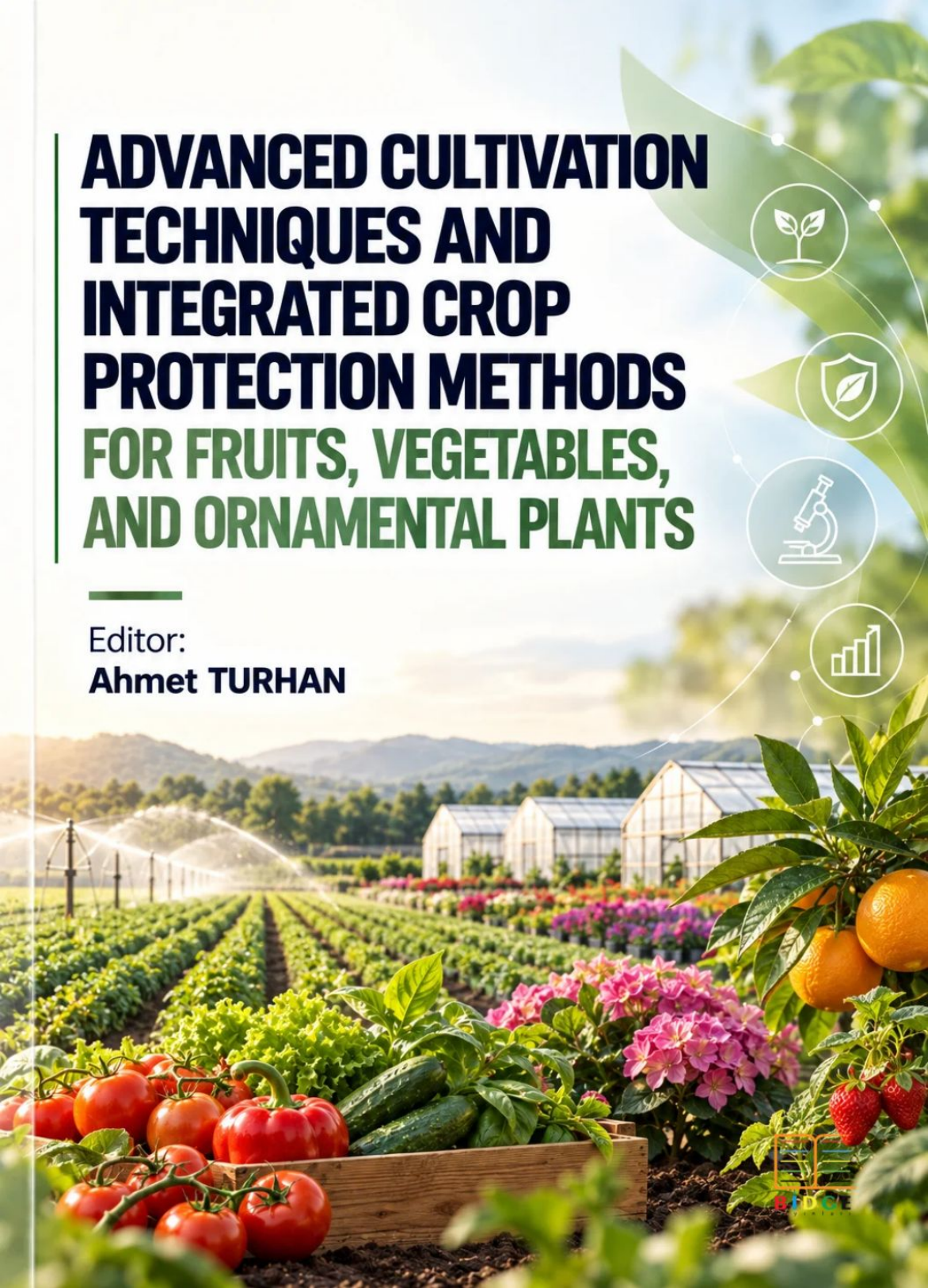
ADVANCED CULTIVATION TECHNIQUES AND INTEGRATED CROP PROTECTION METHODS FOR FRUITS, VEGETABLES, AND ORNAMENTAL PLANTS

Editor:
Ahmet TURHAN



BİDGE Yayınları

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PREFACE

The agricultural sector holds strategic importance for meeting the food demands of a growing global population, ensuring the sustainable use of natural resources, mitigating the impacts of climate change, and safeguarding environmental health. The cultivation of fruits, vegetables, and ornamental plants represents a significant segment of crop production, contributing not only to human nutrition but also carrying substantial economic, social, and environmental dimensions. However, challenges such as shifting climatic conditions, rising production costs, mounting pressure on water and soil resources, the influence of biotic and abiotic stressors, and yield or quality losses caused by pests and diseases necessitate the development of new, sustainable approaches to crop production. Today, the primary objectives in the cultivation of fruits, vegetables, and ornamental plants extend beyond achieving high yields and superior product quality; they also encompass the conservation of natural resources, the efficient use of production inputs, and the minimization of environmental impacts. Modern cultivation techniques play a pivotal role in achieving these goals. One of the major challenges in crop production is the loss of produce due to plant diseases and pests. In traditional control methods, the intensive and indiscriminate use of chemical pesticides can entail various risks, including the development of pest resistance, issues with chemical residues, adverse effects on non-target organisms, and environmental pollution. Consequently, there is a need for holistic strategies in plant protection—approaches that go beyond merely

eliminating harmful organisms to instead prioritize ecological balance, economic viability, and the protection of human health. Integrated Pest Management (IPM) stands out as a fundamental approach that addresses these requirements. In this work, titled “Advanced Cultivation Techniques and Integrated Pest Management for Fruits, Vegetables, and Ornamental Plants,” knowledge and experience from various fields of expertise have been evaluated within a common framework.

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CHAPTER 1

HAPLOID RESEARCH IN *CUCURBITACEAE* TRENDS TECHNIQUES AND BIBLIOMETRIC ASSESSMENT

ESMANUR DEMİREL[1]
ELİF ÇATIKKAŞ[2]

INTRODUCTION

The *Cucurbitaceae* family is a group of plants that includes important commercial species such as melon, watermelon, pumpkin and cucumber. Given the high commercial value of these species, significant efforts are being made to develop varieties that can adapt to innovations through advanced breeding techniques. The inability to obtain results in a short time while developing new varieties has led scientists to seek new ways to shorten the time (Ren et al., 2017). Haploid methods have become an important source of perspective for plant breeding researchers. By acquiring plants containing a singular set of chromosomes, homozygous plants are produced through chromosome duplication. These

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homozygous plants serve as pioneers in the development of new varieties.

Haploidy's contribution holds considerable importance within the *Cucurbitaceae* lineage, yielding notable consequences for the fields of plant breeding, genetics, and evolutionary research (Gałązka & Niemirowicz-Szczytt, 2013). Research on haploidy within the botanical family *Cucurbitaceae* has focused on multiple aspects, including nutrient medium content, appropriate explant selection, and methodologies for practical application (Kurtar et al., 2020). Several studies have explored the occurrence of haploidy in various species within the *Cucurbitaceae* family (Demirel & Onus, 2021; Ebrahimzadeh et al., 2018; Majeed et al., 2023).

Research on haploid production in cucurbits has generally been evaluated in reviews. Bibliometric analysis offers a complementary way to examine publication patterns, contributing authors and research topics over time (Ninkov et al., 2022; Regni et al., 2025). This chapter uses an existing bibliometric dataset to describe the development of haploid research in *Cucurbitaceae* and discusses the findings in relation to the techniques and research directions represented in the literature. The following sections present the scope of the analysis, publication and citation patterns, scientific contributions, and thematic relationships.

SCOPE AND METHOD OF THE BIBLIOMETRIC ASSESSMENT

The analysis covers publications dated from 1987 to the search date of 6 May 2024. The search was conducted in the Web of Science platform under the “All Databases” category using “cucurbitaceae” in the Topic field and “haploid” in the Title field. The document type was restricted to Article and the Preprint Citation Index was excluded. Accordingly, the dataset contains the 63 records retrieved with this strategy, rather than all publications

on haploid production in cucurbits. Publications indexed only under individual crop names or using alternative terminology may have been missed. The 2024 results represent a partial year and should not be compared directly with complete calendar years.

The search retrieved 63 articles. Records were exported and analysed using R version 4.4.0 and the Biblioshiny interface. Bibliometric findings reported below refer to this dataset and its retrieval date; no updated search is incorporated in this chapter.

The findings acquired encompass results of annual scientific output, the citation status over time, a triadic relationship graph illustrating connections between research topic-author-keywords, authors deemed most pertinent to the research area, local authors with the highest citation counts, the contribution of different countries to the scientific output in this field, the most commonly utilized keywords, and an analysis of prevalent research trends through methods such as clustering graphs based on topic similarities and constructing a conceptual map using words from research titles.

BIBLIOMETRIC FINDINGS AND DISCUSSION

The retrieved dataset contains 63 articles published between 1987 and the search date in 2024, involving 196 authors. Three articles were single-authored. The reported annual growth rate was 0%, although annual output fluctuated. International co-authorship accounted for 4.762% of documents. This percentage describes the share of internationally co-authored publications in the collection; it does not support characterising international collaboration as high.

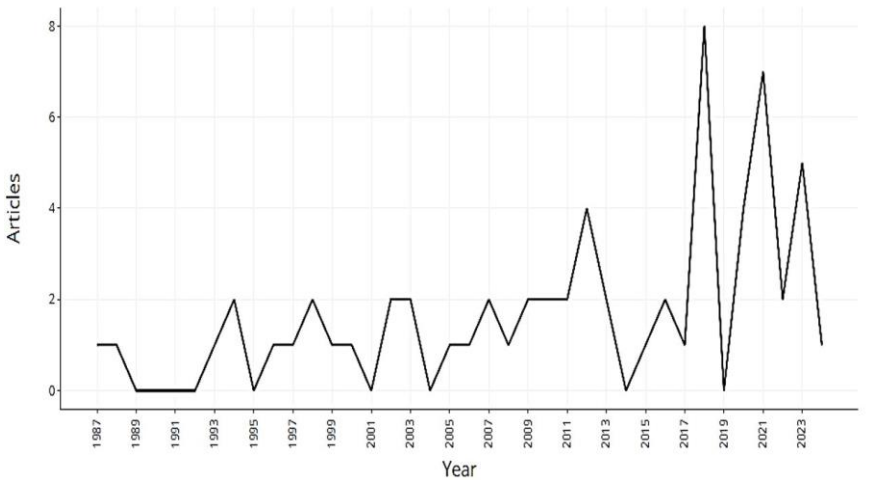
The dataset contains 158 distinct keywords and 1,133 cited references. Articles received an average of 13.76 citations at the time of data retrieval. These measures describe the terminology, reference base and citation visibility of the retrieved publications.

Citation counts require cautious interpretation because they are influenced by publication age and citing practices (Bornmann & Daniel, 2008).

Annual Scientific Production

Annual scientific production fluctuated between 1987 and the search date in 2024 (Figure 1). Output was generally low in the early years, with more pronounced peaks in later years. The highest annual output occurred in 2018, and another peak was observed in 2021. The fluctuations describe the timing of publications in the retrieved dataset. Experimental duration and changes in research funding cannot be inferred from annual publication counts. The 2024 output covers only the period up to 6 May.

Figure 1. Annual scientific production



Source: Author's analysis of the Web of Science dataset retrieved on 6 May 2024.

Average Citations per Year

Average citations per year fluctuated across publication years (Figure 2). As displayed in the figure, the highest peak corresponds to 2011, with another prominent peak in 2016. This indicator describes annual citation averages for publications

grouped by publication year; it should not be read as the total citations received by the field in those calendar years. Differences should be interpreted alongside publication age and the number of articles in each group.

Figure 2. Average number of citations to studies by year

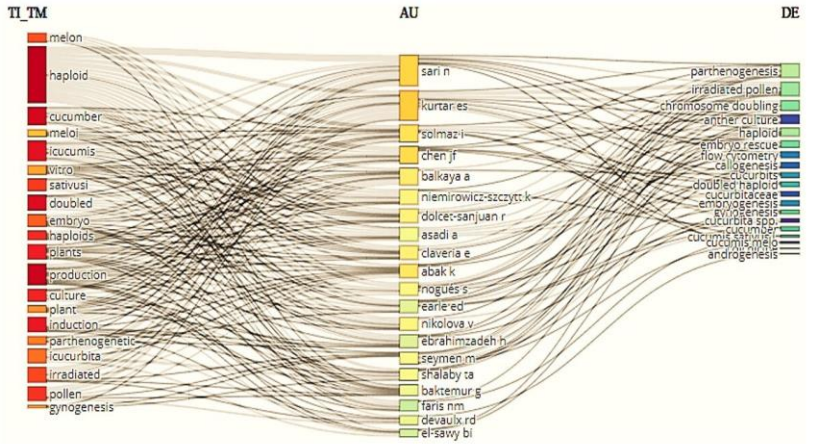


Source: Author's analysis of the Web of Science dataset retrieved on 6 May 2024.

Relationships between Title Terms Authors and Keywords

The three-field plot links terms extracted from titles (TI_TM), authors (AU) and author keywords (DE) (Figure 3). Terms such as "haploid", "cucumber", "production", "embryo" and "irradiated" connect the retrieved publications with their contributing authors and research topics. Sarı N., Kurtar E.S., Chen J.F. and Solmaz İ. have prominent connections in this plot. Keywords including "parthenogenesis", "anther culture", "gynogenesis" and "flow cytometry" indicate attention to haploid induction techniques and ploidy assessment. The plot helps identify associations within the dataset, but the links alone do not demonstrate experimental success, research quality or direct collaboration between authors.

