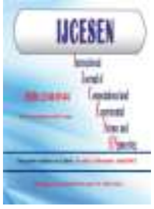
International Journal of Computational and Experimental Science and ENgineering (IJCESEN)

Vol. 12-No.2 (2026) pp. 225-236
http://www.ijcesen.com



ISSN: 2149-9144

Research Article

Comparative agronomic and phytosanitary analysis of parental tomato lines and their F1 hybrids (Lycopersicon esculentum L.) under Mediterranean open-field conditions

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Article Info:

DOI: 10.22399/ijcesen.5171
Received : 10 November 2025
Revised : 15 March 2026
Accepted : 25 April 2026

Keywords

Tomato,
F1 hybrid,
Mediterranean climate,
Production parameters,
Late blight.

Abstract:

For several years, tomato breeding has focused on developing F1 hybrids adapted to agronomic and pedoclimatic conditions, while identifying the best cultivar in order to produce quality seed at lower cost. Favorable climatic conditions and human expertise in Algeria provide an opportunity to produce vegetable seeds, especially tomatoes.In this research project on producing F1 hybrid seeds, we evaluated the characteristics, agronomic performance, and sanitation of certain tomato varieties by comparing them with their F1 hybrids grown in an open field under Mediterranean conditions. The trial was conducted at the Technical Institute of Vegetable and Industrial Crops in Staouéli, Algeria, during the 2004 season. It used a randomized complete block design with three replications. The parameters measured were phenological (date of appearance of flower clusters, flowering, and maturity), production (number of fruits per plant, fruit weight, and yield per plant), and incidence and severity of late blight. The results reveal an early onset of flower buds and maturity for the H*M hybrid, at 20 and 82 days, respectively. The H*B hybrid shows an earlier flowering time of 35 days. Regarding the abortion rate, the results indicate high to very high rates for all cultivars. Production parameters show different results among cultivars. The hybrid S*H has the highest number of fruits per plant (11), and the hybrid I*M has the best fruit weight (135 g) and yield (1.4 kg). Very low tolerance was observed for all genotypes studied.The present study revealed significant diversity among different parameters of F1 tomato hybrids compared to their parents. Therefore, the study recommends using local, resistant genotypes.

1. Introduction

The origins of plant improvement date back to the Neolithic period, when plant species were domesticated and agriculture developed. At this period, the transition was made from gathering to intentional cultivation. The first farmers began selecting individuals with advantageous traits, such as grain quality, yield, and resistance to abiotic conditions (Purugganan & Fuller, 2009). In turn, Acquaah (2012) illustrates that the main objective of this primitive agriculture was to meet human food and non-food needs, both quantitatively and qualitatively.

Water is essential for plant growth and development, directly influencing photosynthesis, mineral nutrition, and productivity. This role becomes even more important in a climate marked by irregular rainfall and extensive droughts (Blum, 2017; FAO, 2021). However, effective management of water resources and the development of cultivars tolerant to water stress are among the most significant economic and environmental challenges.

Therefore, wild plant populations, as well as those derived from cultivated plants, cannot fully respond to edaphic, climatic, and biotic constraints without genetic improvement (Galluzzi et al., 2020).

Hybridization is still an important method. It combines the characteristics of two or more different genotypes to create new combinations. These new combinations have better agronomic properties. This means they are stronger, more resistant to abiotic stresses, and more resistant to diseases (Sharma, 2023; Yetgin et al., 2025). This technique promotes the development of more resistant and productive cultivars.

The objective of this study is to address these concerns by identifying parental combinations that present the best agronomic and sanitary performances under Mediterranean open-field conditions. Additionally, the study aims to determine the extent to which hybridization improves the productivity and resilience of tomato cultivation.

2. Materials And Methods

2.1 Experimental conditions

The trial was conducted in an open field during the 2003/2005 season on the coastal plain of Staouéli in north-central Algeria. This area has a temperate, humid climate in the winter and a hot, dry climate in the summer. Staouéli's average annual temperature is 17.7 °C, with an average annual rainfall of 615 mm (Beck et al., 2018).

• Experimental design

The trial's design was a completely randomized block, with three experimental blocks. Each block included 40 treatments, each corresponding to a different tomato genotype. Each genotype was represented by four plants spaced 30 cm apart and 1 m apart in rows, resulting in a planting density of 2.18 plants/m².

• Studied cultivars

Eight tomato varieties were used as fixed parents in this study: Marmande, Bolivar, Trakia, Saint Pierre, Castlerock, Ideal, Slava, and Heinz 1350. These varieties — introduced from outside the study — served as a basis for performing crosses. The crosses carried out between these parental varieties made it possible to obtain thirty-one (31) F1 hybrids, namely: (B*M, CR*B, CR*I, CR*M, CR*S, CR*T, H*B, H*CR, H*H, H*M, H*S, H*SP, H*T, I*B, I*M, M*CR, M*SP, S*B, S*H, S*I, S*M, S*T, SP*B, SP*CR, SP*I, SP*M, SP*S, SP*T, T*B, T*I, and T*M).

The commercial hybrid Luxor (F1) was used as a control in this experiment.

• Studied parameters

- ➢ **Phenological parameters**
    - ✓ Date of appearance of flower clusters (days after planting),
    - ✓ Date of flowering (days after planting),
    - ✓ Date of maturity (days after planting).
- ➢ **Development parameters**
    - ✓ Average number of flowers per plant,
    - ✓ Abortion rate per plant (%).
- ➢ **Production parameters**
    - ✓ Average number of fruits per plant,
    - ✓ Average fruit weight,
    - ✓ Yield per plant (kg/plant).
- ➢ **Sanitary parameter**
    - ✓ Evaluation of the level of late blight attack on leaves and fruits.

• Statistical analysis

The collected data were analyzed using ANOVA with a probability threshold of $p < 0.05$ to evaluate the significance of the effects of the studied parameters and their interactions.

All statistical analyses were performed using SPSS software (version 26).

3. Results and discussion

3.1 Phenological parameters (date of appearance of flower buds, flowering, and fruit maturity)

In light of the obtained results, the comparison of the means of different tomato cultivars shows a very highly significant difference ($p < 0.001$) with regard to phenological parameters.

The examination of the appearance of flower buds at different times (Fig. 1) reveals significant variation among the various F1 hybrids, their respective parents, and the control group. This heterogeneity reflects the differential expression of the earliness trait depending on the genotype. The hybrid H*M is characterized by its earliness with an average of 20 ± 1 days after planting, followed by the two hybrids (M*CR and S*H), each presenting an average of 21 ± 1 days. Among the parental varieties, CR appears as the earliest parent, with an average of 21 ± 1 days, ranking first compared with the other parental varieties tested in our experiment. This leads us to say that some parents transmit the earliness trait to their offspring, as in the case of the hybrid M*CR. Our results are in agreement with those of Singh *et al*., (2015), who reported that certain parental genotypes can transmit specific traits such as earliness to their descendants.

In contrast, the hybrid CR*T shows a markedly later date, with an average of 32 ± 3 days. The control Luxor is positioned at an intermediate level, with a value of 28.67 ± 1.5 days. According to Acquaah (2012), this heterogeneity explains a differentiated expression of the earliness trait among cultivars, indicating the existence of exploitable genetic variability in a breeding program.

