent et al., 2009). Hence, the importance of vegetative trait characterization when selecting promising tomato varieties along with reproductive and yield traits.

Flowers and fruits setting are important stages to evaluate tomato potential productivity. The shift from vegetative to reproductive growth is controlled by the genes but is profoundly affected by the environment. Temperature is particularly relevant as tomato reproductive development is sensitive to low and high temperatures. Pollen

performance, pollen release, processes of fruit set and fruit maturation can be affected by suboptimal temperatures, as can the germination of pollen and the reduction of fruit set caused by elevated temperatures (Peet et al., 1998; Sato et al., 2000; van der Ploeg & Heuvelink, 2005). In addition, recent reviews also show that high temperature negatively impacts tomato growth, flowering, fruit setting, fruit size, fruit weight, quality and overall yield (Ayyogari et al., 2024). These responses may not be consistent across varieties, which suggests that genotype-specific adaptation may be relevant in temperature stress environments.

Therefore, the agro-climatic environment is an important factor affecting the performance of tomato varieties. Genotype $\times$ environment interactions can cause substantial differences in yield and other horticultural characteristics among varieties when they are evaluated across different environments. Tomato germplasm studies have revealed a high degree of morphological variation, and that environmental and genotype $\times$ environment ($G \times E$) effects are significant contributors to variation in yield and other important traits (Kromdijk et al., 2014). More recent multi-environment testing have also shown that tomato hybrids can vary greatly in productivity and stability between environments, emphasising the need to test varieties in the environments in which they will be grown.

In the semi-arid and warm production regions, environmental constraints are very significant. The availability of water, supply of nutrients, temperature, radiation and soil conditions are important factors in the growth and productivity of tomatoes. Availability of water may affect vegetative growth, fruit development, yields and fruit quality and nutrient management may have significant effects on yield and water use efficiency. As shown in the study by Congreves et al. (2021), a global meta-analysis revealed that the response of tomato to N supply is dependent on environmental and experimental factors, highlighting the importance of considering nutrient-environment interactions when interpreting yield responses. Likewise, irrigation and salinity management can also affect yield quality balance – high osmotic stress will be

detrimental to yield and eventually fruit size (Dorais et al., 2001). These factors further underscore the need for testing varieties in the specific environmental and management conditions faced by local growers.

Other factors to consider when making varietal choices include fruit characteristics – market value is not just based on yield, but also fruit size, shape, appearance, firmness, flavor and nutritional value. Fruit length, diameter and individual fruit weight are easily measured indicators of market class and consumer preference. The process of fruit development is a very complex and tightly regulated biological process that includes cell division, cell expansion, hormonal regulation, carbohydrate allocation, accumulation of pigments, and changes in texture and flavor (Giovannoni, 2004; Klee & Giovannoni, 2011). Thus, a variety which yields a lot but has poor quality may not be the best choice for the grower to use if a variety that produces a moderate yield has the better quality fruit. It is, therefore, imperative to measure yield and fruit characteristics in combination when making recommendations for practical use. The fruit/plant relationship in terms of the number and the weight of the fruit is especially critical to understanding tomato productivity. An increase in fruit number can be a positive effect on yield, but competition of growing fruit for assimilates can affect fruit size. On the other hand, fewer fruits will be offset by heavier fruit weight in varieties that yield fewer fruits. These differences are the result of the partitioning of assimilates and reproductive allocation characteristics of the genotype (Ariizumi et al., 2013; Bertin, 2005). Evaluation of both fruit number and fruit weight can therefore be used to help explain why varieties with different reproductive traits might produce different final yields.

Tomato genetic diversity also plays a role in adaptation to abiotic stresses. The tomato is sensitive to heat, drought, salinity and other environmental constraints which may impact growth, reproductive development, fruit quality and yield. Under the scenario of climate change, the development of stress-tolerant tomato cultivars has thus gained even more significance (Egea et al.,

2022). Wild relatives and a variety of germplasm cultivated in the orchard are sources of genetic resources to be used in breeding for improved environmental stress tolerance and desirable horticultural traits (Foolad, 2007; Bai & Lindhout, 2007). New molecular breeding strategies have also paved the way for new opportunities in the identification of genes and quantitative trait loci related to yield, plant architecture, flowering, fruit development, and stress response (Ariizumi et al., 2013; Li et al., 2025).