Figure 3. Three-field plot linking title terms (TI_TM), authors (AU) and author keywords (DE)

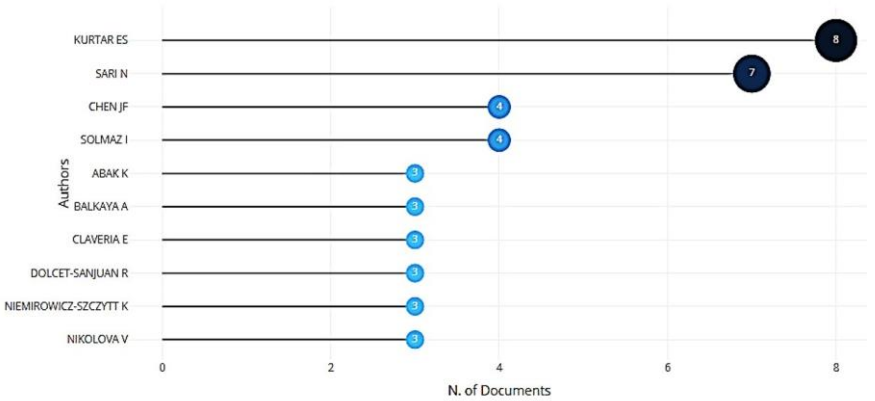


Source: Author's analysis of the Web of Science dataset retrieved on 6 May 2024.

Contributing Authors and Local Citation Impact

Within the retrieved dataset, Kurtar E.S. contributed the most articles (8), followed by Sarı N. (7). Chen J.F. and Solmaz İ. each contributed 4 articles (Figure 4). These counts describe publication output within the selected collection.

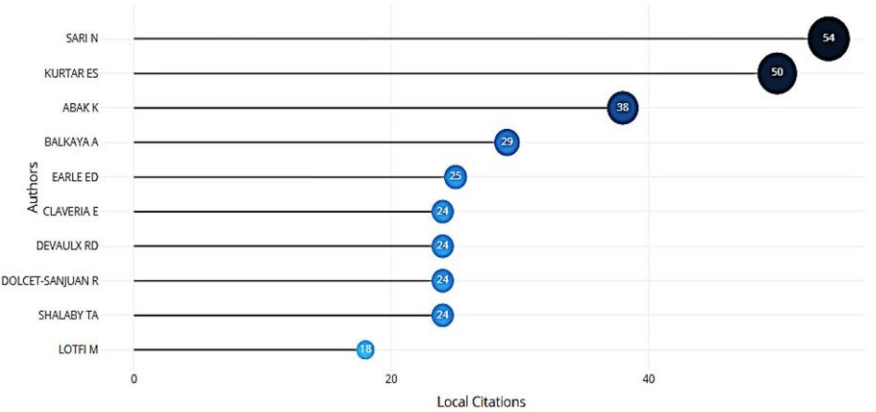
Figure 4. Most relevant authors



Source: Author's analysis of the Web of Science dataset retrieved on 6 May 2024.

Among the authors with the highest local citation counts, Sarı N. received 54 citations, followed by Kurtar E.S. with 50, Abak K. with 38 and Balkaya A. with 29 (Figure 5). Local citation counts refer to citations within the analysed collection and should be distinguished from an author's total citations across databases.

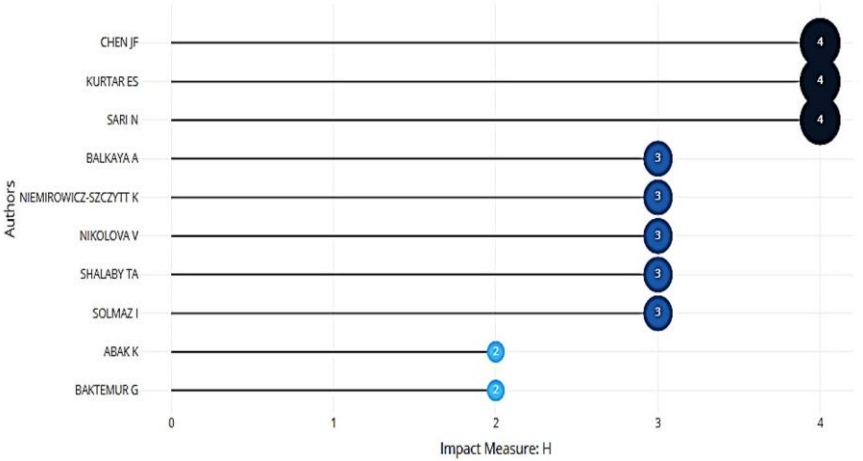
Figure 5. Most local cited authors



Source: Author's analysis of the Web of Science dataset retrieved on 6 May 2024.

The h-index combines publication and citation counts (Subhani et al., 2012). Within this dataset, Chen J.F., Kurtar E.S. and Sarı N. each had an h-index of 4 (Figure 6). Balkaya A., Niemirowicz-Szczytt K., Nikolova V., Shalaby T.A. and Solmaz İ. each had an h-index of 3. These are dataset-specific values and should not be interpreted as the authors' overall career h-indices or as direct measures of research quality.

Figure 6. Authors' h-indices within the analysed dataset

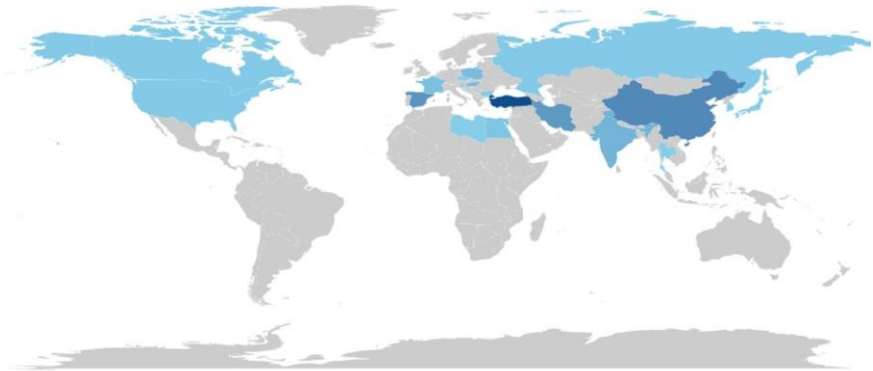


Source: Author's analysis of the Web of Science dataset retrieved on 6 May 2024.

Geographical Distribution of Scientific Production

The geographical distribution of scientific production is shown in Figure 7. Turkey is the most prominent contributor in the displayed distribution, while China and India also contribute substantially. Spain and the USA are represented as well. These findings describe the geographical distribution of the retrieved publications. The map alone does not explain the roles of climate, research infrastructure or financial support in determining national output. Such explanations would require additional evidence.

Figure 7. Geographical distribution of scientific production in the retrieved dataset



Source: Author's analysis of the Web of Science dataset retrieved on 6 May 2024.

Frequently Used Keywords

Frequently used keywords are visualised in the word cloud in Figure 8. Word size reflects frequency in the analysed keyword field (Kulevicz et al., 2020). "Induction" and "plants" are the largest terms. "Plants" is a broad descriptor, whereas "induction" is more closely related to the initiation of embryo formation in this research context. Relevant experimental factors include explant selection, temperature treatments, medium composition and culture conditions (Gałązka & Niemirowicz-Szczytt, 2013; Kurtar & Seymen, 2021). Keyword frequency indicates attention to a topic and does not measure the effectiveness of a technique.

The terms "pollen" and "embryos" are also prominent. Pollen-related terminology may refer to irradiated pollen techniques as well as male gametophyte culture; the word cloud alone does not distinguish their relative contributions. The frequency of "embryos" is consistent with the emphasis on embryo formation in the retrieved literature.

The terms “gynogenesis”, “androgenesis” and “irradiated pollen technique” identify approaches to haploid production. Gynogenesis and androgenesis involve female and male gametophytic pathways, respectively (Demirel & Onus, 2021; Nyirahabimana & Solmaz, 2022). In melon, Sauton and Dumas de Vaulx (1987) obtained haploid plants through gynogenesis induced by irradiated pollen. Hooghvorst and Nogués (2020) discuss irradiated pollen approaches across cucurbit species. The occurrence of “watermelon” and “muskmelon” in the word cloud identifies species represented in the dataset; keyword frequency alone does not establish their status as model species.

Figure 8. Word cloud of frequently used keywords



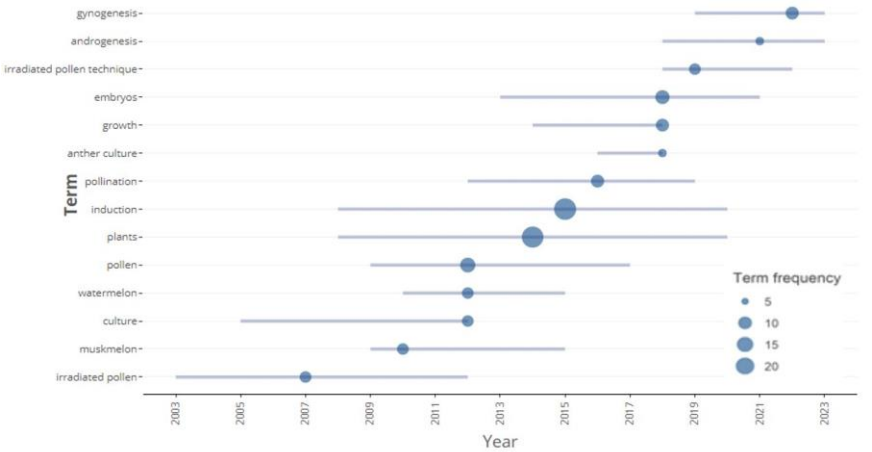
Source: Author’s analysis of the Web of Science dataset retrieved on 6 May 2024.

Research Topics over Time

The trend-topics plot displays the timing and frequency of selected terms in the dataset (Figure 9). Years appear on the horizontal axis and terms on the vertical axis; dot size represents

term frequency. This representation helps describe changes in terminology over time (Duan & Zhu, 2020).

Figure 9. Timing and frequency of selected research terms

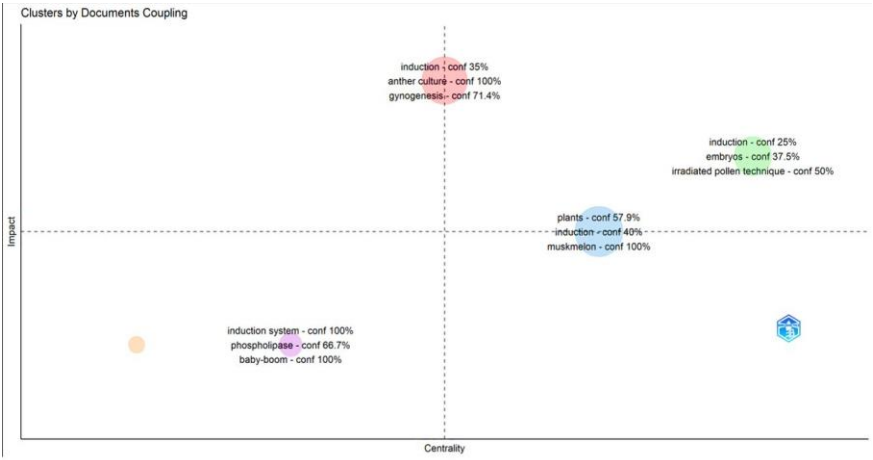


Source: Author's analysis of the Web of Science dataset retrieved on 6 May 2024.

The trend-topics plot places "gynogenesis" and "androgenesis" among terms represented in more recent publications. "Irradiated pollen technique", "irradiated pollen" and "pollination" reflect related terminology that should be considered together when interpreting research directions. The presence of "embryos" and "induction" highlights the continuing focus on embryo formation. Embryo induction and development are central issues in haploid production (Jacquier et al., 2020). However, the timing of keyword occurrences should not be interpreted as proof that a technique has become more effective or that another technique has been abandoned.

Thematic Relationships among Publications

Figure 10. Document coupling clusters and their centrality and impact



Source: Author's analysis of the Web of Science dataset retrieved on 6 May 2024.

The document-coupling map groups publications according to shared references and labels the resulting clusters using associated terms (Figure 10). The horizontal axis represents centrality and the vertical axis represents the impact indicator used in the displayed analysis. The map provides a relative view of thematic relationships within the retrieved dataset; cluster positions are not direct measures of experimental performance.

The pink cluster near the upper centre contains "induction", "anther culture" and "gynogenesis". These terms identify a group of related publications concerned with haploid induction approaches. Its position suggests connections with the wider collection and a relatively high value of the displayed impact indicator. The cluster does not establish that these techniques have equivalent efficiencies across cucurbit species.

The green cluster in the upper-right area includes “induction”, “embryo” and “irradiated pollen technique”. Its position indicates relatively high centrality and impact within this analysis. Hooghvorst and Nogués (2020) review irradiated pollen techniques and their limitations in cucurbits; their publication is not an original experiment demonstrating embryo induction. Bibliometric prominence should be distinguished from species-specific experimental performance.

The blue cluster in the lower central area includes “plants”, “induction” and “muskmelon”. It has a lower value of the displayed impact indicator than the upper clusters. In the literature listed in this chapter, Sauton and Dumas de Vaulx (1987) reported haploid melon plants through gynogenesis induced by irradiated pollen, while Yetisir and Sari (2003) examined chromosome doubling in haploid muskmelon. These publications illustrate distinct stages of haploid and doubled haploid production.

The lower-left cluster contains “induction system”, “phospholipase” and “baby-boom”. These labels identify a molecular dimension of the retrieved literature, but do not demonstrate that the corresponding mechanisms have been functionally validated for haploid induction in cucurbits. Feng et al. (2023) review genetic transformation and gene editing in cucurbit crops. Hooghvorst and Nogués (2020) discuss pollen-specific phospholipase-related induction in cereals and opportunities for haploid inducer systems in cucurbits. Evidence from other crop families should therefore be distinguished from results obtained in cucurbit species. The cluster’s position alone does not establish whether these topics are emerging or declining.

CONCLUSIONS AND RESEARCH PERSPECTIVES

This chapter assessed 63 articles on haploid research in *Cucurbitaceae* retrieved from Web of Science databases. Annual

publication output fluctuated between 1987 and the search date of 6 May 2024, with peaks in 2018 and 2021. These patterns provide a historical description of the retrieved literature rather than evidence of experimental duration or research investment.

The dataset contained 158 distinct keywords. Frequent terms such as “induction”, “plants” and “embryos” reflect attention to embryo formation, while “gynogenesis”, “androgenesis” and irradiated pollen terminology identify the main methodological topics represented in the analysis.