The mean comparison test (Tukey) confirmed these trends; the hybrids H*M, M*CR, and S*H belong to the same statistical group (a), as does the parental variety CR. In contrast, the control Luxor is classified in a distinct moderately late group (h), whereas the hybrid CR*T is positioned in the last group (j).

The study of flowering earliness (see Fig. 2) revealed significant variation among the tested cultivars. The H*B hybrid stands out for its early flowering, averaging 34.33 ± 1 days after planting. In contrast, the T*I hybrid had the longest cycle, flowering on average after 50.67 ± 1.5 days. The CR and B parental varieties also flower early, with respective averages of 35.33 ± 1.5 and 35.67 ± 1.5 days, reflecting their favorable genetic potential for early flowering. The control Luxor exhibits relatively early flowering with an average of 36.33 ± 2 days. This observed earliness can be explained by two factors: the genetic effect of parents on their descendants and environmental and/or non-genetic effects. Studies on tomato behavior in relation to the environment by Hannan et al. (2007) and Pathak et al. (2024) revealed that earliness is a significant agronomic trait. It enables anticipation of harvest and optimization of cultivar adaptation to specific pedoclimatic and agronomic conditions. Others, such as Baranov et al. (2024), have reported that the transition from the vegetative phase to the flowering phase is controlled by gene networks, epigenetic regulators, and environmental conditions such as light and temperature. Furthermore, Zannat et al. (2023) demonstrated significant variability in several phenological traits, particularly flowering time, among 25 tomato cultivars. This finding reveals a strong genetic basis for earliness in this genetic material.The Tukey test ($p < 0.05$) revealed very significant differences among the tested genotypes. The H*B hybrid was the earliest and placed itself in group (a). Similarly, the two parents, CR and B, occupied the same distinct group. Meanwhile, due to its relatively early date, the control Luxor is classified in the homogeneous group (b). In contrast, the hybrid T*I is distinguished by its lateness, occupying the last group (m). In other words, the statistical results highlight marked genetic variability in terms of earliness that can be exploited in a breeding program. A positive correlation between flowering date and the date of appearance of flower buds was shown by the correlation analysis ($r = 0.616$, $p < 0.01$). In other words, genotypes that are early in flower bud emission also tend to flower earlier. Our results align with those reported by Gurung et al. (2020), who found that the timing of phenological stages in tomato, like those in our study, is often influenced by shared genetic factors.

A statistical analysis of fruit maturity (Fig. 3) revealed notable and highly significant differences among the genotypes evaluated. The results show that the H*M hybrid has the earliest average maturity date (77.67 ± 3 days), followed by the S*H cultivar with a value of 78 ± 3.6 days. In contrast, S*B represents the latest cultivar with a value of 146.67 ± 4 days. The control Luxor and the parental line CR, however, record intermediate maturity dates of 88.33 ± 7.5 and 102.33 ± 7.5 days, respectively. The observed difference among genotypes is partly explained by the heterosis effect, an essential factor in improving fruit maturity. Previous studies have shown that heterosis contributes to yield optimization and reduces the vegetative cycle in certain F1 hybrids, promoting flowering and early maturation (Semel, 2006). Others have confirmed that heterosis expression can positively affect fruit set (Figueiredo et al., 2016). Similarly, Kaushik and Dhaliwal (2018) found that the heterosis effect optimizes production cycles, offering a significant advantage in meeting agronomic and commercial requirements. These trends were confirmed by the Tukey mean comparison test ($p < 0.05$). In other words, we grouped the two hybrids, H*M and S*H, in the same homogeneous class (a), reflecting their earliness. The control Luxor and the parental variety CR were put into groups that were the same (c and f). In contrast, S*B, the latest hybrid, was placed in the final group (n). This confirmed its lateness compared to the other cultivars.

However, positive correlations were observed between fruit maturity and the appearance of flower buds ($r = 0.460$, $p < 0.01$) and between flowering and fruit maturity ($r = 0.572$, $p < 0.01$). These results indicate that the three phenological parameters evolve concurrently in the tomato genotypes studied. In other words, the earliness of flower bud emergence can be used as an indicator for selecting tomato genotypes. According to Singh et al. (2017) and Gurung et al. (2020), the early occurrence of phenological stages suggests that these parameters may be influenced by partially overlapping genetic factors. Similarly, Grandillo et al. (1999) and Tanksley (2004) noted that genes controlling early flowering influence fruit maturity as well, supporting the presence of partially overlapping genetic regulation.

3.2 Fertility and fruit set parameters (number of flowers per plant, abortion rate)

Statistical analyses of fertility and fruit set parameters show very highly significant results among the studied genotypes ($p < 0.001$).

Figure 4 shows that the hybrid S*M has the highest number of flowers per plant, with an average of 80.3 ± 27.7 flowers. Next are I*M and S*B, with mean values of 67.3 ± 13.7 and 67 ± 11.2 flowers, respectively. In contrast, the two parental lines, T and H, have the lowest values (31.3 ± 3.7 and 31.3 ± 4.7 flowers, respectively). The control shows a slightly better value of 60.67 ± 5.7 flowers. These results show that F1 hybrids are superior to their parents. This superiority is generally attributed to the heterosis effect, which stimulates vegetative and reproductive vigor, promoting better flowering and increased fruiting potential. Jiang et al. (2020) reported in a diallel analysis of 45 tomato parental variety crosses that several F1 hybrids produced a significantly higher number of flowers per plant than their parents, with high positive heterosis values for this trait. Sharma et al. (2025) confirm that, in line × tester crosses, the number of flowers per plant is consistently higher in hybrids than in the parents.

The Tukey multiple comparison test ($p < 0.05$) confirmed these trends. The S*M hybrid stands out for its superiority, occupying homogeneous group c. Similarly, I*M and S*B occupy the same group due to their relatively high means. In contrast, the control, with its intermediate value, is positioned in group b. The two parental varieties, T and H, with their low means, are classified in distinct group (a). This classification reveals marked heterogeneity among the cultivated genotypes and confirms the superiority of the hybrids, reflecting a positive heterosis effect on the number of flowers per plant.

The analysis of the abortion rate (Fig. 5) highlights very high values for all tested genotypes. According to our results, the hybrid S*H shows the lowest abortion rate with a value of 72.3 ± 2%,

This was followed by the F1 hybrid H*M, which had a mean of 78.6% ± 3.5%. In contrast, the genotypes H*B, I*B, and B*M have the highest abortion rates, reaching 100%. The control Luxor recorded an intermediate mean of 87.3 ± 2.5%, while the parental varieties B and S showed relatively high rates of 94.6 ± 0.5% and 94 ± 1%, respectively. The observed abortion rates are particularly high, certainly influenced by unfavorable environmental conditions (high temperatures and diseases). Research on the same species confirms that excessive temperatures disrupt pollination and fertilization, leading to increased abortion rates (Firon et al., 2006; Egea et al., 2022). Other researchers have found that chronic heat and other abiotic stresses increase pollen sterility and floral abortion in tomatoes (Srivastava et al., 2016; Wu et al., 2024). Da Silva et al. (2021) observed that the abortion rate can influence yield and reach high values under unfavorable conditions in processing and open-field tomatoes, which confirms our results.