Even with advances in tomato breeding local varietal evaluation is still important especially in areas where the environment is significantly different from the conditions in which commercial hybrids were selected for growth. High yielding varieties in one environment may fail to perform as well in another due to genotype × environment interactions. Comparative field evaluation under local conditions can thus give useful information to farmers and researchers as well as to extension programs and be used to select potential germplasm for breeding and adaptation. The area of Uthal, Balochistan is a unique production environment; the evaluation of locally cultivated tomato varieties is important here. Vegetative growth, flowering, fruit set, fruit development, fruit size and production may be affected by environmental conditions. But there is limited information available in comparative performance of the tomato varieties under the specific agro-climatic conditions of Uthal. When evaluating several varieties under the same field management practices, varietal differences in growth and productivity can be compared, and the differences in management practices can be minimized. Therefore, the present study was conducted during 2023–2024 at the agricultural research site of Lasbela University of Agriculture, Water, and Marine Sciences, Uthal, Balochistan, to evaluate the comparative growth, phenological development, fruit characteristics, and yield performance of four tomato varieties. The evaluated varieties were V1 (Almas), V2 (HT-362B), V3 (Investor), and V6 (CKD2). The study assessed vegetative growth, flowering behavior, fruit setting and maturation, fruit number, fruit

dimensions, average fruit weight, and yield per plant. The specific aim was to identify varieties exhibiting superior and desirable combinations of growth, reproductive performance, fruit characteristics, and productivity under the agro-climatic conditions of Uthal, thereby providing an evidence-based basis for local tomato varietal selection.

2. Materials and Methods

2.1 Experimental site and study period

The field experiment was carried out at the agricultural research farm, Lasbela University of Agriculture, Water, and Marine Sciences, (LUAWMS), Uthal, Balochistan, Pakistan in the growing season of 2023-2024. In order to assess the growth, phenological development, fruit properties and yield performance of four tomato (*Solanum lycopersicum* L.) varieties under the prevailing agro climatic conditions of Uthal, the experiment was conducted.

2.2 Experimental design and tomato varieties

The experiment was designed in a Randomized Complete Block Design (RCBD) with three replications. The four tomato varieties tested were: V1 (Almas), V2 (HT-362B), V3 (Investor), and V4 (CKD2). Selection of these varieties was based on their cultivation or their use under local production conditions. The varietal differences were compared within the same replications as each variety was a separate treatment within each replication, and field conditions for the evaluation were uniform.

2.3 Nursery raising and transplanting

All four tomato varieties were taken to the nursery prior to planting into the fields. A uniform seedling with good health, ~4-6" tall was chosen and transplanted into the experimental field. The plot size was 70 × 20 ft, and 90 and 45 cm plant spacing within row and between plants, respectively. There were 4 rows (or replications) for the four treatments. Observations were replicated under RCBD with the experimental layout provided. Agronomic practices were the same for all varieties of tomato throughout the growing

season. Management practices, such as fertilization, irrigation, weed control, and disease and insect control, were employed in the same manner for all the experimental treatments to reduce management-induced variation. Regular control of weeds was carried out and crop protection through regular spraying for insects, pests and diseases was used as necessary. Therefore, varietal differences were mainly considered in the context of what happened when the varieties were grown under the same environmental and cultural conditions at the experimental site.

2.4 Data Collection

All four varieties of tomato were observed for growth, phenological, reproductive, fruit and yield parameters during the crop growing period. Five plants at random were taken from each treatment to measure the number of leaves per plant, number of branches per plant and stem diameter (mm). Plant height (cm) was measured at maturity from the base of the plant to the terminal growing point by measuring tape and stem diameter (cm) was measured at the base of the stem by vernier caliper. Phenological traits that were measured were days to flowering, days to first fruit setting and days to fruit maturation, from the time of transplanting until these development stages occurred. The following reproductive characteristics were calculated from randomly selected plants during flowering time: number of flower clusters plant⁻¹, number of flowers cluster⁻¹, number of flowers plant⁻¹. Harvests were made from the first to last harvest and the number of fruits per plant was recorded. For fruit characteristics, the length (mm), diameter (mm) and mean fruit weight (g) were determined using randomly selected representative fruits and measurements were taken using vernier caliper

and weighing balance, respectively. The weight of the fruits collected at the first to the last picking (kg) was converted to yield plant⁻¹ (kg) and presented by plant. The mean values from the observations of each parameter were used for further statistical analysis for each treatment.\

2.5 Statistical analysis

All the data pertaining to growth, phenology, fruit and yield related were analyzed using Analysis of Variance (ANOVA) under Randomized Complete Block Design. Statistix 8.1 and SPSS software were used for statistical analysis. The Least Significant Difference (LSD) test was used to compare differences among treatments at 5 percent significance. A means with the same letter were not significantly different from each other at the 5% probability level while a means with different letters were said to be significantly different.