Kurtar E.S. and Sarı N. were the most productive authors in the retrieved collection. Turkey, China and India were prominent contributors to its geographical distribution. Author and country indicators describe contributions within the search results and should not be generalised beyond this dataset.

Molecular approaches provide a research direction for further examination alongside culture conditions and genotype-dependent responses. Their potential contribution should be assessed using species-specific evidence and outcomes that distinguish embryo induction, plant recovery, ploidy confirmation and the production of usable doubled haploid lines.

The scope of the search is a limitation: results depend on database coverage, the selected search fields and terms, and the retrieval date. The dataset is limited to 63 records retrieved on 6 May 2024, and subsequent publications are outside the analysis. Species-specific search terms and alternative haploid-related terminology were not incorporated through a new search in this chapter. The findings therefore provide a historical overview of this collection rather than an exhaustive or updated inventory of cucurbit haploid research.

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CHAPTER 2

DETERMINATION OF GROWTH AND DEVELOPMENT TRAITS OF SOME TOMATO (*Solanum Lycopersicum* L.) GENOTYPES COLLECTED FROM BLACK SEA REGION (TÜRKİYE) IN GREENHOUSE[1]

ANDAÇ KUTAY SAKA[2]
HARUN ÖZER[3]

Introduction

Tomato is an important vegetable of great importance for human nutrition and is the second most cultivated vegetable in the world after potato. Tomato is the most important horticultural crop of the Solanaceae family in the world in terms of cultivated area (5.12 million hectares) and total production of about 190 million

[1] This study was presented as an oral presentation at the 5th International Conference on Food Technology & Nutrition, Tetovo, North Macedonia (7-8 May 2025) and was published as an abstract in the conference proceedings book.

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tons) (FAO, 2026). Besides its high yield and ability to adapt to a variety of climates, from open fields to under cover, tomatoes are also rich in health-promoting compounds such as lycopene, β-carotene, vitamin C and flavonoids. (Borguini and Ferraz Da Silva Torres, 2009; Haraira et al., 2022).

As a nutrient, tomatoes contribute significantly to human nutrition and are an important source of vitamins A, B and C, which have proven health benefits such as stimulating gastric secretion and purifying the blood (Gojiya et al., 2022; Ibrahim et al., 2023). If the definition of local varieties is made, they are dynamic populations of crops that have different plant characteristics, are mostly genetically different from each other, have not been subjected to plant breeding, have adapted to the environmental conditions in the area where they are grown locally, are integrated with the traditional agricultural system, have a historical background and are cultivated (Camacho Villa et al., 2005).

Plant genetic resources encompass modern cultivars, breeding lines, genetic stocks (defined as cultivars or lines with one or more specific traits), landraces, ecotypes, traditional varieties, and wild relatives of cultivated plants. Although our country is not the native homeland of many vegetables, it boasts significant plant diversity. Numerous tomato genetic resources are cultivated here. However, research on their phylogenetic relationships remains limited. Recognizing the importance of genetic diversity in tomatoes, local populations have gained prominence to enhance genetic variation within tomato species, leading to increased emphasis on such studies in recent years.

In tomato breeding studies, knowing the variation of genotypes in the gene pool from which parents are selected is an important factor affecting success. Local varieties are of great importance as they represent the gene pool that can be used in breeding programs to develop new tomato varieties with desired

characteristics. Local varieties also help preserve the cultural and agricultural heritage of a region.

In recent years, researches in our country have gained momentum on the identification of candidates with cultivar characteristics by collecting local tomato genotypes (Henareh and Dursun, 2015; Öztürk, 2022; Saka, 2023). With such studies, starting materials for the breeding of varieties suitable for fresh consumption (fresh) and industry (for tomato paste, canned food, etc.) can be obtained in tomato cultivation.

The study of growth and development characteristics of tomato (*Solanum lycopersicum*) genotypes is of critical importance for the preservation of genetic diversity and the success of breeding programs. Recent studies emphasize the necessity of investigating the adaptation abilities of tomato genotypes collected from different geographical regions, particularly to climate change and environmental stress conditions, for sustainable agriculture. In this context, phenotypic evaluations conducted under controlled greenhouse conditions allow the true potential of genotypes to be revealed by minimizing the effect of environmental variables (Elazazi et al., 2024; Sinha et al., 2026).

Evaluating the growth and developmental characteristics of tomato genotypes under controlled greenhouse conditions provides a reliable approach to minimize environmental variability and allows for precise phenotypic assessment. Such evaluations are critical for selecting promising genotypes that exhibit desirable traits such as enhanced vegetative growth, efficient resource use, and favorable developmental timelines. This study aims to characterize selected tomato genotypes collected from the Black Sea region by determining key growth parameters and developmental traits in a greenhouse setting. The findings are expected to contribute valuable knowledge that supports genetic improvement efforts and promotes

sustainable tomato cultivation practices tailored to the region's specific environmental conditions.

Investigation of the growth parameters and developmental characteristics of tomato genotypes in greenhouse conditions enables the objective comparison of criteria such as leaf area, plant height, flowering time, and fruit ripening period. These studies reveal agronomic performance differences among genotypes, providing a scientific basis for selection and breeding programs (Bayomi et al., 2020; Chowdhury et al., 2023; Ismaeel, 2018; Yunandra et al., 2025).

The Black Sea region of Türkiye, with its high humidity, temperate climate, and unique soil structure, harbors significant diversity among tomato genotypes. Determining the growth and development characteristics of genotypes collected from this region forms the basis for developing region-specific breeding material. In addition, evaluating the adaptability and yield potential of these varieties is of strategic importance for increasing the resilience of regional agriculture and improving product quality. The aim of this study was to determine the growth and development performance of some local tomato genotypes collected from the Black Sea Region under greenhouse conditions.

Material and Methods

This study was conducted in a plastic greenhouse (40° 58' 0.3" N, 37° 56' 33" E, and 8 m above sea level) located on the Research and Application Farm of Ordu University Faculty of Agriculture, with dimensions of 7.5 m in width, 7.5 m in length (56.25 m^2), and 3 m high (Figure 1). In the study, four different tomato genotypes cultivated for many years by farmers in the region and one commercial tomato cultivar were used (Table 1).

Table 1 . Local tomato genotypes and commercial tomato cultivar used in the study

Code	***Variety name***	***Seed company***	***Packaging date***
G1	Rio Grande	İstanbul Seed company	January 2024
Code	***Local labelling***	***Collected province***	***Altitude (m)***
G2	Taşlıçay	Ordu-Gülyalı	80
G3	Artvin-2	Artvin-Merkez	345
G4	Yalıköy	Ordu-Fatsa	10
G5	Çayeli-1	Rize-Çayeli	10

Figure 1 . A view of the plastic greenhouse where the study was carried out



As the commercial tomato cultivar, the standard Rio Grande variety which has a vigorous plant structure, is determinate, resistant to transportation, and is a late-maturing processing variety was selected. The seeds of the tomato genotypes and cultivar used in the study were sown on April 15, 2024, in peat:perlite (2:1) substrates.In the study, tomato plants were grown on raised beds measuring 1 m in width and 6.5 m in length. After soil preparation, well-rotted farmyard manure was incorporated into the soil, and then a drip irrigation system was installed on top of the beds. Before transplanting, mulch (jute material, UV-modified, 100 cm wide) was

laid on the beds. After transplanting, a rooting fertilizer containing amino acids (Safa-mino, Safa Tarım, Türkiye) was applied to the seedlings four times at 5-day intervals to promote root development. Throughout the entire growing period, major cultural practices such as weed control, irrigation, fertilization, pruning, and pest and disease management were carried out. Tomato seedlings belonging to the genotypes and cultivars were transplanted onto the beds on June 7, 2024, with 20 plants from each genotype. For each genotype, 6 plants were designated for observation and measurement, and all observations and measurements during the cultivation period were conducted on these plants.

Morphological Characteristics

After planting, certain morphological characteristics in the plants were determined using descriptors established by UPOV (2025) and IPGRI (1996). The morphological characteristics identified in the study are as follows;

Seedling emergence time: The number of days from sowing to the moment of first emergence was recorded.

%50 Seedling emergence time: The number of days from sowing until at least 50% emergence was observed in each genotype was determined.

Anthocyanin formation in hypocotyls during the seedling stage: (1): present, (2): absent.

Number of days to first flowering: The number of days from transplanting to the time of first flowering was determined.

Number of days to 50% first flowering: The number of days from transplanting until first flowering was observed in at least 50% of seedlings of each genotype was determined.

Plant growth type: (1): determinate, (2): indeterminate

Plant strength: (1): weak, (2): medium, (3): strong

Anthocyanin formation in stem: (1): present, (2): absent

Stem pubescence: (1): absent, (2): sparse, (3): moderate, (4): dense

Leaf attitude: (1): semi-erect, (2): horizontal, (3): semi-drooping, (4): mixed

Leaf blade type: (1): simple, (2): compound

Leaf color: (1): light green, (2): medium green, (3): dark green

Leaf width: (1): tight, (2): medium, (3): wide

Leaf glossiness: (1): weak, (2): moderate, (3): strong

Leaf blistering: (1): weak, (2): moderate, (3): strong

Flower color: (1): yellow, (2): orange

Inflorescence type: (1): simple, (2): compound (double inflorescence), (3): compound (triple inflorescence), (4): mixed

Plant growth and development characteristics

Observations in the study were conducted from the time of seedling transplanting and repeated every 10 days. Some plant growth and development characteristics measured in the study are given below.

Plant height: Plant height in centimeters was determined using a steel tape measure from the soil level at the base of the main stem to the apical growth point.

Stem diameter: Measurements were taken at the midpoint between the first and second internodes on the main stem using a digital caliper sensitive to 0.01 mm.

Leaf number: The number of healthy leaves capable of photosynthesis in tomato genotypes was counted and recorded as the leaf number.

Number of clusters: The number of clusters formed on the tomato plants was counted and recorded.

Leaf area: Leaf area of young and mature leaves for each tomato genotype was determined in cm^2. Leaf area was calculated using the formula reported by Beyhan et al., (2008). The sum of the leaf areas of young and mature leaves was expressed as the total leaf area.

$$LA = 31.6–18.41*(-0.36+1.02*LLL – 0.02*LLL^2) + 2.40*(-0.36+1.02*LLL–0.02*LLL^2)^2+0.45*LLL^2*LLW \quad (1)$$

Stomatal conductance: Stomatal conductance was measured in the afternoon hours (14:00–15:00) using an LI-600 leaf porometer (LI-COR, Lincoln, NB, USA) and is expressed in mol $m^{-2}s^{-1}$ (Jensen et al., 2024).

Photosynthetic rate: The photosynthetic rate in tomato plants was determined with a photosynthesis meter (miniPPM-300, EARS, Delft, Netherlands) (Li et al., 2023). The photosynthetic rate is given in μmol $m^{-2}s^{-1}$.

Chlorophyll index (SPAD): In tomato genotypes, the chlorophyll concentration present in the leaves, measured in the early hours of the day on old, intermediate, and young leaves with a SPAD meter (Konica Minolta SPAD-502, Japan), was expressed as cci (chlorophyll content index) (Li et al., 2023; Saka, 2023).

Data Evaluation

Differences among the means of plant growth and development traits of the genotypes examined in the study were determined by the LSD multiple comparison test at the significance level of $p < 0.05$. Analysis of variance was performed using the JMP statistical software package. Graphs of quantitative traits were prepared in Microsoft Excel and GraphPad Prism 10. Principal component analysis and cluster analysis, using morphological traits along with growth and development traits, were performed with the

PAST 3 software package. For the cluster analysis, the UPGMA paired group and Euclidean similarity index method were used.

Results and Discussion

Descriptive Statistics

Table 2 presents the basic statistical values for the phenological and morphological characteristics of the local tomato genotypes and the control variety examined in the study. In the tomato genotypes examined in the study, seedling emergence occurred on average in 9.8 days, with variability between genotypes ranging from 7 to 12 days (CV=0.19). Emergence of 50% of the seedlings was completed in an average of 13.8 days, with this value ranging between 11 and 16 days (CV=0.13).

Table 2 Descriptive statistics for the phenological and plant growth and development traits of tomato genotypes

Traits	Min.	Max.	Avg.	Std. Dev.(±)	CV
Seedling emergence (day)	7	12	9.8	1.92	0.19
%50 Seedling emergence (day)	11	16	13.8	1.92	0.13
First inflorescence date (day)	7	17	13.8	4.08	0.29
%50 inflorescence date (day)	19	32	27.2	5.26	0.19
Plant height (cm)	70	210	120.3	44.9	0.37
Stem diameter (mm)	7.2	11.0	8.8	1.22	0.13
Leaf number	6	24	11.7	5.05	0.43
Truss number	1.5	5.5	2.4	1.22	0.50
Young leaf area (cm^2)	29.4	357.0	177.0	98.1	0.55
Old leaf area (cm^2)	70.9	798.2	440.3	250.3	0.56
Stomatal conductance (mol $m^{-2}s^{-1}$)	0.12	0.93	0.5	0.23	0.46
Photosynthesis rate (µmol $m^{-2}s^{-1}$)	11	23.5	14.9	3.31	0.22
SPAD (cci)	33.6	63.5	47.2	6.9	0.14

The time to first inflorescence formation was determined as an average of 13.8 days, varying widely from 7 to 17 days among genotypes (CV=0.29). The time at which 50% of the plants reached flowering was recorded as an average of 27.2 days (ranging between 19 and 32 days, CV=0.19). A very high degree of variation was detected among genotypes in terms of plant height; the average plant height was 120.3 cm, varying between 70 and 210 cm, and this trait showed high variability with a CV=0.37. Stem diameter averaged

8.8 mm, ranging from 7.2 to 11.0 mm (CV=0.13). The average number of leaves was determined as 11.7, with this trait varying widely among genotypes between 6 and 24 (CV=0.43). The number of clusters averaged 2.4, ranging from 1.5 to 5.5, and had one of the highest coefficients of variation (CV=0.50).

Distinct differences were observed in leaf area between young and old leaves. Young leaf area averaged 177.0 cm^2 (ranging from 29.4 to 357.0 cm^2, CV=0.55), while old leaf area averaged 440.3 cm^2 (ranging from 70.9 to 798.2 cm^2, CV=0.56); both traits were among those with the highest variability among the parameters examined.