The Tukey comparison test ($p < 0.05$) confirmed significant differences among the genotypes. Due to its low abortion rate, the hybrid S*H is classified in group (a). H*M, with its relatively low value, is positioned in the homogeneous group (b). The control Luxor, with an intermediate value, is placed in distinct group e. The two parental varieties, S and H, which have high abortion rates, are in the same group (j). In contrast, the three hybrids B*M, I*B, and H*B have the highest abortion rates and are in the last group (k).

3.3 Production parameters (number of fruits per plant, fruit weight, fruit yield)

Statistical analyses of all production parameters revealed highly significant differences among the genotypes studied, indicating substantial genetic variability for these traits. This variability underscores the significant genotypic effects associated with the performed crosses.

As shown in the figure, the two hybrids S*H and H*M stand out as the most productive genetic combinations, with respective means of 12 ± 3.6 and 11 ± 1 fruits. These results suggest strong genetic complementarity between the parents and a positive heterosis effect. According to Liu et al. (2021), heterosis is a phenomenon frequently reported in interspecific breeding studies. In contrast, the B*M, I*B, and H*B hybrids did not produce any fruit, which indicates probable reproductive incompatibility related to genetic barriers that limit fertilization and fruit set. Similar results have been reported in numerous interspecific or intravarietal crosses (Kumar & Paliwal, 2016).

Furthermore, the CR parental line (5.3 ± 1.5 fruits) demonstrates moderate productivity. In contrast, the Luxor control line (9.6 ± 2.5 fruits) exhibits relative superiority compared to many of the cultivars tested in this experiment. These results suggest that certain hybrid combinations can surpass the productivity of their parents and the standard control. Thus, such crosses are a fundamental lever for the success of varietal breeding programs aimed at increasing yield profitability (Acquaah, 2012).

A Tukey multiple comparison test ($p < 0.05$) was applied to the means of this parameter, revealing highly significant differences among the tested cultivars. Due to their high fruit number, the two hybrids S*H and H*M are placed in group (i), whereas the control Luxor occupies the distinct group (h). In contrast, the three hybrids B*M, I*B, and H*B, which produced no fruit, are in group a. The parental variety CR, characterized by moderately low productivity, occupies group d.

Additionally, a highly significant negative correlation was observed between fruit number and abortion rate ($r = -0.86$, $p < 0.001$). This indicates that an increase in abortion rate is accompanied by a decrease in fruit number, and vice versa. Our results align with those of Zhou et al. (2022) and Felix (2024), who found that post-fertilization losses, frequently resulting from physiological imbalances or genetic incompatibilities, are a primary factor limiting yield. Conversely, the number of flowers per plant positively correlates with the number of fruits per plant ($r = 0.38$, $p < 0.05$), suggesting that floral initiation determines fruit induction. Similar findings have been reported in various cultivated plant species, particularly tomato (Acharya et al., 2018; Singh et al., 2019; Zhou, 2022), where abundant flowering is generally associated with high yield potential. These results highlight relevant genetic and phenotypic associations for selecting the most productive genotypes. They emphasize the importance of promoting traits that are positively correlated with yield, such as the number of flowers and fruits, while considering negative correlations that could hinder expected genetic progress (Aisyah et al., 2016; Singh et al., 2019).

Furthermore, the cultivar I*M had the highest average fruit weight (Fig. 7), with a mean of 148.6 ± 43.5 g. S*M followed with 134.3 ± 10.1 g. Luxor ranked third with an average weight of 125.5 ± 5.8 g, while hybrid H*I showed the lowest average fruit weight at 42.5 ± 2.3 g.

The three cultivars B*M, I*B, and H*B did not produce any fruit. Among the parental lines, variety B had the highest average fruit weight, at 78.3 ± 4.7 g. Despite these results, the average fruit weights remained relatively low. These low weights may be attributed to unfavorable climatic conditions for tomato cultivation, such as high temperatures and dry air, which were observed during the growth period. Abiotic factors like these are known to negatively affect fruit size development and, consequently, final weight (Bita & Gerats, 2013; Saputra et al., 2017).

The Tukey multiple comparison test ($p < 0.05$) shows that hybrid I*M, which has the highest mean, occupies a distinct group (j). Hybrid S*M and the control Luxor follow in group (i). In contrast, the three cultivars B*M, I*B, and H*B, which did not produce fruit, belong to the lowest homogeneous group (a).

According to Fig. 8, fruit yield shows very highly significant differences among the tested genotypes ($p < 0.001$). The highest average yield was recorded for Hybrid S*M at 1.3 ± 46.8 kg/plant, followed by I*M at 1.28 ± 78.7 kg/plant. The control, Luxor, shows moderately good performance, with a yield of 0.9 ± 25.9 kg/plant. In contrast, the H*SP genotype recorded the lowest yield, with an average of 0.09 ± 5.5 kg/plant. The parental line CR, however, stands out as one of the most productive parents with an average yield of 0.3 ± 24.1 kg/plant. The three genotypes M*B, I*B, and H*B produced no f The low yields recorded were influenced by unfavorable environmental conditions, particularly high temperatures, which led to increased flower drop and high abortion rates. The presence of late blight also caused significant damage despite the application of phytosanitary treatments. Genotypes that produced fruit under these constraints likely express hybrid vigor resulting from crosses between parental lines that are more tolerant of thermal stress and pathogens. Our results are consistent with those of Foolad (2007), Nowicki et al. (2012), and Beddows et al. (2017), who determined that thermal stress and fungal diseases are major limiting factors of tomato yield. Others have confirmed that high temperatures reduce pollen fertility and fruit set, resulting in a decline in yield (Ruan et al., 2010; Zhou et al., 2015). Similarly, Kumar et al. (2017) and Chemina et al. (2024) indicated that varietal resistance and hybrid vigor play decisive roles in tolerance to thermal stress and diseases and in yield stability under adverse growing conditions,fruit, resulting in a zero yield (0 kg/plant).

Significant differences among cultivars are highlighted by the multiple comparison test of Tukey ($p < 0.05$). The most productive genotypes are the hybrids S*M and I*M, which belong to the same group (n). The control Luxor, which had a satisfactory yield, is classified in a distinct homogeneous group (m). In contrast, the homogeneous group (a) is where genotypes B*M, I*B, and H*B, which produced no fruits, are grouped. These results confirm the significant genetic variability among the exploited crosses and emphasize the impact of genotypic combination on the productive potential of hybrids.