4. Results

4.1 Effect of tomato varieties on vegetative growth

There were significant variations between the four tomato varieties in all vegetative growth parameters measured (Figure 1). The analysis of variance indicated that variety was significantly ($P < 0.001$) affecting the number of leaves plant⁻¹. CKD2 produced the highest number of leaves (148.66 plant⁻¹), followed by HT-362B (135.33), Investor (111.33), and Almas (95.66 leaves plant⁻¹). HT-362B attained the greatest plant height (144.00 cm), followed by CKD2 (135.00 cm), Almas (108.66 cm), and Investor (107.66 cm). CKD2 produced the highest number of branches (19.60 plant⁻¹), followed by Investor (16.46), HT-362B (14.33), and Almas (12.66 branches plant⁻¹). CKD2 recorded the greatest stem diameter (11.33 mm), followed by Almas (10.36 mm), Investor (9.39 mm), and HT-362B (8.52 mm).

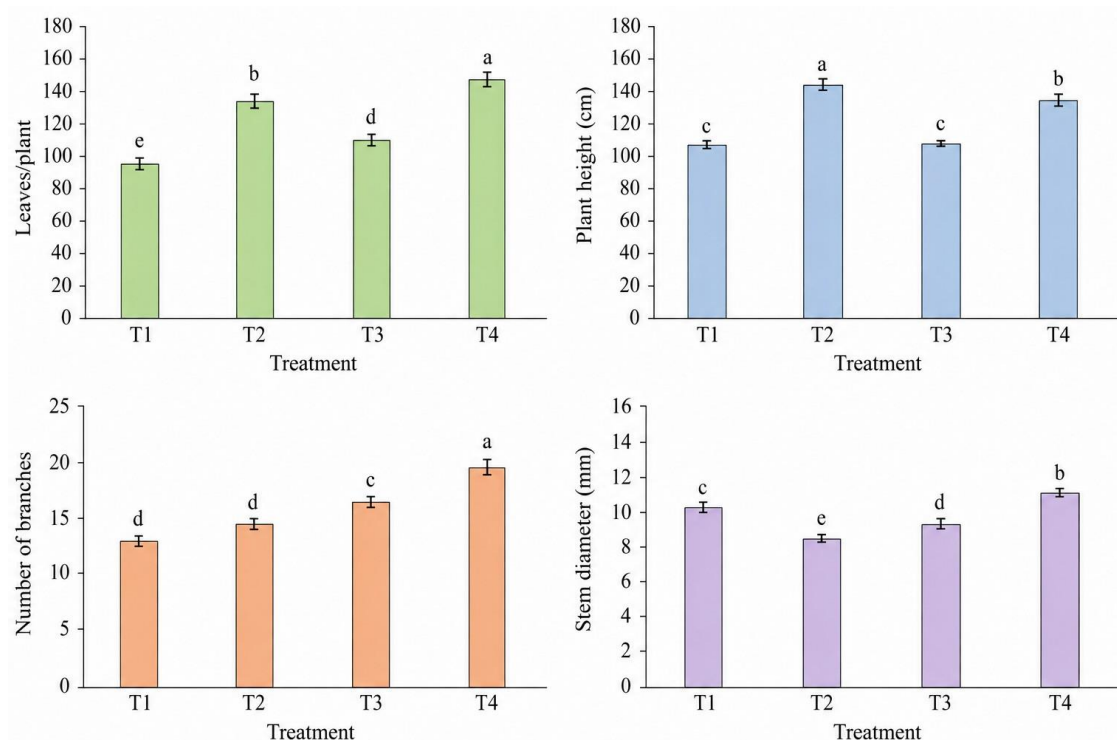


Figure 1. Effects of different treatments on plant growth attributes. Bars represent the mean values of leaves per plant, plant height (cm), number of branches, and stem diameter (mm) under treatments T1, T2, T3 and T4. Error bars represent variability around the mean ($\pm$ SE). Different lowercase letters above the bars indicate significant differences among treatments at $p \leq 0.05$.

4.2 Flowering and reproductive characteristics

There were also great varietal differences in flowering and reproductive development (Figure 2). There was a significant difference in the number of days to first flowering among varieties ($P < 0.001$). The earliest variety to flower was CKD2 (26.86 days), followed by HT-362B (31.93 days), Investor (33.60 days), and Almas (33.66 days). CKD2 produced the highest number of clusters (10.62 plant^{-1}), followed by HT-362B (7.62), Investor (7.13), and Almas (6.67 plant^{-1}).