In terms of physiological traits, stomatal conductance averaged 0.5 mol $m^{-2}s^{-1}$ (ranging 0.12–0.93, CV=0.46) and photosynthetic rate averaged 14.9 µmol $m^{-2}s^{-1}$ (ranging 11-23.5, CV=0.22). The SPAD value, an indicator of chlorophyll content, averaged 47.2 cci and ranged from 33.6 to 63.5, making it the trait with the lowest coefficient of variation (CV=0.14). Overall, traits such as leaf area and number of clusters displayed the highest variation among genotypes, whereas traits such as SPAD and seedling emergence time remained relatively more stable; this indicates a rich genetic diversity in the morphological and physiological characteristics of the tomato genotypes studied.

In studies conducted on tomato, heritability levels exceeding 98% have been found for traits such as leaf area, plant height and leaf number, indicating that the difference between genotypes is largely genetic and is little affected by environmental factors (Pavankumar et al., 2025). Similarly, high genotypic and phenotypic coefficients of variation have been found for traits such as yield per plant and flower/fruit number per cluster in another study, and these traits were reported to be efficient for selection (Rasheed et al., 2023).

The CV=0.50 obtained in this study directly corresponds to this finding. This result suggests that this trait may have high potential for breeding or selection. The high CVs (0.55-0.56) in young and old leaf area suggest that leaf area, which is positively correlated with yield, could be prioritized during selection processes (Ene et al., 2022).

That SPAD value had the lowest CV (0.14) suggests that chlorophyll content is a relatively conserved trait among genotypes. This result is consistent with findings that, under stress conditions, morphological traits do not change markedly, but physiological activity (photosynthesis, carbon assimilation) is affected by decreased nitrogen and water. Although physiological traits are more stable among genotypes, they may nonetheless be sensitive to environmental stress (Tripodi et al., 2022).

The moderate level of variation in photosynthesis and stomatal conductance parallels results reported in the literature. Significant diversity in dynamic photosynthetic response has been observed between wild tomato species and cultivated varieties, with some wild species exhibiting more rapid photosynthetic induction than cultivated varieties (Yoshiyama et al., 2024). The results obtained from the current study regarding differences in stomatal conductance/photosynthetic rates among genotypes can be evaluated as a reflection of this genetically based variation.

Morphological Characteristics

Anthocyanin formation was detected in all tomato seedlings belonging to the genotypes and control variety examined in the study. The absence of a difference in anthocyanin formation among genotypes during the seedling stage is thought to be due to its occurrence in wild species. Similarly, flower color was determined to be yellow in all genotypes and in the control variety. Examination of leaf colors in tomatoes showed that 2 genotypes possessed dark

green leaves, and in 2 genotypes the leaf color was medium green. In the plants of the tomato variety, leaf color was determined as dark green. When leaf blistering was examined, one genotype displayed weak blistering, three genotypes moderate blistering, and the commercial tomato variety strong blistering.

The five tomato genotypes examined differed in terms of plant growth type, pubescence, leaf posture, leaf type, pubescence density, and inflorescence structure (Table 3).

The G1 genotype has a determinate growth habit and is characterized by intense pubescence, semi-drooping leaf posture, and pubescent leaf structure. The pubescence density was determined as weak, and the inflorescence structure as solitary.

G2, G3, G4, and G5 genotypes have indeterminate growth habits, and all these genotypes exhibited sparse pubescence and semi-erect leaf posture. In terms of leaf type, G2, G4, and G5 genotypes were pinnate, whereas the G3 genotype differed from the others with its bipinnate (double-pinnate) leaf structure. Regarding pubescence density, G2 and G5 genotypes remained at a weak level, while G3 and G4 genotypes exhibited intermediate to strong pubescence. In terms of inflorescence structure, G3 and G4 genotypes showed uniparous characteristics, while G2 and G5 genotypes had a multiparous (multiflowered) inflorescence structure.

Overall, the G1 genotype is distinctly separated from the other four genotypes by its determinate growth characteristic; among the indeterminate genotypes, differentiation is especially notable in leaf type (the bipinnate structure of G3), pubescence density, and inflorescence structure. These findings reveal the presence of significant morphological diversity among the genotypes examined. In the study, the observation of anthocyanin formation during the seedling stage in five tomato genotypes and the control variety, and the absence of a significant difference among the genotypes, is

consistent with the widespread occurrence of this trait in wild species.

Table 3 Morphological characteristics of tomato genotypes

Genotype	PGT	SH	LA	LT	LG	IT
G1	Determinate	Many	Semi-drooping	Pinnate	Weak	Uniparous
G2	Indeterminate	Few	Semi erect	Pinnate	Weak	Multiparous
G3	Indeterminate	Few	Semi erect	Bipinnate	Medium to strong	Uniparous
G4	Indeterminate	Few	Semi erect	Pinnate	Medium to strong	Uniparous
G5	Indeterminate	Few	Semi erect	Pinnate	Weak	Multiparous

PGT: Plant groth type, SH: Stem hairiness, LA: Leaf attitude, LT: Leaf type, LG: Leaf glossiness, IT: Inflorescence type

Indeed, in morphological characterization studies conducted in tomato and its close relatives, traits such as hypocotyl/stem anthocyanin pigmentation and leaf green color intensity have been reported to be common in most genotypes but variable in intensity; thus, they are considered to be among the characteristics used both in variety identification and in adaptation-related traits (Salim et al., 2020; Reyes-Fuentes et al., 2026).

The fact that flower color is yellow in all genotypes and in the control also aligns with the literature; because in modern tomato materials, petal color is largely fixed and is considered, rather than a distinguishing trait, a species-level descriptive feature (Salim et al., 2020). Differences observed in leaf color and type, as well as the density of trichomes on the plant, are among the significant indicators of inter-genotype morphological diversity in tomato. In various studies, vegetative traits such as hypocotyl pubescence, leaf type (pinnate, potato type, standard, etc.), leaf angle, and leaf dissection degree have been reported to be “diagnostic” features for genotype differentiation, and many genotypes can be distinguished from each other by one or more such features (Salim et al., 2020). Similarly, in this study, the differentiation of genotype G3 from the others by its bipinnate leaf structure coincides with the leaf type-

based differentiation emphasized in the literature regarding morphological distinctness.

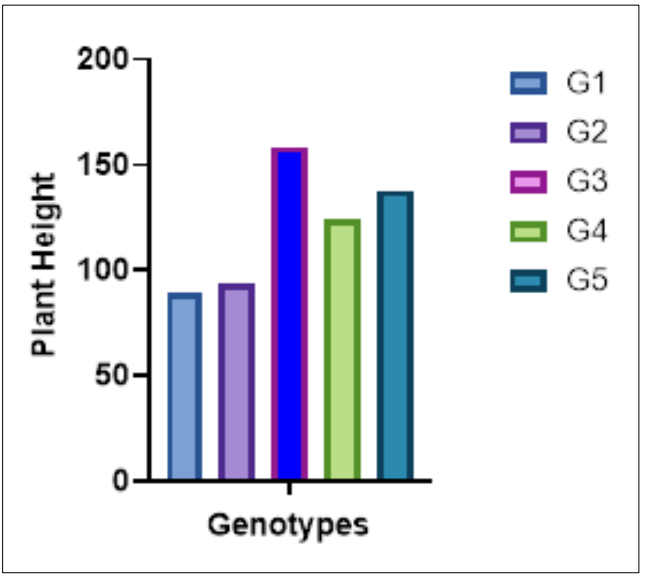
With respect to plant growth habit, the determinate growth of G1 and the indeterminate growth observed in the other four genotypes parallels the architectural variation widely reported in tomato genetic resources. In various morphological and molecular characterization studies, growth habit, due to its association with plant architecture, flowering time, and yield, is treated as a key criterion in genotype grouping (Wang et al., 2009; Anjum, 2020; Tejaswini et al., 2023). In this study as well, the fact that G1 can be clearly distinguished from the others by its growth habit alone supports the diagnostic power of this trait. Regarding inflorescence structure, the differences observed among genotypes in uniparous and multiparous (multi-flowered) arrangements are in harmony with the previously reported tomato inflorescence types (Öztürk, 2022; Saka, 2023). In the current study, the uniparous inflorescence structure of G3 and G4 and the multiparous inflorescence structure of G2 and G5 reflect a similar pattern of variation.

In conclusion, the notable differences found among the five genotypes studied in terms of growth habit, leaf type, pubescence density, and inflorescence structure are consistent with the high morphological diversity in tomato germplasm frequently emphasized in the literature. This diversity constitutes an important resource both for the identification and registration of genotypes and for the selection of parents suitable for different cultivation conditions and breeding objectives (such as plant architecture, yield, and ease of harvest).

Traits of Plant Growth and Developments

When the plant height values of the tomato genotypes were examined, the average plant heights among the genotypes ranged from 88.8 (G1) to 158.3 (G3) cm (Graph 1).

Graph 1 Plant height values for tomato genotypes



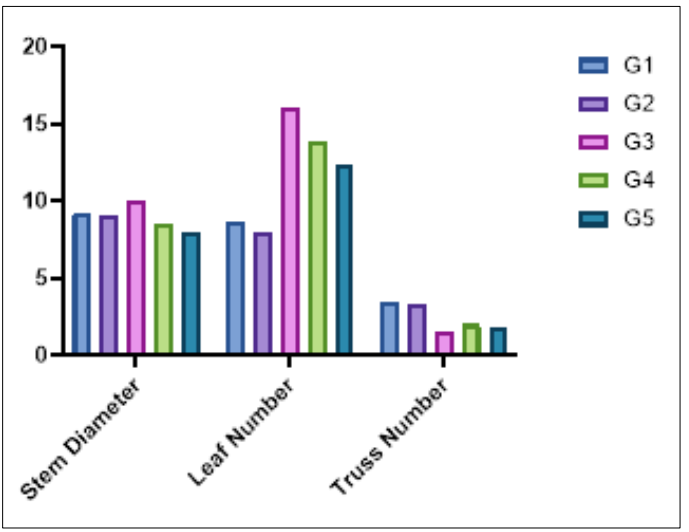
In the literature, growth habit is defined as one of the main determinants of plant height and vegetative development in tomato. Determinate tomatoes are plants with shorter and more compact structure that terminate vegetative growth at a certain height and generally display intensive fruit set in a single flush, whereas indeterminate types are characterized by continued growth, longer vegetative stems, and continuous flower fruit formation. Therefore, it is reported that indeterminate types generally attain greater plant height and that the vegetative–generative balance differs (Vicente et al., 2015). In addition, the height of the tomato plant can range from approximately 30 cm to well over 2-3 m, depending on environmental conditions and cultural practices; in vine types grown under greenhouse conditions, much greater heights can be achieved with appropriate support and care.

In a study conducted on 19 tomato accessions, plant heights showed significant variation in the range of 98.3-143.3 cm (Yadav et al., 2025).

No statistically significant difference was found in terms of plant height between bush type (G1) and vine type (G2-G5) genotypes in the study. This may be due to all genotypes being grown under greenhouse conditions with similar nutrition and care strategies, which may have balanced out some of the potential differences arising from growth habit, or to the genetic structure of the vine genotypes used. Plant height is associated with a high degree of heritability in many heritability/variance component studies. In one study, a high broad-sense heritability of 98% was reported for plant height (Rasheed et al., 2023).

The stem diameter, leaf number, and truss number traits recorded in the study showed marked differences among genotypes (Graph 2).

Graph 2 . Stem diameter, number of leaves, and number of clusters for tomato genotypes



However, for all three traits, no statistically significant difference was found between genotype means. The highest stem diameter value was obtained from G3 genotype with 10.08, while the lowest value was measured in G5 genotype with 7.92.

G1 and G2 genotypes, with stem diameter values of 9.17 and 9.07, respectively, exhibited similar vegetative performance. When leaf numbers were examined, G3 genotype stood out as having the highest number of leaves with a value of 16.00. This was followed by G4 with 13.83 and G5 with 12.33. The lowest leaf number in the study was recorded in G2 genotype with 8.00.

Truss number exhibited a different trend from the vegetative growth parameters. The G3 genotype, which yielded the highest values for stem diameter and leaf number, had the lowest truss number at 1.50. In contrast, the highest truss number was determined in G1 genotype (commercial variety) at 3.50, with G2 genotype closely following at 3.33. Overall, G3, G4, and G5 genotypes were superior in terms of leaf development, whereas G1 and G2 genotypes showed better performance in cluster formation, a generative parameter.

The fact that the G3 genotype exhibited the highest stem diameter and leaf number in the study reveals that this genotype possesses a strong vegetative growth capacity. Stem diameter is a key trait reflecting the plant's capacity for water and nutrient transport, and it has been reported that plants with thicker stems are more efficient in transporting photosynthetic products. However, vigorous vegetative growth does not always translate into high generative performance. Indeed, despite having the highest stem diameter and leaf number, the G3 genotype produced the lowest number of clusters in the study. This indicates that the physiological balance between vegetative and generative growth in tomato can vary depending on the genotype. Similarly, it has been noted that excessive development of vegetative organs results in photosynthetic products being primarily directed towards shoot and leaf growth, which can, in turn, limit generative processes such as flowering and fruit set (Heuvelink, 1997; Sarlikioti et al., 2011). Although a high leaf number theoretically increases photosynthetic

capacity, it is not by itself an indicator of high yield or generative development. The efficient translocation of photosynthetic products to flowers and fruits is just as important as their production. In the study, the fact that genotypes G3, G4, and G5, despite having a high number of leaves, formed fewer clusters suggests that in these genotypes, the majority of assimilates may have been allocated to vegetative growth. Sarlikioti et al. (2011) reported that an increase in leaf area in tomato supports photosynthesis up to a certain level, but that vegetative growth beyond the optimum can negatively affect light use efficiency and the source–sink balance. Notably, in this study, the commercial variety G1 had the highest number of clusters. Modern commercial tomato cultivars are developed through many years of breeding, not only for high yield but also to achieve balanced growth between vegetative and generative development. Therefore, it is expected that commercial varieties can form more flower clusters despite having fewer leaves.