Furthermore, correlation analyses illustrate the relationships between yield and other yield components. A significant positive correlation was observed between yield and the number of flowers ($r = 0.39$, $p < 0.05$), suggesting that abundant flowering contributes to higher yields. Another noteworthy positive relationship exists between yield and the number of fruits ($r = 0.89$, $p < 0.01$), suggesting that successful fruit set is pivotal to productivity. Similarly, the highly significant positive correlation between yield and fruit weight (r = 0.64, p < 0.01) confirms that fruit size and weight directly impact overall performance. These findings are consistent with those reported by Dramé et al. (2021) and Kumar and Srivastava (2021). On converse, a highly significant negative correlation was observed between yield and abortion rate (r = −0.81, p < 0.01). This shows that the reproductive organs are sensitive to environmental stress. An increase in the abortion rate significantly reduces fruit set and, consequently, final yield. Our results corroborate those of Bita and Gerats (2013) and Zhou et al. (2015), who found that excessive heat disrupts anther development and pollen viability, resulting in reduced fruiting. So, these results underscore the importance of hybrid vigor, reproductive stability, and tolerance to thermal and pathogenic stresses as key selection criteria for enhancing tomato yield in challenging agroclimatic conditions.

3.4 Sanitary parameter (late blight)

Observations on all genotypes revealed that all plants were affected by late blight, though to varying degrees depending on the cross. Cultivars B*M, I*B, and H*B were the most susceptible. These results suggest that these hybrids have low genetic resistance, which they probably inherited from their parents. Conversely, S*M, I*M, S*H, CR*T, and H*M exhibited greater tolerance to late blight and relative resistance to climatic constraints, especially high temperatures during the tomato growing cycle. This increased resistance may be due to a heterosis effect caused by favorable genetic combinations that improve tolerance to pathogens and abiotic stresses. Previous research has demonstrated that hybrid vigor significantly contributes to physiological robustness and reduces fungal disease severity in tomatoes (Foolad, 2007; Khazaei & Madduri, 2022).

The control Luxor exhibited moderate resistance, maintaining average productivity despite its sensitivity to late blight. These results confirm genetic variability among crosses and underscore the importance of selecting resistant parental lines to develop new hybrids adapted to challenging agroclimatic conditions. These results are consistent with those reported by Nowicki et al. (2012), Haverkort et al. (2016), and Jehani et al. (2025), who emphasize the need to prioritize genetic resistance to late blight in Solanaceae breeding programs, especially for tomatoes.