The number of flowers cluster $^{-1}$ also differed significantly among varieties ($P < 0.001$). There were the highest number of flowers cluster $^{-1}$ in the case of CKD2 (5.68) followed by Investor (3.99) and Almas (3.55), while HT-362B (2.52 flowers cluster $^{-1}$) had the lowest value. There was also a strong varietal effect on number of flowers plant $^{-1}$ ($P < 0.001$). CKD2 produced the greatest number of flowers (53.00 plant^{-1}), followed by HT-362B (30.66), Investor (24.66), and Almas ($24.00 \text{ flowers plant}^{-1}$).

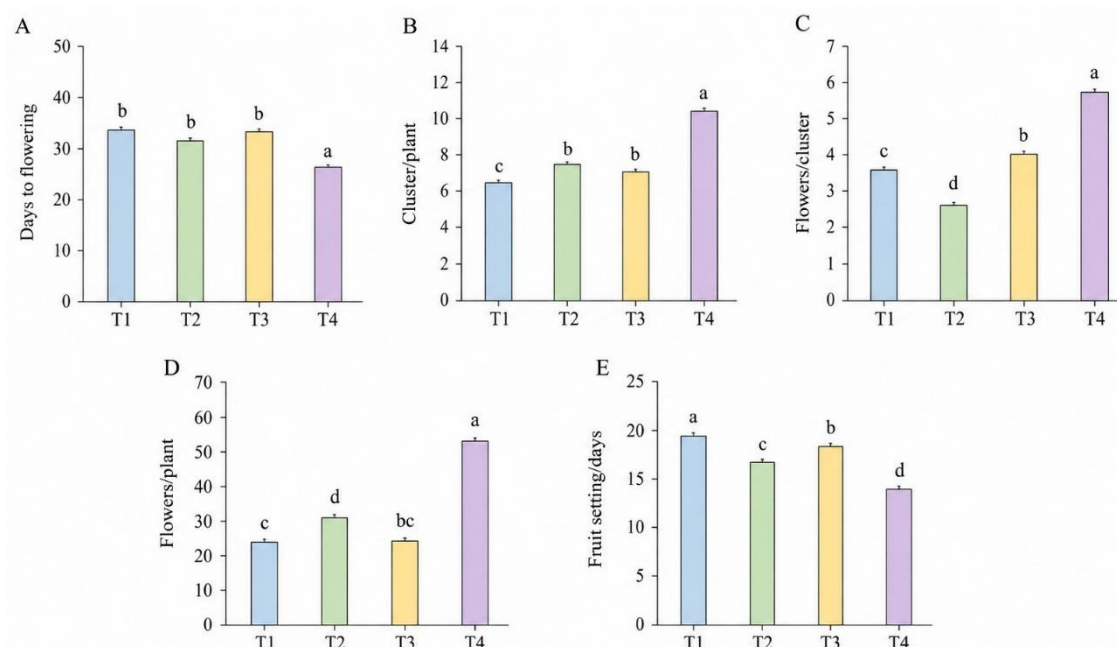


Figure 2. Effects of different treatments on flowering and fruit-setting attributes. Bars represent the mean values of days to first flowering, number of clusters, flowers per cluster, flowers per plant, and days to first fruit setting under treatments T1, T2, T3 and T4. Error bars represent variability around the mean ($\pm$ SE). Different lowercase letters above the bars indicate significant differences among treatments at $p \leq 0.05$.

4.3 Days to first fruit setting and fruit maturation

There were significant differences ($P < 0.001$) in the number of days to setting first fruit among the tested varieties (Figure 2). The first fruit setting dates of the cultivars were: CKD2 (14.00 days), HT-362B (17.33 days), Investor (18.66 days), and Almas (19.33 days). The growth of CKD2 was quickest with a development time of 62.02 days, followed by that of Investor (79.65 days), HT-362B (80.29 days), and Almas (87.36 days). The longest fruit maturation days were 87.36 days in case of Almas.