In determining yield potential in tomato, the number of clusters is one of the most important yield components, and this trait has been reported to have a high degree of heritability and to be relatively less affected by environmental factors (Grandillo and Tanksley, 1996; Foolad, 2007). The fact that the G2 genotype also produced a high number of clusters similar to G1 suggests that this genotype may possess superior features in terms of generative development. Conversely, the low cluster formation of G3 despite its vigorous vegetative growth aligns with the classical “vegetative-generative balance” approach. It is reported that for optimal plant development in tomato, vegetative growth should not become dominant over generative development (Jones, 2007). In particular, it is noted that in plants with excessive stem thickness and leaf development, floral differentiation may be delayed and the formation of initial clusters may be limited.

The results obtained indicate that, rather than being used directly for high yield, local genotypes are important for being evaluated as breeding material with different superior traits. While the G3 genotype may be a valuable parental material in terms of stress tolerance or biomass production due to its vigorous vegetative growth, G1 and G2 genotypes can be considered as candidates for use in yield-oriented breeding programs due to their high cluster formation capacities.

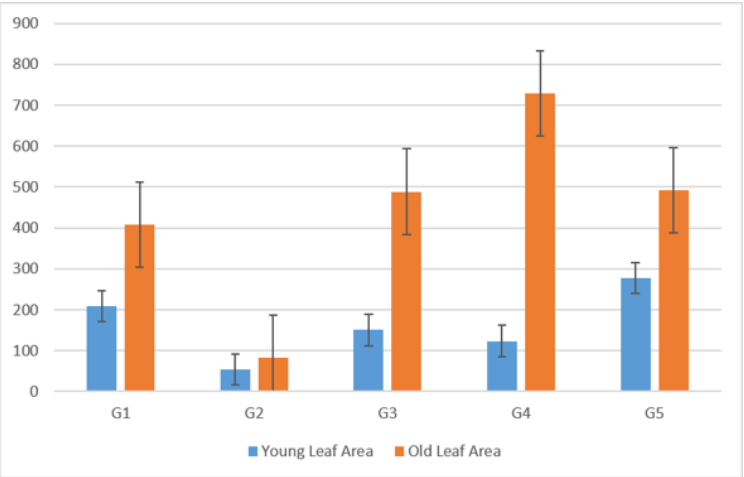
Recent genomic studies also demonstrate that vegetative growth and flowering traits in tomato are controlled by different genetic mechanisms, and that simultaneous selection of these traits provides a significant advantage in new cultivar development (Soyk et al., 2017).

Leaf Traits

In the study, leaf characteristics of tomato genotypes, namely young and mature leaf area, photosynthetic rate, stomatal conductance, and leaf chlorophyll index (SPAD), were determined. When examining the leaf area characteristics, it is apparent that there are distinct differences between the young and mature leaf areas of the five different genotypes (Graph 3). In all genotypes, the mature leaf area was found to have higher values than the young leaf area.

The mean leaf areas of young and old leaves were found to differ significantly among genotypes ($p<0.01$). In terms of young leaf area, the genotype with the highest value was G5 with 277.02, followed by G1 with 208.54 cm^2. The lowest young leaf area was measured in the G2 genotype with a value of 53.34 cm^2. The young leaf areas of the G3 and G4 genotypes were recorded as 150.61 and 123.71 cm^2, respectively. Regarding old leaf area development, it was observed that the highest value was by far in the G4 genotype with 729.24 cm^2.

Graph 3 Leaf area values for young and mature leaves of tomato genotypes



This was followed by the G5 (491.85 cm^2) and G3 (488.61 cm^2) genotypes with very close values, while in the G1 genotype this value was 408.61. As with the young leaf area, the genotype with the lowest old leaf area (83.29 cm^2) was G2. The G2 genotype exhibited the lowest values in both leaf development parameters, making it the genotype with the smallest leaf area. While the G5 genotype reached the highest value in young leaves, in old leaves this superiority passed to the G4 genotype, which produced the largest leaf area value (729.24 cm^2) among all the data.

Mendoza Perez et al. (2022) reported that the leaf area index changes throughout the plant growth and development period. The dominance of G5 at the young leaf stage, but the subsequent superiority of G4 at the mature leaf stage, is a significant detail. Studies examining the development of tomato leaves throughout ontogenesis have shown that leaf shape and size are not fixed traits, that the leaf changes through allometric growth during its own developmental process, and that genotype-specific regulators can act uniformly on all leaves or specifically on leaves at certain

developmental stages (Coneva et al., 2017). This finding supports the interpretation of the reversal in ranking as a genuine biological signal: G5 may initially expand its leaves more rapidly (rapid primary cell expansion), whereas G4 continues expanding its leaf area for a longer duration or reaches a higher final expansion limit; overall, this leads to the largest mature leaf size (729.24 cm^2).

An analysis of the findings in Table 4 revealed no significant differences in photosynthetic rate and stomatal conductance values among the five different genotypes (G1, G2, G3, G4, G5). Regarding photosynthetic rate, the genotype with the highest value was G3, with 15.83 µmol $m^{-2}s^{-1}$. G3 was followed by genotypes G5 with 13.7 µmol $m^{-2}s^{-1}$ and G4 with 12.38 µmol $m^{-2}s^{-1}$, respectively. The lowest photosynthetic rate values were measured in G2 with 9.33 and G1 with 8.88 µmol $m^{-2}s^{-1}$.

When stomatal conductance values are examined, the highest value was again found in genotype G3 (1.01 mol $m^{-2}s^{-1}$). This was followed by G1 with 0.91 and G2 with 0.90 mol $m^{-2}s^{-1}$, which had similar values. The lowest stomatal conductance values were recorded in genotypes G4 with 0.84 and G5 with 0.79 mol $m^{-2}s^{-1}$.

The G3 genotype stood out in both physiological parameters, achieving the highest values in both photosynthetic rate and stomatal conductance. Another notable finding is that, although the G5 genotype had a high photosynthetic rate (13.7 µmol $m^{-2}s^{-1}$), it showed the lowest measured stomatal conductance value (0.79 mol $m^{-2}s^{-1}$). While the lowest photosynthetic rate was observed in the G1 genotype (8.8 µmol $m^{-2}s^{-1}$), the lowest value in terms of stomatal conductance belonged to genotype G5. Studies on interspecific variation between wild and cultivated tomatoes have shown that stomatal characteristics do not differ significantly from each other. This indicates that traits related to photosynthesis are similar (Song et al., 2023).

Table 4 Photosynthesis rates and stomatal conductance values for tomato genotypes

Genotype	Photosynthesis rate (µmol $m^{-2}s^{-1}$)	Stomatal Conductance (mol $m^{-2}s^{-1}$)
G1	8.8	0.91
G2	9.3	0.90
G3	15.8	1.01
G4	12.3	0.84
G5	13.7	0.79
LSD	n.s.	n.s.

n.s.: Not significant.

The identification of significant differences in photosynthetic rate among genotypes indicates that carbon assimilation capacity is largely influenced by genetic factors. These differences in photosynthetic capacity may stem from variations in leaf anatomy, chlorophyll content, and stomatal conductance among genotypes. Studies have shown that photosynthetic rate is closely related not only to the utilization of light energy but also to CO_2 diffusion and biochemical carbon fixation capacity (Flexas et al., 2012; Evans, 2013).

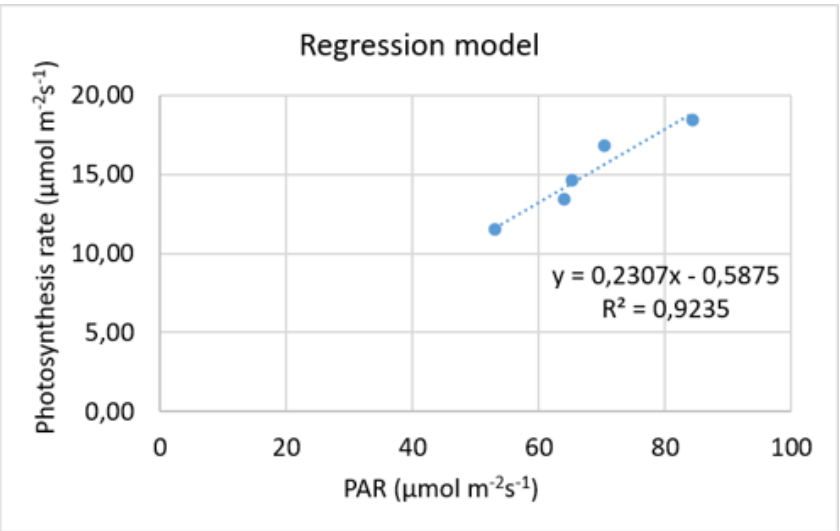
In this study, the fact that the G3 genotype exhibited the highest photosynthetic rate, when considered together with the previously identified high stem diameter and leaf number, supports a robust vegetative growth strategy. Genotypic differences in photosynthetic rate are also associated with stomatal behavior. Stomatal aperture is reported to be a key regulatory mechanism between photosynthesis and water use efficiency and can exhibit significant differences among genotypes (Lawson and Blatt, 2014; Flexas et al., 2014).

In recent years, studies conducted on the tomato genome have also shown that photosynthetic capacity is controlled by numerous quantitative trait loci (QTL). The cooperation of genes regulating leaf development, chloroplast functions, and carbon metabolism leads to significant photosynthetic differences among genotypes (Simkin et al., 2019). Therefore, the G3 genotype

identified in the study as having high photosynthetic capacity can be considered a valuable genetic material, especially for breeding programs aimed at biomass production or stress tolerance.

The relationship between photosynthesis rate and photosynthetically active radiation (P) was determined in tomato genotypes grown in greenhouse. The degree of relationship (r^2) between photosynthesis rate and photosynthetically active radiation was 0.92 (Graph 4).

Graph 4 The Regression Relationship Between Photosynthesis Rate and Par in Tomato Genotypes

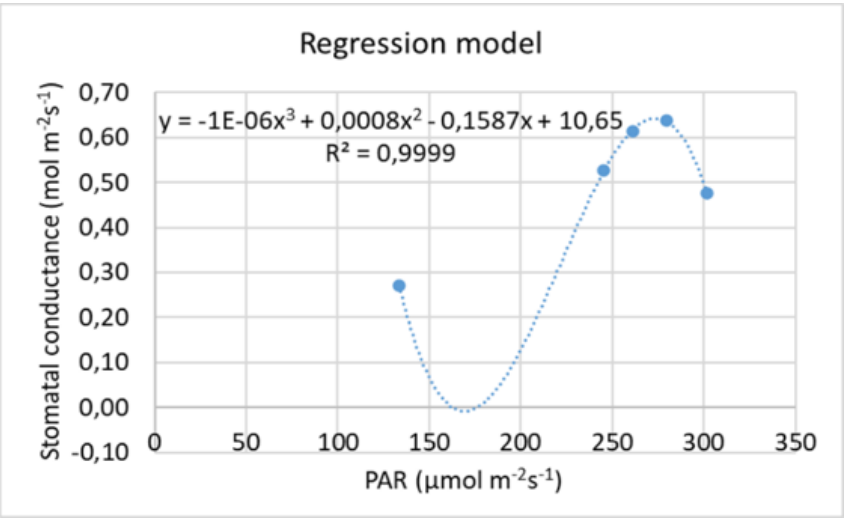


A high regression coefficient indicates that the variation in photosynthetic rate in the genotypes studied is largely explained by PAR. This finding is consistent with many studies examining the relationship between light intensity and photosynthesis in tomato.

The regression model successfully explains the light use efficiency of the genotypes within the examined PAR range. The relationship between stomatal conductance and photosynthetically active radiation (PAR) was determined in tomato genotypes grown

in greenhouse. The degree of relationship (r^2) between stomatal conductance and photosynthetically active radiation was 0.99 (Graph 5). When the model is examined, the resulting regression analysis reveals that stomatal conductance increases in a light-sensitive manner at low and moderate PAR levels, and after reaching an optimum level, it tends to show a slight decrease due to regulatory mechanisms aimed at maintaining water use efficiency. When SPAD findings are examined, it is seen that there are differences among the SPAD values of the five different genotypes (G1, G2, G3, G4, G5), but no statistically significant differences were found between the means.

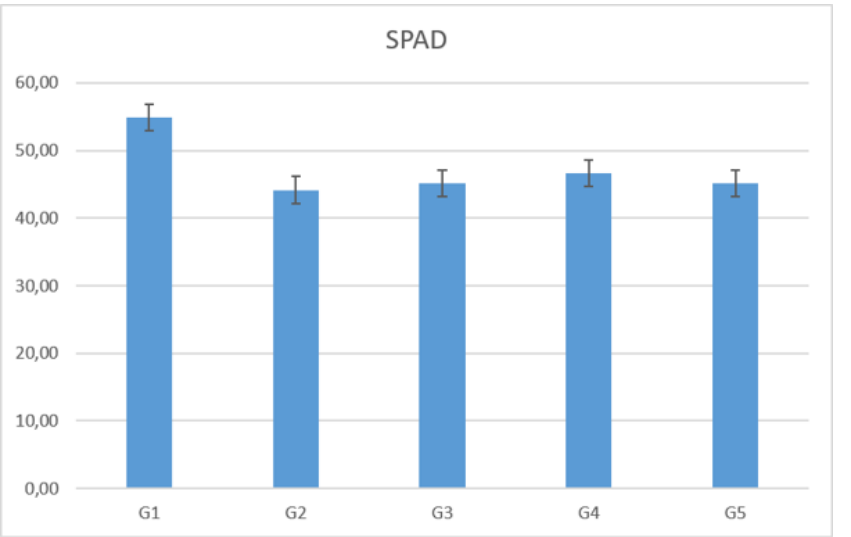
Graph 5 The Regression Relationship Between Stomatal Conductance and Par in Tomato Genotypes



Among the SPAD values, the genotype with the highest value was clearly G1, with 54.92 cci. Genotype G4 follows G1 with a SPAD value of 46.63 cci. In genotypes G3 and G5, the SPAD value was measured to be exactly the same (45.13 cci). The lowest SPAD value was recorded in genotype G2 with 44.17 cci (Graph 6). With its measured SPAD value, genotype G1 stood out from all other genotypes by exhibiting the highest value. While G3 and G5 shared

the same value, G2 was the genotype with the lowest value for this parameter within the group. Although SPAD measurements in tomato are considered a reliable indicator of leaf nitrogen status and total chlorophyll content, on their own they do not fully explain photosynthetic capacity or yield performance (Uddling et al., 2007). Despite the fact that the G1 genotype had the highest SPAD value, its being one of the genotypes with the lowest photosynthetic rate shows that high chlorophyll content does not always correspond to a high photosynthetic rate and that this may be influenced by different physiological factors (Evans, 2013).