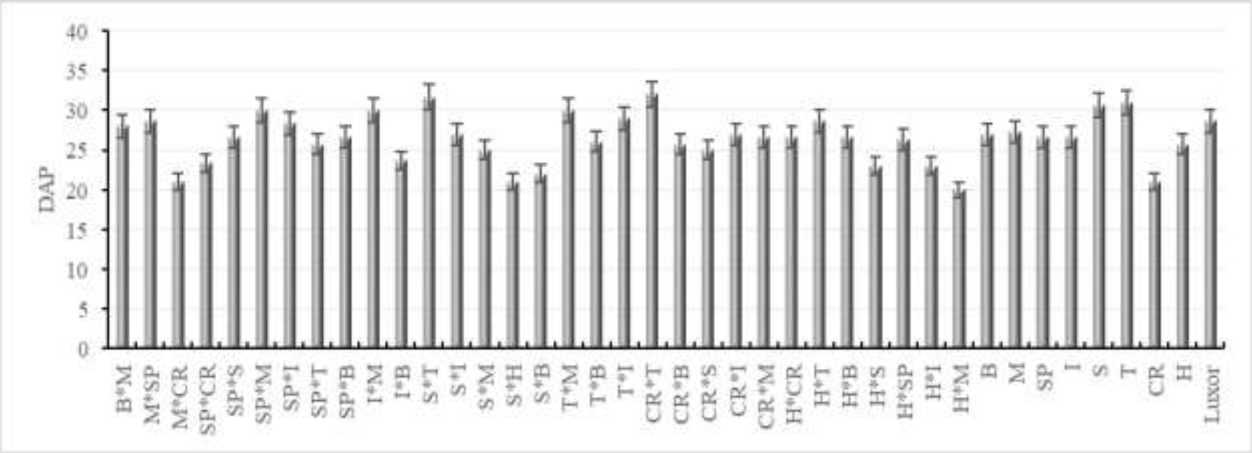

Figure 1. *Date of appearance of flower buds*

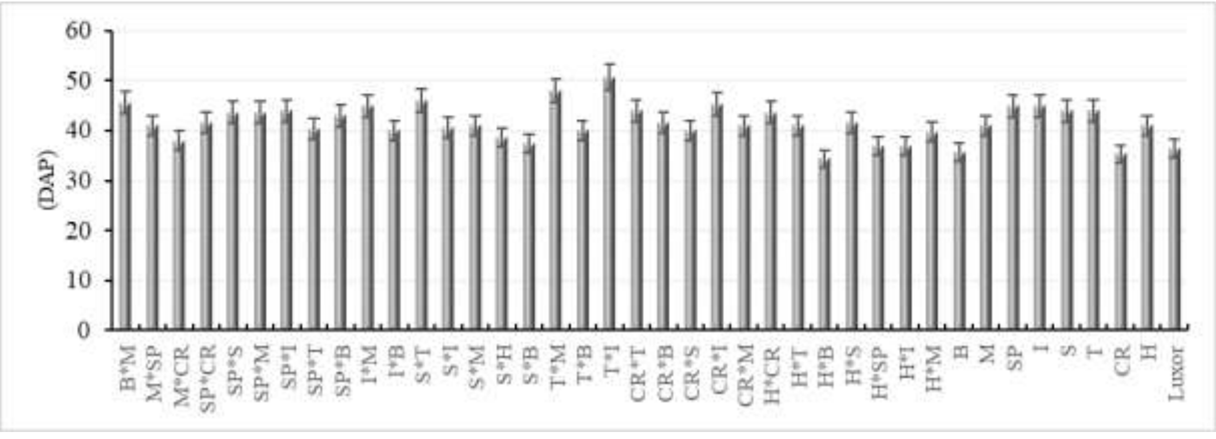

Figure 2. *Date of flowering.*

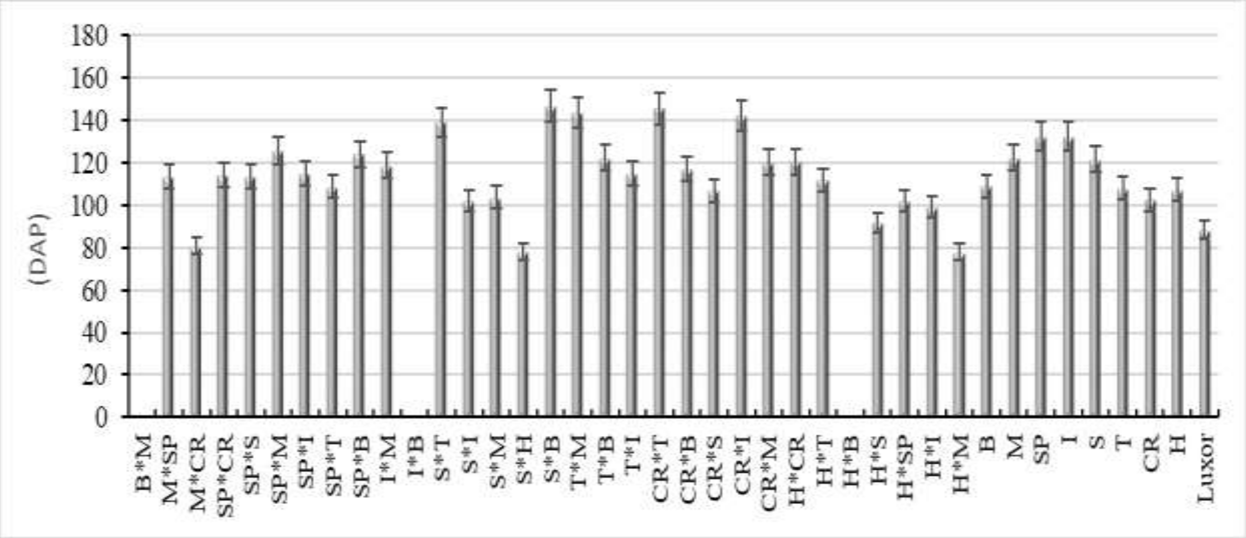

Figure 3. Date of fruit maturity

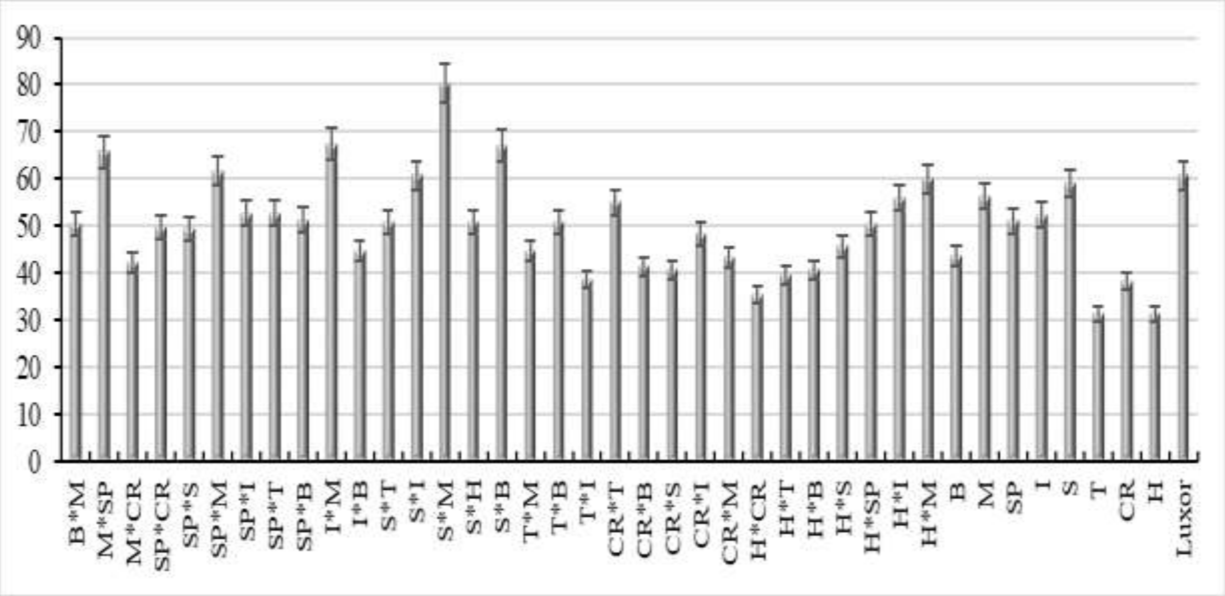

Figure 4. *Number of flowers per plant*

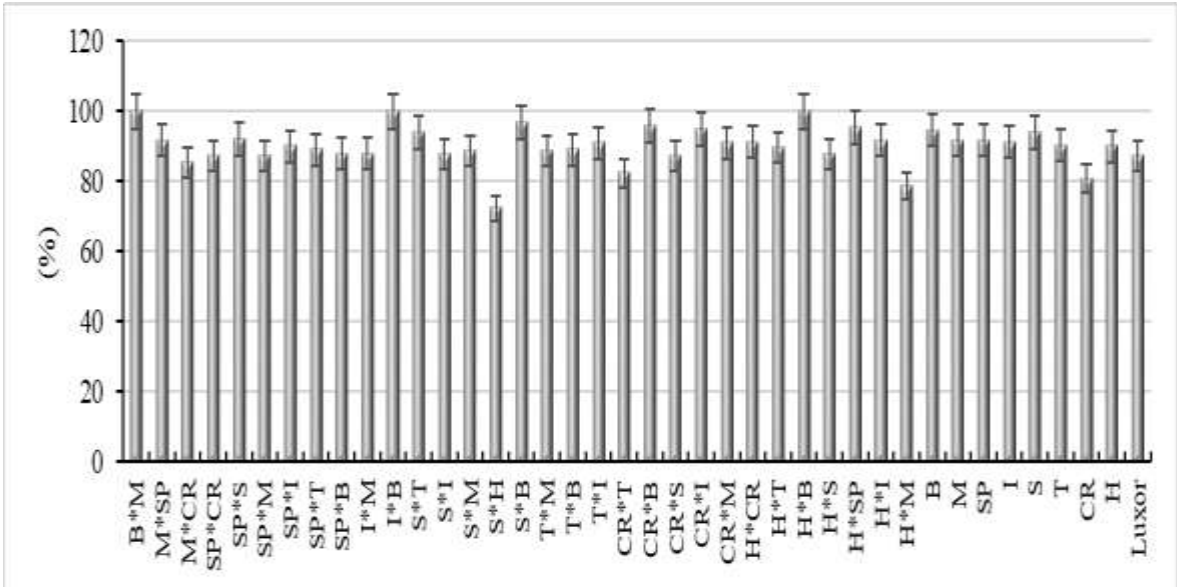

Figure 5. *Abortion rate per cultivar.*

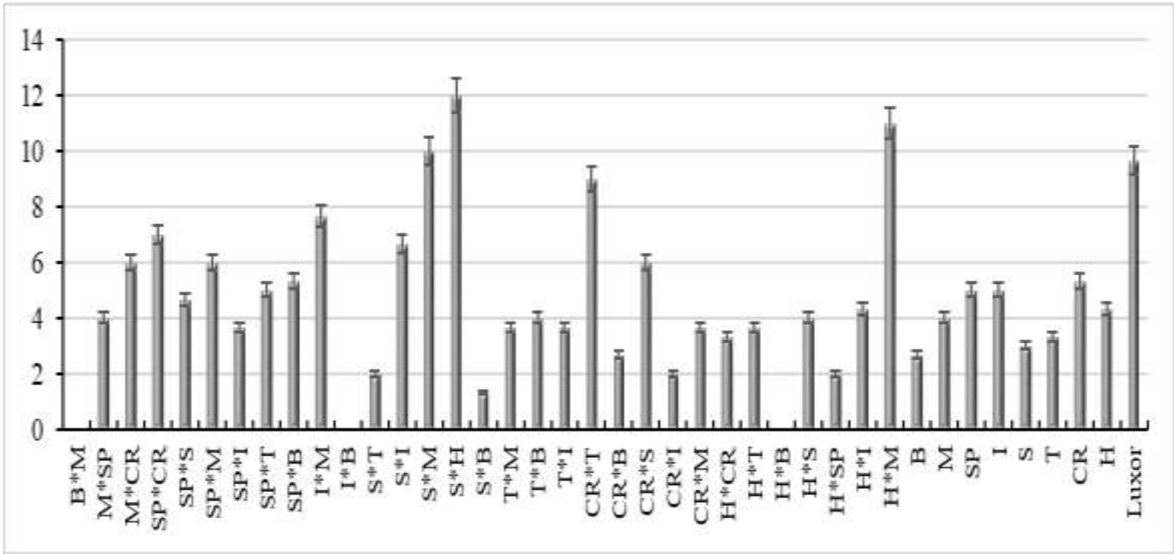

Figure 6. *Number of fruits per plant.*

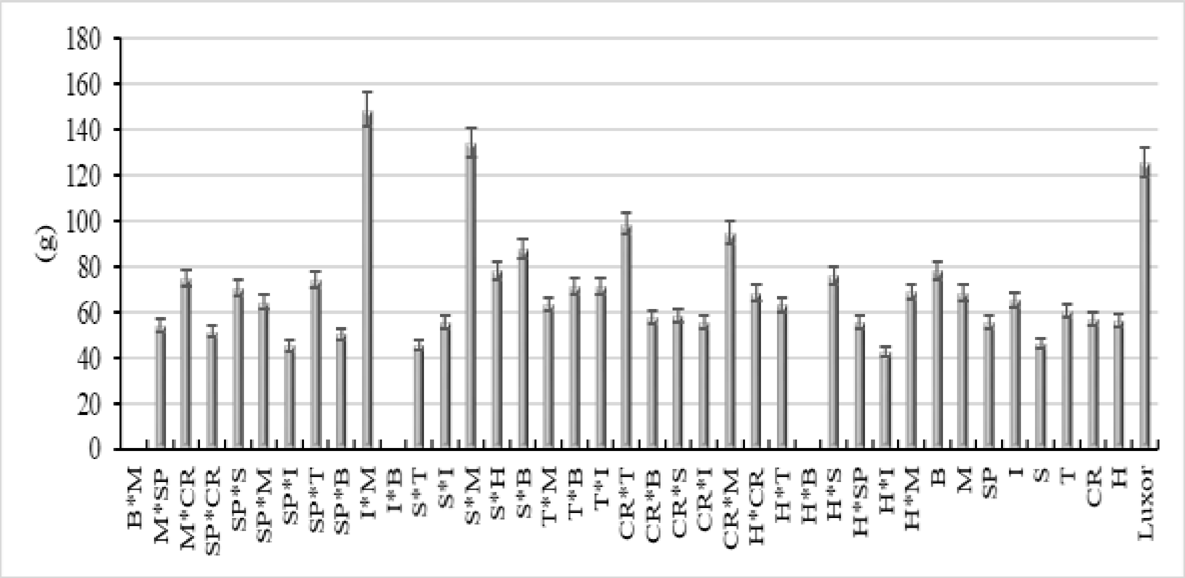

Figure 7. *Fruit weight per cultivar.*

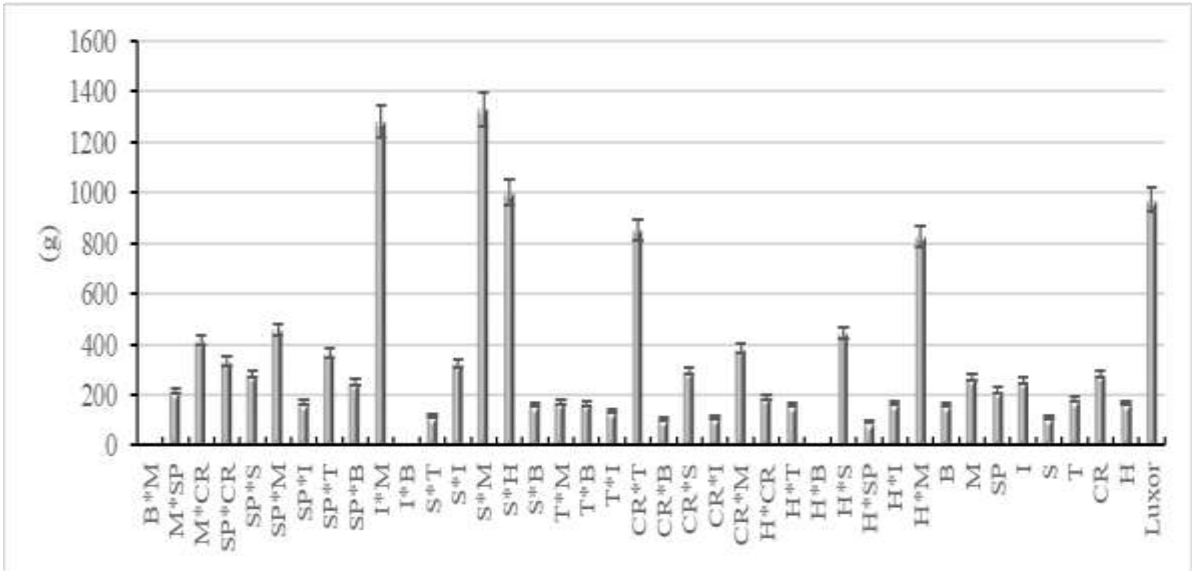

Figure 8. *Yield per plant of the genotypes.*

Figure 9. *Late blight on stem.*

4. Conclusions

In this section conclusions of work should be given. The results of this study highlight significant genetic variability among tomato genotypes for phenological, reproductive, yield, and phytosanitary resistance components. This diversity is a valuable genetic resource for breeding and varietal selection programs that aim to strengthen the productivity and resistance of this species in unfavorable agroclimatic environments.

From a phenological perspective, crosses H*M, M*CR, and S*H are characterized by early flowering and maturity. This reflects favorable genetic inheritance and a significant heterosis effect on these traits.

However, regarding flowering and fruiting parameters, the hybrids S*M, I*M, and S*B showed a remarkable flowering rate. This rate was compared with the other genotypes.

From a productivity standpoint, the S*M and I*M genotypes stand out due to their superior yield performance, which results from favorable genetic interactions between their parents and effective expression of hybrid vigor.

Phytosanitary evaluation revealed that all genotypes were affected by late blight, but with varying levels of sensitivity. The hybrids S*M, I*M, S*H, CR*T, and H*M expressed higher tolerance, suggesting the existence of effective genetic defense mechanisms and improved physiological stability against infection.

The results of this study confirm the effectiveness of hybridization as a strategy for genetic improvement in tomatoes. The S*M, I*M, S*H, and H*M hybrids stood out for their overall agronomic performance, combining earliness, reproductive vigor, high yield, and good sanitary tolerance. Therefore, these genotypes appear promising for multi-location trials and integration into breeding programs targeting adaptation to local agroclimatic conditions.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.
- **Use of AI Tools:** The author(s) declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

References

[1] Acharya, B., Dutta, S., Dutta, S., and Chattopadhyay, A. (2018). Breeding Tomato for Simultaneous Improvement of Processing Quality, Fruit Yield, and Dual Disease Tolerance. *International Journal of Vegetable Science*, 24(5): 407–423. DOI: https://doi.org/10.1080/19315260.2018.1427648.