4.4 Fruit production and fruit characteristics

Tomato variety ($P < 0.001$) significantly affected the number of fruits plant⁻¹ (Figure 3). CKD2

produced the highest number of fruits (41.00 plant⁻¹), followed by HT-362B (27.66), Almas (22.33), and Investor (22.00 fruits plant⁻¹). There was a significant difference ($P < 0.001$) in fruit length between varieties. The fruits were the longest with an average length of 78.12 mm for CKD2, followed by Investor (64.89 mm), HT-362B (56.05 mm), and Almas (55.07 mm). CKD2 also recorded the greatest fruit diameter (65.59 mm), followed by Investor (54.72 mm), Almas (52.22 mm), and HT-362B (45.91 mm). Fruit weight was significantly different between varieties ($P = 0.007$) (Figure 4). The fruits produced by CKD2 were the heaviest (137.73 g) then followed by Investor (100.16 g), HT-362B (97.53 g), and Almas (93.93 g).

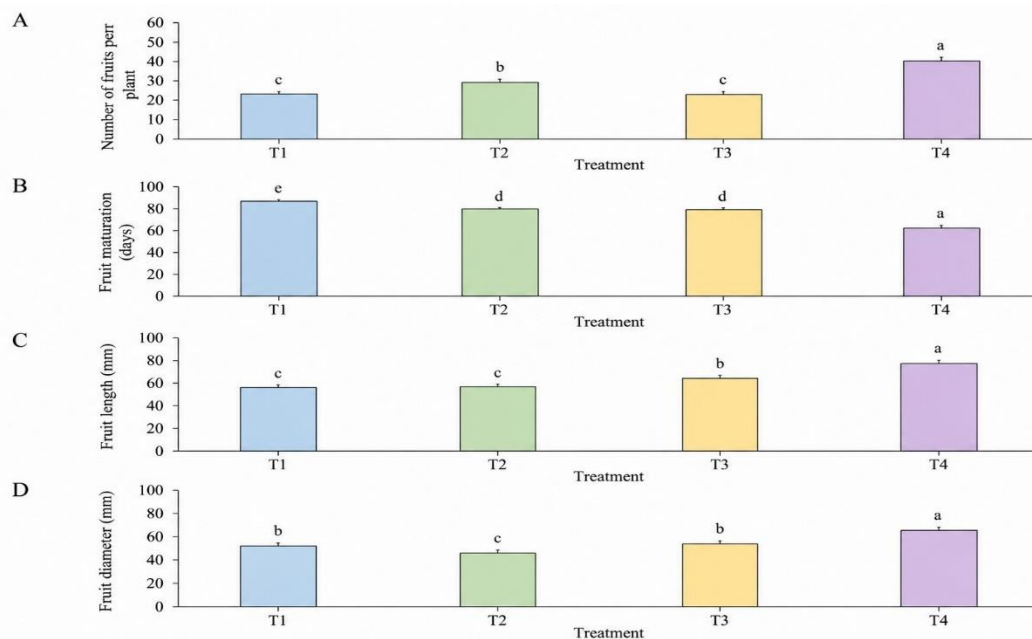


Figure 3. Effect of different treatments (T1, T2, T3 and T4) on fruit yield and fruit characteristics: (A) number of fruits per plant, (B) fruit maturation period (days), (C) fruit length (mm), and (D) fruit diameter (mm). Bars represent mean $\pm$ standard error. Different lowercase letters above the bars indicate significant differences among treatments.

4.5 Yield performance

The effect of variety was highly significant with respect to yield plant⁻¹ ($P < 0.001$). CKD2 produced the highest yield, with 5.04 kg plant⁻¹, followed by HT-362B (2.72 kg plant⁻¹), Investor (2.18 kg plant⁻¹), and Almas (2.07 kg plant⁻¹). In general, the results showed that significant

differences occur between varieties in vegetative growth, fruit development, fruit characteristics and yield. CKD2 exhibited good performance in several yield-related traits such as flower clusters, flowers cluster⁻¹, flowers plant⁻¹, fruits plant⁻¹, fruit dimensions, average fruit weight and final yield.