Graph 6 SPAD values for tomato genotypes



The lack of a statistically significant difference between SPAD values also suggests that the genotypes may have similar nitrogen use efficiencies.

SPAD measurements are particularly strongly correlated with leaf nitrogen concentration, and chlorophyll differences between genotypes may remain limited in plants grown under sufficient nitrogen conditions (Uddling et al., 2007). Therefore, in the present study, the fact that all genotypes were grown under similar

cultivation conditions may have contributed to the variation between SPAD values not reaching a statistically significant level.

Principal Component and Cluster Analysis

The eigenvalues of all principal components are greater than 1. PC 1 and PC 2 have high variance (%39.5 and %30.7). 2 principal component axis explained about %71 total of variance (Table 5).

Table 5 Main coordinates obtained as a result of principal component analysis in tomato genotypes

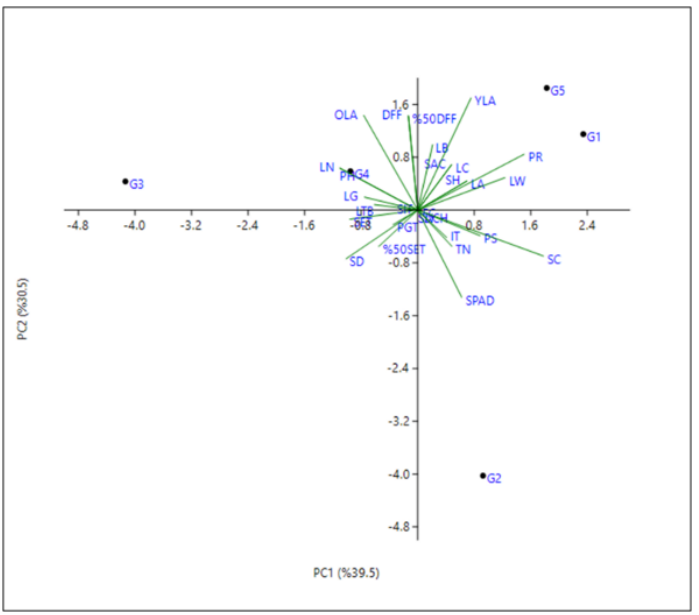
Traits	PC 1	PC 2	PC 3	PC 4
DFF	-0,09	0,90	-0,22	0,36
%50DFF	-0,09	0,90	-0,22	0,36
SET	-0,87	-0,11	0,39	0,28
%50SET	-0,40	-0,35	0,69	0,49
PGT	-0,50	-0,28	0,82	0,02
PS	0,63	-0,24	0,61	-0,41
SAC	0,56	0,71	0,09	-0,43
SH	0,50	0,28	-0,82	-0,02
LA	0,50	0,28	-0,82	-0,02
LT	-0,88	0,10	-0,20	0,42
LC	0,56	0,71	0,09	-0,43
LW	0,94	0,33	0,03	0,00
LB	0,19	0,79	-0,58	-0,08
LG	-0,88	0,20	0,04	-0,42
IT	0,48	-0,43	0,63	0,44
PH	-0,84	0,43	0,28	0,18
SD	-0,57	-0,36	-0,71	0,19
LN	-0,84	0,43	0,28	0,18
TN	0,57	-0,57	-0,60	0,07
YLA	0,42	0,84	0,17	0,29
OLA	-0,43	0,71	0,35	-0,44
SC	0,87	-0,30	0,32	0,22
PR	0,84	0,42	0,29	0,17
SPAD	0,44	-0,83	-0,32	0,09
Variance	39.5	30.7	21.6	8.1
Total variance	39.5	70.2	91.9	100
Eigen value	6.92	6.37	3.79	1.41

DFF: Day to first flowering, %50DFF: %50 Days to flowering, SET: Seedling emergence time, %50SET: Seedling emergence time, PGT: Plant growth type, PS: Plant strength, SAC: Stem anthocyanin formation, SH: Stem hairiness, LA: Leaf attitude, LTB: Leaf type, LC: Leaf colour, LW: Leaf width, LB: Leaf blistering, LG: Leaf glossiness, IT: Inflorescence type, PH: Plant height, SD: Stem diameter, LN: Leaf number, TN: Truss number, YLA: Young leaf area, OLA: Old leaf area, SC: Stomatal conductivity, PR: photosynthesis rate, SPAD: Chlorophyll index, PC: Principal component

The eigenvalue of PC 1 is 6.92 and it alone explains 39.5% of the total variance (Graph 7). The traits with the highest positive loadings on this component are, in order: leaf width (LW, 0.94),

stomatal conductance (SC, 0.87), photosynthetic rate (PR, 0.84), plant vigor (PS, 0.63), number of clusters (TN, 0.57), stem anthocyanin content (SAC, 0.56), and leaf color (LC, 0.56). In addition, stem pubescence (SH, 0.50) and leaf attitude (LA, 0.50) made a moderate positive contribution.

Graph 7 Principal component 2D biplot graph for growth and development traits of tomato genotypes



The traits most strongly negatively associated with PC 1 are: leaf blade type (LTB, -0.88), leaf glossiness (LG, -0.88), seedling emergence time (SET, -0.87), plant height (PH, -0.84), and number of leaves (LN, -0.84). These are followed by stem diameter (SD, -0.57) and plant growth type (PGT, -0.50).

The eigenvalue of PC 2 is 6.37 and it explains 30.7% of the variance. The cumulative total variance explained by the first two components (PC 1 and PC 2) reaches 70.2%. The traits with the highest positive effects on this component are: days to first flowering (DFF, 0.90), days to 50% flowering (%50DFF, 0.90), young leaf area

(YLA, 0.84), and leaf blistering (LB, 0.79). Stem anthocyanin content (SAC, 0.71), leaf color (LC, 0.71), and old leaf area (OLA, 0.71) are also among the strongly positive traits. The main trait distinctly negatively associated with PC 2 was chlorophyll index (SPAD, -0.83). Number of clusters (TN, -0.57) and inflorescence type (IT, -0.43) also had negative loadings on this component.

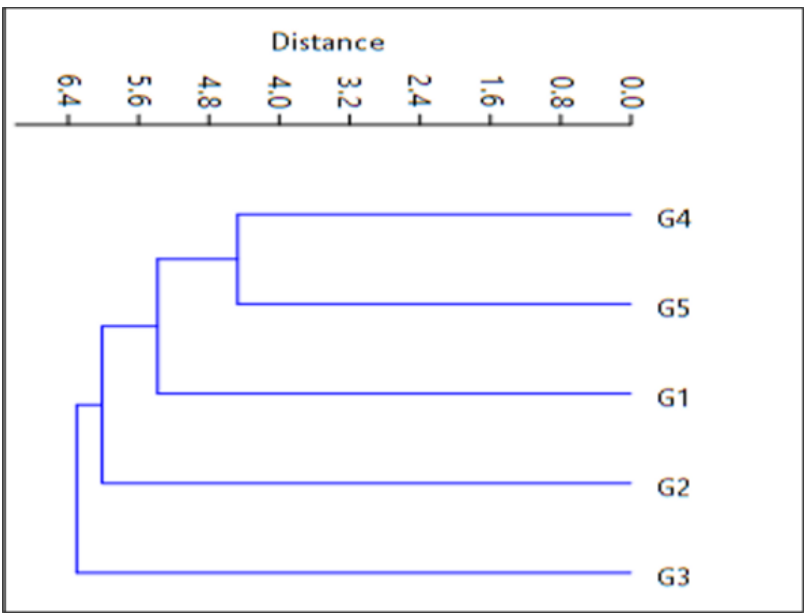
The fact that the first two principal components explain approximately 70% of the total variance indicates that the evaluated traits successfully represent the differentiation among genotypes. In the characterization of plant genetic resources, the first two or three principal components explaining 60-80% of the total variance demonstrates that PCA has high discriminative power (Iezzoni and Pritts, 1991; Mohammadi and Prasanna, 2003). Similarly, in many studies conducted on tomato, it has been reported that the first two principal components explain 55-75% of the total variance, and the 70.2% explained in this study is consistent with the literature (Bhattarai et al., 2016). The results of the PCA indicate that the examined traits cluster into two main groups representing different biological processes. The first axis is mainly associated with photosynthetic performance, stomatal behavior, and vigor, while the second axis represents flowering time and leaf morphology. This separation demonstrates that yield and adaptation in tomato are shaped by the combined effect of numerous physiological and morphological mechanisms.

PCA results indicate that the characters examined are clustered into two main groups representing different biological processes. The first axis is primarily associated with photosynthetic performance, stomatal behavior, and growth vigor, while the second axis represents flowering time and leaf morphology. This separation demonstrates that yield and adaptation in tomato are shaped by the combined effects of numerous physiological and morphological mechanisms. In this study, the fact that the first two principal

components explain 70% of the total variance and the concentration of physiological traits in the first component show that characteristics such as photosynthetic rate, stomatal conductance, and leaf width are strong markers for genotype differentiation. Conversely, the prominence of flowering time and leaf morphology in the second component suggests that phenological adaptation is the second major mechanism driving differentiation among genotypes. Therefore, in future tomato breeding programs, considering not only yield traits but also physiological and phenological traits with high factor loadings in PCA will enable more accurate selection of superior genotypes.

In the clustering analysis based on the morphological criteria and growth and development characteristics examined in the study, G3 genotype alone formed the 1st group. The other 4 genotypes are in the 2nd main group (Graph 8).

Graph 8 Similarity dendrogram resulting from cluster analysis of tomato genotypes



There are 2 subgroups in the 2nd group. While G2 alone is in the first subgroup, G1, G4 and G5 genotypes are in the 2nd subgroup. The commercial tomato variety alone is clustered in the subgroup.

Genotypes G4 and G5 were the most similar to each other and genotypes G3 and G4 were the most distant to each other.

Correlation

The correlations among the traits examined in the study are presented in Table 6. As a result of the correlation analysis, positive and negative relationships at various levels were identified among the traits examined in tomato genotypes.

Table 6 Correlation relationship among the traits examined in tomato genotypes

Traits	DFF	%50DFF	SET	%50SET	PH	SD	LN	TN	YLA	OLA	SC	PR	SPAD
DFF	1.00												
%50DFF	0.99**	1.00											
SET	0.27	0.30	1.00										
%50SET	0.08	0.15	0.94*	1.00									
PH	0.56	0.57	0.09	-0.04	1.00								
SD	0.10	0.18	0.87	0.96**	0.13	1.00							
LN	0.57	0.55	0.28	0.06	0.94*	0.18	1.00						
TN	-0.51	-0.49	0.01	0.20	-0.97**	0.04	-0.95*	1.00					
YLA	0.78	0.76	-0.32	-0.43	0.28	-0.42	0.17	-0.28	1.00				
OLA	0.62	0.52	0.14	-0.21	0.52	-0.25	0.71	-0.65	0.40	1.00			
SC	-0.47	-0.49	-0.84	-0.72	-0.60	-0.77	-0.72	0.50	0.16	-0.38	1.00		
PR	0.08	0.07	-0.71	-0.65	-0.40	-0.71	-0.55	0.35	0.66	-0.15	0.82	1.00	
SPAD	0.37	0.34	0.37	0.30	-0.53	0.10	-0.39	0.55	0.33	0.11	0.02	0.33	1.00

DFF: Day to first flowering, %50DFF: %50 Days to flowering, SET: Seedling emergence time, %50SET: Seedling emergence time, PH: Plant height, SD: Stem diameter, LN: Leaf number, TN: Truss number, YLA: Young leaf area, OLA: Old leaf area, SC: Stomatal conductivity, PR: photosynthesis rate, SPAD: Chlorophyll index, *Correlation is significant at the 0.05 level ($p < 0.05$), **Correlation is significant at the 0.01 level ($p < 0.01$).

A very strong positive relationship (r= 0.99) was found between the number of days to first flowering (DFF) and the time to 50% flowering (%50DFF). DFF also showed a positive relationship with young leaf area (YLA; r= 0.78), old leaf area (OLA; r= 0.62), leaf number (LN; r= 0.57), and plant height (PH; r= 0.56), while it exhibited a negative relationship with truss number (TN; r= -0.51) and stomatal conductance (SC; r= -0.47). A very strong positive correlation (r= 0.94) was also determined between emergence time (SET) and time to 50% emergence (%50SET). It was found that SET had a high positive relationship with stem diameter (SD; r= 0.87),

but showed a strong negative relationship with stomatal conductance (SC; r= -0.84) and photosynthetic rate (PR; r= -0.71). Plant height (PH) had a very strong positive correlation with leaf number (LN; r= 0.94), and, in contrast, a very strong negative correlation with truss number (TN; r= -0.97).

Similarly, a strong negative relationship (r= -0.95) was determined between leaf number and truss number. Stem diameter (SD) showed a very strong positive relationship with time to 50% emergence (r= 0.96) and a strong positive relationship with emergence time (r = 0.87), while showing strong negative relationships with stomatal conductance (SC; r= -0.77) and photosynthetic rate (PR; r= -0.71).

A moderate to high positive relationship (r= 0.66) was determined between young leaf area (YLA) and photosynthetic rate (PR), while a strong positive correlation (r= 0.71) was detected between old leaf area (OLA) and leaf number. Conversely, a negative relationship (r= -0.65) was observed between old leaf area and truss number. Stomatal conductance (SC) showed a high positive correlation with photosynthetic rate (r= 0.82). In addition, SC was found to be negatively related to emergence time (SET; r= -0.84), stem diameter (SD; r= -0.77), time to 50% emergence (%50SET; r= -0.72), leaf number (LN; r= -0.72), and plant height (PH; r= -0.60).