[2] Acquaah, G. (2012). Principles of Plant Genetics and Breeding. 2nd ed., Wiley-Blackwell, Oxford, UK: 768 p. DOI:10.1002/9781118313718

[3] Aisyah, S.I., Wahyuni, S., Syukur, M., and Witono, J.R. (2016). The Estimation of Combining Ability and Heterosis Effect for Yield and Yield Components in Tomato (*Solanum lycopersicum* Mill.) at Lowland. *Journal of Crop Breeding and Genetics*, 2(1): 23–29.

[4] Baranov, D., Dolgov, S., and Dolgov, S. (2024). New Advances in the Study of Regulation of Tomato Flowering-Related Genes Using Biotechnological Approaches. *Plants*, 13(3), 359 : 1–34. DOI: https://doi.org/10.3390/plants13030359.

[5] Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., and Wood, E.F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data*, 5(1), 180214. DOI: https://doi.org/10.1038/sdata.2018.214.

[6] Beddows, I., Reddy, A., Kloesges, T., and Rose, L.E. (2017). Population genomics in wild tomatoes the interplay of divergence and admixture. *Genome Biology and Evolution*, 9(11), 3023–3038. DOI: https://doi.org/10.1093/gbe/evx224.

[7] Bita, C.E., and Gerats, T. (2013). Plant tolerance to high temperature in a changing environment: scientific fundamentals and production of heat stress-tolerant crops. *Frontiers in Plant Science*, 4(273), 1–18. DOI: https://doi.org/10.3389/fpls.2013.00273.

[8] Blum, A. (2017). *Plant Breeding for Water-Limited Environments,* Springer, 270 p. DOI: https://doi.org/10.1007/978-1-4419-7491-4.

[9] Chiwina, K.E., Bhattarai, G., Xiong, H., Joshi, N.K., Dickson, R.W., Phiri, T.M., Alatawi, I., Chen, Y., Stansell, Z., Ling, K.S., and Shi, A. (2024). Evaluation of Drought Tolerance in USDA Tomato Germplasm at Seedling Stage. *Agronomy*, 14(2), 380, 1–22. DOI: https://doi.org/10.3390/agronomy14020380.

[10] Da Silva, B.L., Filho, M.N.C., Tagliaferre, C., Mesquita, N.L.S., and Guedes, M.O. (2021). Tomato in the semi-arid: Plastic mulching, plant population and irrigation. Comunicata Scientiae, 12, 3779, 1–7. DOI: https://doi.org/10.14295/CS.v12.3779.

[11] Drame, B., Kane, P.D., Mbaye, A.A., Faye, A., and Noba, K. (2021). Study of varietal sensitivity of tomato (*Solanum lycopersicum* L.) to bacterial wilt caused by Ralstonia solanacearum in the Senegal River Valley. *International Journal of Advanced Research*, 9(01), 1–11. DOI: https://doi.org/10.21474/IJAR01/12273.

[12] Egea, I., Estrada, Y., Flores, F.B., and Bolarín, M.C. (2022). Improving production and fruit quality of tomato under abiotic stress: Genes for the future of tomato breeding for a sustainable agriculture. *Environmental and Experimental Botany*, 204, 105086, pp. 1–23. DOI: https://doi.org/10.1016/j.envexpbot.2022.105086.

[13] Felix, G. (2024). Genetic Improvement of Tomato. Applied Genetics Course – L.-A. Minsar, 1–14.

[14] Figueiredo, A.S.T., Resende, J.T.V., Faria, M.V., Da-Silva, P.R., Fagundes, B.S., and Morales, R.G.F. (2006). Prediction of industrial tomato hybrids from agronomic traits and ISSR molecular markers. *Genetics and Molecular Research*, 15(2), 1–9. DOI: http://dx.doi.org/10.4238/gmr16019402.

[15] Firon, N., Shaked, R., Peet, M.M., Pharr, D.M., Zamski, E., Rosenfeld, K., Althan, L., and Pressman, E. (2006). Pollen grains of heat-tolerant tomato cultivars retain higher carbohydrate concentration under heat stress conditions. *Scientia Horticulturae*, 109(3), 212–217. DOI: https://doi.org/10.1016/j.scienta.2006.03.007.

[16] FAO. (2021). The State of the World’s Land and Water Resources for Food and Agriculture: Systems at Breaking Point. Synthesis Report 2021, Rome, 83 p. DOI: https://doi.org/10.4060/cb7654en.

[17] Foolad, M.R., (2007). Genome Mapping and Molecular Breeding of Tomato. *International Journal of Plant Genomics*, 64358, 52 p. DOI: https://doi.org/10.1155/2007/64358.

[18] Galluzzi, G., Seyoum, A., Halewood, M., Noriega, I.L., and Welch, E.W. (2020). The Role of Genetic Resources in Breeding for Climate Change: The Case of Public Breeding Programmes in Eighteen Developing Countries. *Plants*, 9(9), 1129, 1–19. DOI: https://doi.org/10.3390/plants9091129.

[19] Grandillo, S., Ku, H.M., and Tanksley, S.D. (1999). Identifying the loci responsible for natural variation in fruit size and shape in tomato. *Theoretical and Applied Genetics*, 99, 978–987. DOI: https://doi.org/10.1007/s001220051405.

[20] Gurung S., Adhikari P., Giri K., Gotame T.P., and Shrestha S.L., (2020). Growth and yield performance of hybrid tomato (*Solanum lycopersicum* L.) lines at Parwanipur, Bara, Nepal. *Journal of Agriculture and Natural Resources*, 3(1), 180–189. DOI: https://doi.org/10.3126/janr.v3i1.27166.

[21] Hannan, R.M., Fery, R.L., and Smith, J.R. (2007). Plant genetic resources and diversity in crop improvement. *Plant Genetic Resources: Characterization and Utilization*, 5(3), 121–134.

[22] Jehani, M.D., Mohamed, J.M., Cheemala, S., Nath, B.C., Chonzik, E.K., and Srivastava, S. (2025). From Pathogen to Protection: Integrated Disease Management Strategies for Tomato Late Blight. *Journal of Pure and Applied Microbiology*, 19(3): 1686-1704. DOI: https://doi.org/10.22207/JPAM.19.3.33.

[23] Jiang, S., Luo, Z., and Dai, J. (2020). Use YeastFab to Construct Genetic Parts and Multicomponent Pathways for Metabolic Engineering. *Methods in Molecular Biology*, 2196, 167–180. DOI: https://doi.org/10.1007/978-1-0716-0868-5_13.

[24] Kaushik, P., and Dhaliwal, M.S., (2018). Diallel Analysis for Morphological and Biochemical Traits in Tomato Cultivated under the Influence of Tomato Leaf Curl Virus. *Agronomy*, 8, 153, 1–15. DOI: https://doi.org/10.3390/agronomy8080153.

[25] Khazaei, H., and Madduri, A. (2022). The role of tomato wild relatives in breeding disease-free varieties. *Genetic Resources*, 3(6), 64–73. DOI: https://doi.org/10.46265/genresj.PSES6766.

[26] Kumar, P., Choudhary, R., and Jat, B.L., (2017). Heterosis breeding in tomato for yield and quality contributing traits. *Asian Journal of Bio Science*, 12(2), 259–279.