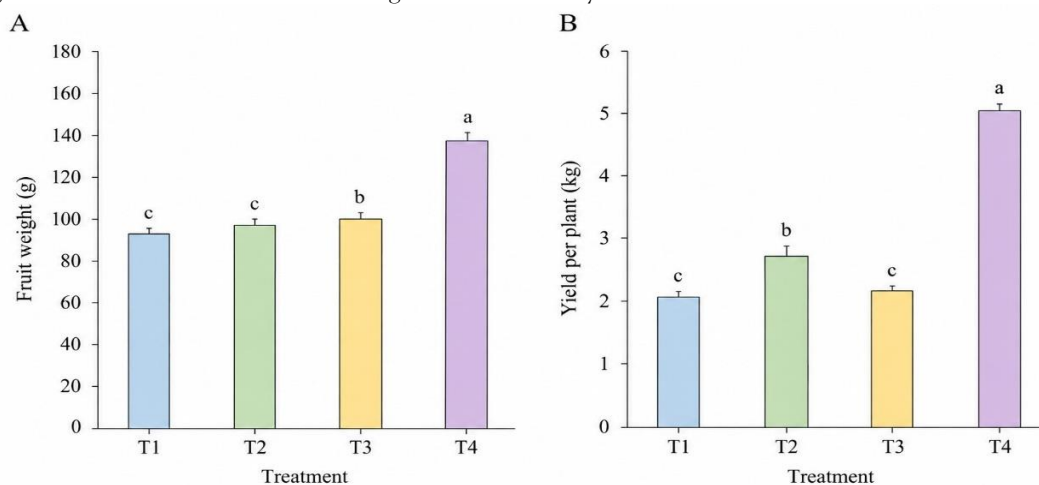


Figure 4. Effect of different treatments (T1, T2, T3 and T4) on fruit yield and fruit weight (A) fruit weight, (B) number of fruit/plant. Bars represent mean $\pm$ standard error. Different lowercase letters above the bars indicate significant differences among treatments.

4.6 Integrated Heat-map Analysis of Varietal Performance

The heat-map (Figure 5) showed significant differences between the four tomato varieties in the vegetative, phenological, fruit, and yield traits. The overall positive standardized values of most growth, reproductive, fruit and yield traits were greatest for CKD2 (T4) especially leaves per plant, branches per plant, number of clusters, flowers per cluster, flowers per plant, fruits per plant, fruit dimensions, fruit weight and yield per plant. Conversely, the days to first flowering, days to first

fruit setting and fruit maturation had negative standardized values for CKD2 as it needed shorter days to reach these developmental stages, meaning it was more earlier than the other cultivars. The standardized values for plant height were relatively high for HT-362B (T2) and were generally lower for most growth and yield traits and higher for developmental duration for ALMAS (T1). For most measured characteristics, INVESTOR (T3) had an intermediate pattern. The overall heat-map shows the contrasting performance of the four varieties for the traits assessed.

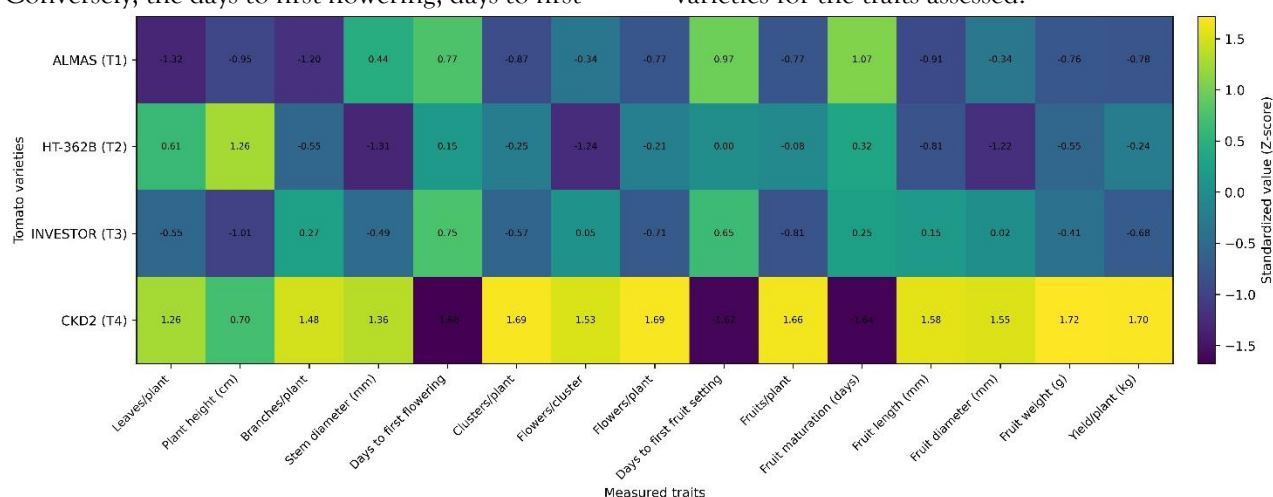


Figure 5. Heat-map showing the standardized performance of four tomato varieties (T1, T2, T3 and T4) across growth, phenological, reproductive, fruit, and yield-related traits.