The chlorophyll index (SPAD) showed a moderate positive relationship with truss number (r= 0.55), a moderate negative relationship with plant height (r= -0.53), and weak correlations with other traits. When the correlation relationships among growth and development traits of tomato genotypes were evaluated in general, it was found that particularly strong linear relationships existed among flowering times, emergence traits, plant height, leaf number, and physiological parameters, while truss number was found to have an inverse relationship with most plant development traits. It is to be expected that strong correlations are found between phenological traits and vegetative growth characteristics in studies (Soyk et al.,

2017; Lifschitz et al., 2014). The strong positive relationship identified between plant height and leaf number indicates that plant growth progresses in a coordinated manner. The fact that taller plants produce more leaves is a natural consequence of the simultaneous occurrence of internode development and shoot growth (Jones, 2007). Overall, the findings from the correlation analysis demonstrate that growth, physiological performance, and generative development in tomato genotypes are not independent traits, but rather are shaped by common physiological processes.

Conclusion

The results of the study revealed that genotypes with earlier seedling emergence time and earlier flowering time than the commercial tomato cultivar in the study. The number of truss, which is an important trait that may affect yield, was highest in G1 commercial tomato variety and G2 tomato genotype respectively. Leaf area, which is an important parameter in photosynthesis, gave high values in genotypes (young leaf-G5, old leaf-G4). Genotype G2 had the lowest averages in these young and old leaf area values. Young and old leaf area averages of the genotypes differed significantly ($p<0.05$). Genotype G5 showed high values in stomatal conductance and photosynthesis rate. G5 and G2 genotypes stood out in terms of these two traits which are important for yield. In leaf chlorophyll index (SPAD), the commercial tomato variety had the highest chlorophyll index, followed by genotype G4.

When we evaluate the results of cluster analysis, we can say that G4 and G5 genotypes are very close to each other in terms of morphological criteria and growth and development characteristics. These genotypes are also close to the commercial tomato variety in the study. Genotypes G2 and G3 formed the group in which they were found alone. Especially G3 genotype alone was in the first main group and showed that it was different from the genotypes in the

study in terms of the aforementioned traits. As a result of the study, it was revealed that each genotype has its own characteristic features. While G5 and G2 genotypes stood out in terms of characteristics that may affect yield, G3 genotype was found hopeful in terms of plant growth and development characteristics.

This research was carried out to determine the greenhouse performance of some tomato genotypes whose morphological characteristics, yield and fruit quality characteristics were previously determined under open field conditions. Thus, it is a preliminary study for future yield and fruit quality determination researches in protected cultivation. The main objective of this study is to achieve success in variety development by knowing the characteristics of promising genotypes to be used in breeding studies.

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CHAPTER 3

VITICULTURE IN PAKISTAN

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Introduction

Grapes (*Vitis vinifera* L.), belonging to the family *Vitaceae*, is one of the most extensively cultivated fruit worldwide recognize for its delicious taste and highly nutritional value (Ates et al., 2024; Kunter et al., 2024). Grapes is the earliest domesticated fruit crop in the world, approximately 6000 years ago, between the Black Sea and the Caspian region (Khaliq et al., 2025). Grapes are classified within the berry family due to their cluster development pattern (Karakus et al., 2023; Kaya, 2024). Berries are primarily in the shape of rectangular to globose and utilized in fresh form as table fruit and in the processed form as jam, jelly, wine and juice (Ghasemnezhad et al., 2013). The grapes were utilized in the production of wine (57%), table grapes (36%), and dried grapes (7%) (Atak, 2024). Grapes is one of the highly palatable food that offers numerous nutritional and medicinal advantages to consumers. It is a nutrient-dense berry fruit comprising carbs, fats, vitamin A and potassium (Kaya et al., 2022; Karakus et al., 2023). Numerous phytochemical substances, such as carotenoids, phenolic, and melatonin, are derived from grape skin, juice, and seeds, which possess significant therapeutic properties, including anti-inflammatory, anti-carcinogenic, anti-oxidant and anti-microbial effects. Eating grapes on a daily basis is linked to better cardiovascular health. It is highly advantageous against atherosclerosis because it enhances oxidation. (Khaliq et al., 2025). Grapes are abundantly cultivated crops accounting for around 7.4 million hectares globally, with a total yield of 77.8 million metric tons. China, Italy, Spain, the United States, France, India, and Türkiye are the main producers of grapes. China produces about 16.8 million tons followed by Italy 7.6, Spain 5.4, United States 4.9, France 4.7, India 3.9 and Türkiye 3.5 million tons of annual grape production (FAO, 2026).

Grapes Cultıvatıon in Pakistan

In Pakistan, grape is still considered a minor fruit crop and is ranked 56th internationally with an annual yield of 125.89 thousand tons on 15 200 ha of total area (FAO, 2026). Earlier projections placed production at roughly 66.98 thousand tons of grapes on an area of 15.72 thousand hectares in 2022, with variation in the 60.000-100.000 ton range in prior years (Anjum et al., 2022). In 2023, the country's annual production was about 62.413 tons of grapes, contributing roughly 0.09% to total global output. In Pakistan, approximately 87% of the harvest ends up as fresh table grapes, while the remaining 13% is dried and sold as raisins due to the soft skin of these grape cultivars, making it difficult to transport as fresh (Muhammad et al., 2020).

According to the Planning Commission of Pakistan, Ministry of Planning, Development & Special Initiatives (2020), grape production in Pakistan has historic roots but is still a small-scale commercial activity when compared to commonly grown fruits like mangoes, citrus, and dates. Balochistan province of Pakistan, known as the fruit basket, is the largest grape producing-region with 66.21 thousand tons on an area of 15.59 thousand ha. Production is mainly concentrated in the arid and mountainous regions of Balochistan province, which accounts for more than 70-90% of national output, significantly in districts like Pishin, Quetta, Mastung, Kharan, Killa Abdullah, and Kalat (GOP, 2025). A smaller percentage comes from Khyber Pakhtunkhwa and fewer places in Punjab (Khan et al., 2020). The area under cultivation increased from around 12.5 thousand hectares in 2001-02 to over 15-16 thousand hectares by the mid-2010s, with production growing proportionally from roughly 76.000 to more than 96.000 tons during that period; however, yields have remained poor. The average yield in Pakistan is roughly 4 tons per hectare, which is much lower than the global average of approximately 10-11 tons per hectare, due to traditional farming techniques, water management concerns, variety selection, and post-

harvest issues. Despite these limits, grapes contribute significantly to the local economy of growing regions, largely as fresh table grapes, with some drying into raisins. Historical patterns suggest modest long-term growth (about 0.6% per year since the 1960s), with potential for development through improved cultivars, irrigation, and management approaches (Planning Commission of Pakistan, Ministry of Planning, Development & Special Initiatives, 2020).

Grapes are important to Pakistan's agricultural and economic sectors, especially in the Balochistan region, which produces 90% of the nation's grape yield. Viticulture, a highly profitable cash crop well-suited to the province's arid and mountainous climate, offers essential income diversification and economic support for smallholder farmers in significant regions. Agriculture provides the foundation of Balochistan's rural economy, with horticulture products like grapes generating essential cash income on inadequate soils when growing possibilities are limited. The sector significantly contributes to income production for smallholders by the sale of fresh table grapes and value-added products such as raisins (Muhammad et al., 2020).

Agro-climatic regions in Pakistan

Grape. (*Vitis vinifera* L) is one of the oldest and most significant horticultural perennial crops grown globally for wine and table consumption. It is one of the most lucrative fruit crops in Pakistan, mostly cultivated for table purposes. (Akram et al., 2021). Grapes are among the world's rarest fruits, cultivated from tropical to temperate zones due to their extreme diversification. It is estimated that genus Vitis has more than 100 species, 44 of which are thought to be ambiguous owing to interspecific hybrids (Sajid et al., 2006). It has been reported that in recently developed viticultural regions of the world, including the United States, China, and Australia, as well

as the traditionally viticultural regions in Europe, a small number of varieties are grown as elite cultivars, representing a narrow portion of the grape's germplasm diversity (Wolkovich et al., 2018).

Pakistan is ideal for the adaptation of a wide range of fruits, including grapes, due to its various agroclimatic conditions. Viticulture is practiced in various parts of Pakistan and is becoming increasingly popular among farmers (Munir et al., 2015). In Pakistan grapes are grown over an area of 15.2 thousand ha with annual production of 125.89 thousand tons (FAO, 2026), Baluchistan is the major viticultural region for fruit production, with the rest coming from Khyber Pakhtunkhwa and Punjab (Akram et al., 2020; Muhammad et al., 2020). Baluchistan's major growing areas are Pishin, Quetta, Mastung, Kharan, Killa Abdullah, Kalat, and Ziarat, which are reported to produce approximately 193.176 tons on an area of 15832 hectares, while Punjab produces 7146 tons on an area of 906 hectares and Khyber Pakhtunkhwa grows 1262 tons of grapes on a total area of 144 hectares (GOP, 2025). Pakistan maintained 99.70 % of its import share from Afghanistan during 2008 to 2023 (Wardak et al., 2024). In 2025, Pakistan imports almost 25.712 tons of dried grapes from Afghanistan, Iran, China and Turkiye. It imports 50.9 thousand US dollars (134.314 tonnes) of fresh grapes from Afghanistan to meet year-round local demand (ITC, 2025). Pakistan exports its total of 132 tons of grapes to Kazakhstan, America and Bangladesh in the form of dried grapes (ITC, 2025). Furthermore, due to the day-by-day growing demand for grapes in the country, cultivation of grapes has begun in South Punjab (Feroze et al., 2018).

The climate of Baluchistan is the most favorable for viticulture because of a lack of humidity throughout the ripening season (Anjum et al., 2022). The province demonstrates a natural comparative advantage in terms of agro-ecological characteristics, with well-drained soils, flat plains, and a mountainous subtropical climate with hot weather in the summer and cold in the winter,

making the region suited for producing commercial grape cultivars (Muhammad et al., 2020). If early-grown cultivars are available, grape can be successfully grown in Punjab's agroclimatic conditions (Khan et al., 2011). Monsoon rains are considered one of the biggest issues and difficulties to grape cultivation in Punjab. Monsoon rains during fruit maturation induce berry breaking, cracking, and rotting, which eventually invites various fungal infections. Sugars and high temperatures in the summer give a great environment for fungal growth and development, affecting fruit quality. To overcome the rotting berry issue caused by monsoon rains, early ripening grape varieties should be examined in terms of physical and chemical properties (Akram et al., 2020). Because of the region's ideal temperature conditions, the Potohar area in Punjab province is becoming well-known for the commercial cultivation of early maturity genotypes of grapes. In grapes, early mature cultivars are often selected for low altitude locations, whereas late-maturing varieties are cultivated at high altitude (Sabir et al., 2009). Sultanina, a promising early ripening cultivar with great production potential and good quality, was discovered to be suited to the Pothwar area. Similarly, in subtropical parts of Punjab, early-maturing cultivars are preferred (Anjum et al., 2022). The variety of grapes and crop yield are greatly influenced by the climate of a particular area (Akram et al., 2019). Grapes' quality is determined by their physical and chemical compounds, which is significantly influenced by biotic and abiotic variables (Akram et al., 2020).

Grape growth, productivity, and fruit quality are all significantly impacted by climate, which also has an effect on grape diversity. Climate factors include the temperature, precipitation, wind, light, and humidity of a certain place. Among these criteria, temperature is the most important aspect for economic viticulture. The temperature range of 25-30°C is considered excellent for shoot development and physiological functions (Ramos et al., 2013).

Nevertheless, as a temperate plant, it required less than 10°C for bud bursting and 30-35°C for fruit ripening. Punjab satisfactorily meets these parameters, with temperatures over 2°C in the winter and above 40°C in the summer. Temperature also influences the colour of grapes and their aromas. Rainfall, frost and humidity during the growing season also affect grape quality. Rainfall indirectly influences the sugars, acids, and phenolic contents of berries, but it directly influences vine growth and vigor (Akram et al., 2020). In addition to environmental considerations, grape genotype has significant effects on the chemical composition of grapes. Grape phenology is thought to be a crucial aspect in grape cultivation (Köse, 2014). It is also categorized as a unique crop in phenology, with the most important phenological stages being budburst, bloom, fruit set, and harvest (Pscheidt, 2007). In Pakistan's subtropical regions, grape bud burst after dormancy occurs between the last week of February and the first week of March and the monsoon rains start from early July. There is a need to evaluate early mature cultivars, which will be harvested before the monsoon season to prevent loss of berry rotting and splitting due to rains. Limited information is available on early - maturing grapes germplasm for cultivation in arid subtropical climate of Pakistan where monsoon rain is of serious concern issue in the present scenario.

Grape Varieties in Pakistan

Grape is one of the most lucrative summer fruit crops. It is native to the warm temperate zone between 34 °N (North) and 49 °S (South) latitude. Grape is the oldest and most important perennial fruit crop worldwide. It is represented by about 60 species. It belongs to the genus Vitis. But most of the varieties used for commercial purposes are derived from *Vitis vinifera* L. (Kausar, 2017).

Thousands of distinct varieties of grapes are cultivated all over the world, yet all these varieties can be categorized as European

or American. European grapes have tight skins that stick to the fruit, while the American varieties have loose skin, or slip-skin, that falls off the fruit easily when cut or bitten. Another classification also considers the French-American hybrids as a third category of grape cultivars.