[27] Kumar, P., and Paliwal, A., (2016). Heterosis breeding for quality improvement in tomato (*Lycopersicon esculentum* Mill.) for cultivation in mid hills of Uttarakhand. *International Journal of New Technology and Research*, 2(10), 75–87.

[28] Kumar, R., and Srivastava, K., (2021). Gene Effects and Heritability for Yield Traits in Tomato (*Solanum lycopersicum* L.). *Bangladesh Journal of Botany*, 50(3), 453–465. DOI: https://doi.org/10.3329/bjb.v50i3.55823.

[29] Liu, Z., Jiang, J., Ren, A., Xu, X., Zhang, H., Zhao, T., Jiang, X., Sun, Y., Li, J., and Yang, H. (2021). Heterosis and Combining Ability Analysis of Fruit Yield, Early Maturity, and Quality in Tomato. *Agronomy*, 11(4), 807, 1–15. DOI: https://doi.org/10.3390/agronomy11040807.

[30] Nowicki, M., Foolad, M.R., Nowakowska, F.N., and Kozik, E.U. (2012). Potato and Tomato Late Blight Caused by Phytophthora infestans: An Overview of Pathology and Resistance Breeding. *Plant Disease*, 96(1), 4–17. DOI: https://doi.org/10.1094/PDIS-05-11-0458.

[31] Pathak, R.K., Singh, S., Meghna, Kumar, S., Narayan, A., and Chaudhary, S. (2024). Genetic variability, heritability and genetic advance in tomato (*Solanum lycopersicum* L.). *International Journal of Advanced Biochemistry Research*, SP-8(8), 184–187. DOI: https://doi.org/10.33545/26174693.2024.v8.i8Sc.1762.

[32] Purugganan, M.D., and Fuller, D.Q. (2009). The nature of selection during plant domestication. *Nature*, 457(7231), 843–848. DOI: https://doi.org/10.1038/nature07895.

[33] Ruan, Y.L., Jin, Y., Yang, Y.J., Li, G.J., and Boyer, J.S. (2010). Sugar input, metabolism, and signaling mediated by invertase: roles in development, yield potential, and response to drought and heat. *Molecular Plant*, 3(6), 942–955. DOI: 10.1093/mp/ssq044

[34] Saputra, H.E., Syukur, M., and Aisyah, S.I., (2017). Characterization and Similarity Analysis of 15 Tomato Genotypes in Lowlands Based on Morphological Characters. *Agrotech Journal*, 2(2), 1–6. DOI: https://doi.org/10.31327/atj.v2i2.309.

[35] Semel, Y., Nissenbaum, J., Menda, N., Zinder, M., Krieger, U., Issman, N., Pleban, T., Lippman, Z., Gur, A., and Zamir, D. (2006). Overdominant quantitative trait loci for yield and fitness in tomato. *PNAS*, 103(35), 12981–12986. DOI: https://doi.org/10.1073/pnas.060463510.

[36] Sharma, A., Meena, R.K., Sharma, M., Sharma, J., Sharma, R.N., and Pancholi, R. (2025). Investigations to Identify the Relationship between Weather Parameters and Okra Shoot and Fruit Borer Infestation. *Journal of Experimental Agriculture International*, 47(5), 257–262. DOI: https://doi.org/10.9734/jeai/2025/v47i53413.

[37] Sharma, L. (2023). Pioneering Sustainable Agriculture. *Journal of Agriculture*, 6(3), 85–87. DOI: https://doi.org/10.37532/jagri.2023.6%283%29.85-87.

[38] Singh, A.K., Solankey, S.S., Kumari, M., and Singh, N. (2019). Morpho-chemical quality improvement in tomato (*Solanum lycopersicum*) through heterosis breeding. *Indian Journal of Agricultural Sciences*, 89(8), 35–39. DOI: https://doi.org/10.56093/ijas.v89i8.92838

[39] Singh, N., Ram, C.N., Deo, C., Yadav, G.C., and Singh, D.P., (2015). Genetic variability, heritability and genetic advance in tomato (*Solanum lycopersicum* L.). *Plant Archives*, 15(2), 705–709.

[40] Singh, R., Pandey, K.D., Kuma,r A., and Singh, M. (2017). PGPR isolates from the rhizosphere of vegetable crop Momordica charantia: Characterization and application as biofertilizer. *International Journal of Current Microbiology and Applied Sciences*, 6(3), 1789–1802. DOI: https://doi.org/10.20546/ijcmas.2017.603.205.

[41] Srivastava, K., Kumar, S., Bhandari, H.R., and Vaishampayan, A. (2016). Search for tomato hybrids suited for high temperature stress condition. Proceedings of SABRAO 13th Congress and International Conference, September 14–16, Bogor, Indonesia, 137–150.

[42] Tanksley, S.D. (2004). The Genetic, Developmental, and Molecular Bases of Fruit Size and Shape Variation in Tomato. *The Plant Cell*, 16(1), 181–189. DOI: https://doi.org/10.1105/tpc.018119.

[43] Yetgin, A., Srivastava, R.K., Panda, S., and Rath, S., (2025). Plant Breeding Strategies for Sustainable Agriculture in Climate Change Context: A Literature Review. Springer, 359–380. DOI: https://doi.org/10.1007/978-981-95-0389-6_17.

[44] Wu, J., Li, P., Li, M., Zhu, D., Ma, H., Xu, H., Li, S., Wei, J., Bian, X., Wang, M., Lai, Y., Peng, Y., Li, H., Rahman, A., and Wu, S. (2024). Heat stress impairs floral meristem termination and fruit development by affecting the BR-SlCRCa cascade in tomato. *Plant Communications*, 5, 100790, 1–16. DOI: https://doi.org/10.1016/j.xplc.2023.100790.

[45] Zannat, A., Hussain, M.A., Abdullah, A.H.M., Hossain, M.I., Saifullah, M., Safhi, F.A., Alshallash, K.S., Mansour, E., ElSayed, A.I., and Hossain, M.S. (2023). Exploring genotypic variability and interrelationships among growth, yield, and quality characteristics in diverse tomato genotypes. *Heliyon*, 9(8), e18958, 1–11. DOI: https://doi.org/10.1016/j.heliyon.2023.e18958.

[46] Zhou, R., Wu, Z., Cao, X., and Jiang, F.L. (2015). Genetic diversity of cultivated and wild tomatoes revealed by morphological traits and SSR markers. *Genetics and Molecular Research*, 14(4), 13868–13879. DOI: http://dx.doi.org/10.4238/2015.October.29.7.

[47] Zhou, Y., Zhang, Z., Bao, Z., Li, H., Lyu, Y., Zan, Y., Wu, Y., Cheng, L., Fang, Y., Wu, K., Zhang, J., Lyu, H., Lin, T., Gao, Q., Saha, S., Mueller, L., Fei, Z., Städler, T., Xu, S., Zhang, Z., Speed, D., and Huang, S. (2022). Graph pangenome captures missing heritability and empowers tomato breeding. *Nature*, 606(7914), 527–534. DOI: https://doi.org/10.1038/s41586-022-04808-9.