5. Discussion

The present study revealed significant variation in vegetative growth, reproductive development, fruit characteristics and yield of four tomato varieties under agro-climatic conditions of Uthal, Balochistan. For most of the traits studied, there were marked varietal differences, which were suggestive of substantial differences in growth and reproductive potential. Variation in other traits such as plant height, flowering time, fruit number, fruit weight, and yield has also been reported among tomato germplasm, emphasizing the need for evaluation of the various cultivars to identify productive and locally adapted cultivars.

5.1 Vegetative Growth and Reproductive Development

The variation in vegetative vigor was shown by significant differences in branch number, plant height, leaf number and stem diameter between

tested varieties (Figure 1). CKD2 formed the most leaves and had the widest stem diameter, while HT-362B had the tallest plant height and the most branches was generated by CKD2. The lack of uniformity in the superiority of the individual varieties for vegetative characteristics suggests that the vegetative characteristics were manifested differently in the various varieties. The differences in plant height and leaf production may be due to differences in plant architecture, internode development, leaf initiation, and vegetative growth rate. A similar inter-cultivar difference has been previously reported for tomato cultivars, which further underscores the significance of the inter-cultivar variation in vegetative development. But not all vegetative growth leads to increased yield, since assimilates need to be allocated between vegetative and reproductive parts of the plant. The high yield of CKD2 in the present study was thus

more closely related to its reproductive and fruit productivity.

The flowering periods were significantly different for the varieties, as were the numbers of flowers per cluster and flowers per plant (Figure 2). The varieties had significantly different flowering periods, flower-cluster production, and number of flowers per cluster and flowers per plant. The latest flowering variety was Almas and the earliest one was CKD2. The reproductive performance of CKD2 was found to be better than other cultivars, with the highest number of flower clusters, flowers per cluster and flowers per plant. These differences suggest a high varietal influence on vegetative to reproductive development. The observed variation is also in line with the findings of Rasheed et al. (2023), who showed that there was a significant genetic variation among tomato genotypes for various reproductive traits including flowering time, number of flowers per cluster, fruit setting and yield-related traits, with high heritability for several reproductive traits. The difference in reproductive output between CKD2 and the other cultivars was also evident in the amount of fruit produced, indicating that reproductive ability played a major part in the production of the fruit.

5.2 Earliness, Fruit Characteristics and Yield

Significant differences in flowering, first fruit setting and fruit maturation were detected among the different varieties (Figures 2 and 3). The flowering time, fruit setting and maturity were the earliest in CKD2 while relatively late in Almas. Earliness may be desirable if a short production cycle and early market availability are critical. The phenological variation observed is similar to what Panchbhai and Kulkarni (2023) observed where they reported that there were significant differences in days to 50% flowering among tomato genotypes and considerable genetic variability for this trait. Important, however, is that relatively low fruit number, fruit size and yield were not associated with the early maturity of CKD2, demonstrating that earliness did not hamper productivity under the conditions of this experiment. The number, length, diameter and weight of fruits was significantly different between varieties (Figures 3 and 4). The highest fruit

length, diameter and average fruit weight were obtained with the fruits from CKD2 which also gave the highest fruit production per plant. These qualities are essential to tomato productivity as fruit size and numbers are both crucial factors of final yield. The findings are similar to those of Rasheed et al. (2023) who reported significant variation for fruit number, fruit weight and yield, and Zannat et al. (2023) who reported high correlations between fruit number, fruit diameter, fruit weight and yield. Therefore, the better performance of the CKD2 is likely to have been produced by the breeding of a combination of fruit characteristics, and not just one.

The most distinct varietal differences were found for yield (Figure 4). The highest yield (5.04 kg plant⁻¹) was obtained by CKD2 followed by HT-362B (2.72 kg plant⁻¹), Investor (2.18 kg plant⁻¹), and Almas (2.07 kg plant⁻¹). The high yield of CKD2 was found to be associated with higher number of flowers, fruits and their size and weight. The number of fruits, fruit diameter and fruit weight were also found significant fruit parameters affecting tomato yield in previous studies (Rasheed et al., 2023; Zannat et al., 2023). The current results thus suggest that the high productivity of CKD2 was correlated with synchronized reproductive and fruit development performance.

5.3 Agronomic Significance and Varietal Selection

CKD2 proved to be the best performer overall owing to its high reproductive activity, fruit production and yield. The different but valuable performance pattern of the other varieties was associated with differences in flowering, maturation, fruit production and yield. The differential properties suggest that cultivar choice should not be based exclusively on yield but rather specific production goals. Almas and Investor exhibited relatively poor performance for a number of yield-related characteristics. The results of their lower performance are however to be taken with a grain of salt, because the experiment was carried out over one growth period. Therefore varietal differences may have been influenced by environmental factors.

There was a significant difference between the four varieties and therefore information is provided for tomato selection for the agro climatic conditions of Uthal. Fruit number, fruit weight, fruit dimensions and reproductive traits seem to be of special value in determining high-yielding varieties. Previous studies have also shown that there is significant genetic variation for these traits (Rasheed et al., 2023; Panchbhai & Kulkarni, 2023; Zannat et al., 2023). However, the present study did not assess heritability, nor genotype $\times$ environment interaction. Hence, any superiority of CKD2 should be taken as site specific and season specific agronomic performance and not as proof of genetic superiority in all environments.

5.4 Overall Interpretation of Varietal Performance

The vegetative growth, reproductive development, phenology, fruit characteristics and yield among the four tomato varieties were significantly different. CKD2 was the earliest flowering and maturing variety and was also the more productive variety. The high yield of CKD2 was correlated with the higher reproductive output, fruit number, fruit size and fruit weight. The results indicate that local varietal screening is valuable for the selection of tomato cultivars that are well adapted to agro-climatic conditions of Uthal, Balochistan and have high productivity. More than one season and multiple evaluation locations should be used to ensure consistency of these varietal responses.

The heatmap gives an overall view of the different agronomic performance of the four tomato varieties, with a very good performance of the variety CKD2. The high productivity was correlated with coordinated aspects of flowering and fruit setting, as well as with increased numbers of flowers, fruits, fruit size, fruit weight and final yield, rather than any single attribute. This interpretation is consistent with the significant genotypic differences previously observed in tomato growth, flowering, fruit traits and yield. Zannat et al. (2023) found high correlations between fruit number, fruit diameter and fruit yield, while Rasheed et al. (2023) observed high variability and significant associations between fruit weight, flower/fruit traits and yield. Likewise, Kumar et al. (2013) found that fruit weight, fruit

number, fruit diameter and fruit-cluster traits are useful parameters for improving tomato yield. Hence, it can be concluded that under the condition of the present experiment the heatmap revealed that CKD2 was the most promising variety, but the performance of a variety should be considered from the combined effect of vegetative, phenological, fruit and yield traits and not just yield.

6. Conclusion

The present field experiment showed significant variability between the tested four varieties of tomato (*Solanum lycopersicum* L) grown during 2023-2024 in agro climatic conditions of Uthal, Balochistan. Significant varietal differences were seen in vegetative growth, flowering and fruiting habit, fruit traits and yield, indicating that varietal selection is a critical factor that influences tomato performance under local production conditions.

The overall performance of the varieties was evaluated and CKD2 proved to be the most uniform for the various characteristics, especially reproductive and yield related. It yielded the most branches, flower clusters, flowers/cluster, flowers/plant, fruit/plant, fruit length, fruit diameter and average fruit weight and had the best fruit yield per plant. Thus, the yield of CKD2 was the highest (5.04 kg plant⁻¹) followed by HT-362B (2.72 kg plant⁻¹). These findings suggest that the high productivity of the cultivar CKD2 could be attributed to an interaction between the three yield components of the cultivar not to any one of them.

In addition, CKD2 showed good agronomic promise, as it exhibited very early flowering, early fruit setting, and early fruit maturation, together with high fruit production and yield. The early maturity and yield of this combination could be beneficial in production systems where early market availability is critical and crop duration short. Agricultural performance of Almas and Investor were in contrast, generally lower, for several reproductive and yield related traits under present experimental conditions.

In conclusion, CKD2 can be recommended as the most suitable variety for tomato production at Uthal, Balochistan. This information should be

used in conjunction with the current season and experimental site, however. Sustaining these varietal responses under varying environmental conditions to further validate the recommendations for commercial tomato production in Balochistan is recommended to be continued over the course of several years in varied locations.

Author Contributions: Muhammad Ilyas conducted field sampling, data collection, and laboratory analyses; Aadil Hameed conceptualized and supervised the study and served as supervisor; Muhammad Abuzar Jaffar and **Muhammad Rashid** assisted with laboratory experimentation and data collection; Shahmir Ali Kalhoro performed statistical analysis, organized the data, prepared the figures, and contributed to manuscript preparation; and Muhammad Ikram contributed to literature review and manuscript editing. All authors reviewed and approved the final manuscript.

Data and material availability

This article contains all the soil and plant analysis data generated during the course of this research study. The analysis and the resulting data presented herein may be obtained at the reasonable request of the corresponding author.

Conflicts of interest

Authors declare no potential conflicts of interests

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