Grapes are categorized into two categories, seedless or seeded. Another way to categorize grapes is by their intended use: table grapes for consumption, grapes used to make raisins, grapes used in commercial goods, and grapes used to make wine or juice. Depending on the market for wine and table grapes, especially Thompson Seedless, some grapes in low quality wine may be sold as table grapes. The choice of variety depends upon a number of factors, including adaptation to a particular area and market demand. Pakistan has around specified grape varieties (Haita, Shandao Khani (also called Sunder Khani), Spin Kishmish, Sra Kishmish, Sahibi, Tor, Hussaini, Shekh Ali, Khal Chini, Kuddak, Askari, Flame seedless, King's Ruby, Black Prince, Tandon, Sara Laal, Spin Laal, grown (largely in Balochistan). Kishmish, Shundokhani, Haita and Sahibi grape varieties are produced in bulk from these varieties. These are sweet and fulfill the local consumer taste. Haita and Sahibi are seeded, while the other two varieties are seedless. Non-traditional varieties like Ruby Red and Pearlet (Perlette) were introduced under an FAO Project, namely Transfer of Fruit Technology in Balochistan, in the 1990s but somehow or the other have not been widely grown, perhaps due to their sour taste. From the USA, a couple of varieties like Atom Red have recently been introduced and are fetching good price as they are early in the season. Since these varieties are suitable for winemaking, it is believed that they will not have a long shelf life in Pakistan. However, it still wouldn't be quite right to make an assessment regarding their future. Pakistani consumers like sweet and seedless grapes. Therefore, Kishmish and Shundokhani are the preferred choices (Balochistan

Agriculture Project, 2021). Commercial grape production is dependent on self-rooted vines; however, there is a growing focus on researching wild germplasm as rootstock to increase resistance to abiotic stress (Nazir et al., 2022).

In Pakistan, only European grapes are grown for consumption. Sunda Khani, Sra Kishmish, Askari, Flame Seedles, and Kings Ruby are the main varieties of grapes used to cultivate in Pakistan and they are worldwide famous for their taste and quality. However, some grapes are seeded, and these are classified based on their growth pattern and the area of cultivation. Haita, Black Prince, Sahihi, Hussaini, and Tando are cultivated in Pakistan (Khan et al., 2020).

Traditional grapevine varieties, including Gola, Haita, Kishmish, Sahibi, Shekhail, and Sundar Khani, have been grown mostly in the Balochistan area of Pakistan (Rafique et al., 2025). An increasing trend of grape cultivation in Pakistan have seen recently (GOP, 2024; Rafique et al., 2025). Early-maturing varieties including Flame Seedless, King's Ruby, NARC Black, Perlette, Sugraone, and Sultanina have improved grape agriculture on Punjab's Pothwar Plateau (Rafique et al., 2021), where they make a significant contribution to regional grape production (Rafique et al., 2025). The pheno-physiological characterization of these cultivars makes them highly suitable in the Pothwar region (Rafique et al., 2023). The most suitable varieties for Potohar are early cultivars that mature before the monsoon. The Potohar area has a lot of potential for grape production because of its favorable climate (Khaliq et al., 2025). However, it remains a neglected region, with little information available on early developing grape germplasm, indicating a need for more focus and scientific investigation. It has a large number of grape germplasms, both native and exotic, but identification and characterization based on morphology and biochemistry are critical for cultivar improvement.

Cultivation Technique in Viticulture

Grape training is very important since the growth pattern of different grape cultivars is different and proper training techniques are very important in controlling vine vigor while maintaining continuous production. The trench system, the Kniffen Trellis System (Fig. 1) and the Y-Trellis System are employed, with the trench system being the most popular due to the low rainfall in Balochistan. These systems are ideal in Balochistan for cultivars with low or moderate vigor. They improve sunlight penetration, air circulation, simplicity of cultural operations, and overall vine maintenance as compared to traditional approaches. Trellis systems are systematically arranged to effectively support the vines, leading to enhanced fruit quality and improved harvest productivity (PHDEC, 2023).

In Balochistan, vines are extensively cultivated on mud walls without any structural reinforcement. Pruning typically occurs in late winter (February-March), yet producers' technical knowledge remains inadequate. Aujla et al. (2011) assert that inadequate pruning and training techniques are significant contributors to diminished yields in Balochistan, potentially resulting in production declines of up to 70% in the absence of effective management.

The new territory areas of Punjab range from a hot, dry environment in the south to subhumid regions in the north; thus, high summer heat and abundant rains provide a significant barrier to grape cultivation (Rafique et al., 2024). To cope with these challenges, heat unit-based phenology models (Rafique et al., 2024) and process-based phenology models, such as STICS (Rafique et al., 2024b), and the grapevine fruit quality model have been developed for this region. Recent research has also focused on improving pruning duration, bud load, and biochemical evaluation for cultivar suitability evaluation (Khan et al., 2026).

Cane and spur-pruning, both cultivars, are cultivated in this region (Rafique et al., 2023). Common trellis systems include vertical (I-shaped) and semi-horizontal (Y-shaped). Furrow and drip irrigation are the two most popular irrigation technologies used in grape cultivation (Khan et al., 2026).

I-shaped and Y-shaped trellis systems are used for viticulture (PHDEC, 2023) (Fig. 2)

Fig 1. Four-cane Kniffen Trellis System

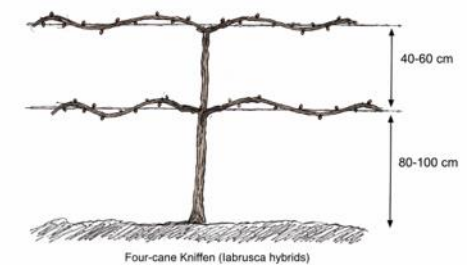


Fig 2. I-shaped and Y-shaped trellis systems





Maintaining Grapevines' health and vigor is vital for gaining higher yields and increased fruit quality. Proper and balanced nutrition through the addition of chemical and organic fertilizers plays a crucial role in this regard.

Table 1 The fertilizer requirements of grapevines vary according to the age of the vineyard

Age of Vine	Farmyard Manure (kg)	Nitrogen (g)	Phosphorus (g)	Potassium (g)
1st year	-	100	150	-
2nd year	150	150	100	5
3rd year & onwards	250	200	150	7

Each year, grapevines should get one full dose of farmyard manure as well as the necessary amount of chemical fertilizer (NPK). Half of the nitrogen and phosphorus doses are provided during pruning, with the remaining half given following fruit set. Typically, the entire potassium dosage is given in the pit during planting. It is vital to highlight that overuse of chemical fertilizers should be avoided because it not only harms soil health but also results in poor fruit quality. As a result, integrated nutrient management combining balanced use of organic and inorganic fertilizers is strongly recommended for sustainable grape production and long-term soil fertility (PHDEC, 2023).

Conclusion

Pakistan possesses great natural potential for grape cultivation but it is highly restricted due to continuous deficiencies in production, post-harvest, storage and marketing systems. Native cultivars of Balochistan offer tremendous commercial potential, but insufficient farm management practices reduce yields substantially below feasible levels. Post-harvest losses averaging 20–24% show serious deficiencies in harvesting processes, packaging standards, and handling techniques. The total absence of cold storage infrastructure and refrigerated transport eliminates access to distant markets and encourages food deterioration. The absence of defined market platforms, pricing information systems, and grading standards also promotes economic vulnerability at the agricultural

level, while contractor-dominated marketing arrangements further deprive producers of equal price realization. Addressing these interconnected difficulties through coordinated investment in post-harvest technology, cold chain expansion, marketing reform, and extension services is vital for unleashing the sector's full productive and export potential.

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CHAPTER 4

EFFECTS OF CLIMATE CHANGE ON SEED QUALITY AND LONGEVITY

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Introduction

Global agriculture is facing increasing pressure to meet the growing food demands of a rapidly expanding world population. According to the United Nations World Population Prospects, the global population is projected to reach approximately 8.5 billion by 2030 and 9.7 billion by 2050 (IPCC, 2013). At the same time, the continued decline in available agricultural land, rapid urbanization, and reductions in the rural labor force are creating substantial challenges for maintaining sustainable food production. Since 1960, the global population has increased at an average annual rate of approximately 1.9%, whereas food production has increased by about 2.8% per year, largely as a result of technological advances

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and improvements in agricultural productivity. However, future increases in demand for food and fiber will require greater production from increasingly limited land, water, and other natural resources. Consequently, improving productivity while simultaneously enhancing resource-use efficiency, environmental sustainability, and the resilience of agricultural systems to climate change has become a major priority for global agriculture (IPCC, 2013).

Over the past five decades, annual yields of major field crops have increased by approximately 1–3% worldwide (Bruins, 2009). These yield gains have primarily resulted from genetic improvements achieved through plant breeding, supported by advances in agricultural inputs and crop management practices (Ceccarelli et al., 2010). Nevertheless, the sustainability of these productivity gains is increasingly challenged by climate change. Changes in temperature regimes, soil and water resources, atmospheric CO_2 concentrations, and the frequency and intensity of extreme weather events can substantially influence crop growth, development, and yield stability (Kurukulasuriya et al., 2019). Although the impacts of climate change on agricultural production are widely recognized, their magnitude and direction may vary considerably among crops, regions, and production systems (Eitzinger et al., 2010). Several studies have emphasized that climate change may adversely affect agricultural productivity and pose a significant threat to global food security, particularly through increased heat and drought stress and greater climatic variability. In contrast, other studies have suggested that technological progress, improved management practices, and the development of climate-adapted crops may enable substantial increases in global crop production without a corresponding expansion of agricultural land (Jaggard et al., 2010; Challinor et al., 2014). Thus, maintaining and further increasing crop productivity under future environmental

conditions will depend largely on the development of crop varieties with enhanced adaptation and resilience to abiotic stresses, highlighting the continuing importance of advances in plant breeding (Ainsworth et al., 2008; Ceccarelli et al., 2010).

Within this context, seed represents one of the most fundamental inputs in agricultural production and serves as the primary biological basis for establishing a productive crop stand (Maity, 2013). The availability of sufficient quantities of high-quality seed is therefore essential for achieving stable and efficient agricultural production. Seed quality encompasses several interrelated attributes, including genetic, physical, physiological, and sanitary quality, all of which contribute to successful crop establishment and subsequent plant performance. However, climate change poses increasing challenges to the production, maintenance, and preservation of high-quality seed (Singh et al., 2013). Elevated temperatures, water deficits, unpredictable weather patterns, and other climate-related stresses can adversely affect seed development, maturation, physiological quality, and longevity. These challenges highlight the need for innovative seed technologies and management strategies capable of maintaining seed quality and improving crop establishment under increasingly variable and stressful environmental conditions.

Effects of Climate Change on Seed Production and Quality

Climate change has emerged as one of the major environmental factors threatening the sustainability of agricultural production. In association with global environmental change, atmospheric carbon dioxide (CO_2) concentrations are projected to increase from approximately 370 ppm to around 550 ppm by 2050 and to reach 730–1010 ppm by 2100 (Solomon et al., 2007). Concurrent changes in climatic conditions are expected to increase global mean temperatures by approximately 1.4–5.8 °C (Houghton et al., 2001). Elevated atmospheric CO_2 concentrations may increase

yield in many C3 crops by approximately 13%, whereas relatively limited yield responses are generally expected in C4 crops (Jaggard et al., 2010). However, increases in temperature, particularly during reproductive development, may substantially constrain the positive effects of CO_2 enrichment on crop productivity in C3 species (Wheeler et al., 2000). Furthermore, climate change is expected to increase the frequency and intensity of extreme weather events, while maximum daily temperatures in many agricultural regions may rise by approximately 3 °C by 2050 (Gornall et al., 2010).

The effects of elevated CO_2 on seed production are complex and strongly dependent on crop species and environmental conditions. Increased atmospheric CO_2 may reduce stomatal conductance and thereby improve water-use efficiency, potentially supporting seed retention under water-limited conditions (Singh et al., 2013). However, the response of seed weight to elevated CO_2 varies considerably depending on species and growing conditions (Vanaja et al., 2007; Hampton et al., 2013). In contrast, increased temperature can adversely affect plant metabolic activity, developmental processes, and source–sink relationships, thereby limiting seed production, particularly during the reproductive phase (Farrar et al., 1991; Madan et al., 2012). Temperatures exceeding the optimum range may reduce seed number, shorten the duration of seed filling, and decrease seed weight in some crops (Singh et al., 2013). Consequently, yield losses associated with heat stress may substantially offset the potential productivity benefits of increasing atmospheric CO_2 concentrations.

Seeds are reproductive structures that develop from fertilized ovules and generally consist of an embryo, seed coat, and storage tissues, including cotyledons in many species. In seed technology, however, the term *seed* may also encompass various plant structures used for commercial propagation and crop establishment. High-quality seed intended for agricultural production should possess high

germination capacity and vigor, adequate genetic and physical purity, freedom from seed-borne pathogens and pests, and an appropriate moisture content for safe handling and storage (Verma et al., 2007). These characteristics are essential for rapid and uniform germination, successful field emergence, and vigorous subsequent plant development.

Seed quality is one of the fundamental determinants of crop establishment and productivity, and the use of high-quality seed has been reported to contribute approximately 20–25% to crop productivity (Pal et al., 2016). Seed quality is not determined solely at harvest or during storage; rather, it develops through a continuous process extending from crop establishment and reproductive development to seed maturation and subsequent post-harvest operations. Environmental conditions during flowering, gamete development, fertilization, seed development, and maturation can strongly influence the physiological and physical characteristics acquired by the seed. Following harvest, threshing, drying, processing, storage, and transportation may further modify seed quality. Throughout these stages, temperature, precipitation, atmospheric CO_2 concentration, and ultraviolet (UV) radiation can directly or indirectly affect seed performance and planting value (Hampton et al., 2016).

Therefore, the effects of climate change on seed systems should be considered beyond changes in crop growth and yield alone. Climatic factors can influence seed production, development, maturation, physiological quality, and subsequent storage potential, ultimately affecting the capacity of seeds to establish vigorous and uniform crops under changing environmental conditions. Understanding these responses is consequently essential for developing climate-resilient seed production and management strategies and for maintaining the long-term sustainability of agricultural production.

Climate Change and Seed Longevity

Although studies examining the effects of elevated atmospheric CO_2 and temperature on seed production in vegetable crops remain limited, available evidence indicates that these effects may vary considerably depending on species and thermal conditions. Elevated CO_2 concentrations have been reported to stimulate vegetative growth in some vegetable crops, including carrot and radish; however, the magnitude and direction of these responses are closely associated with temperature conditions (Usuda et al., 1998). In contrast, the effects of elevated CO_2 on flowering and seed production appear to be species-specific (Case et al., 1998). Increasing temperature, however, may have more pronounced adverse effects, particularly during reproductive development and seed filling. In radish and cabbage, for example, elevated temperature has been reported to reduce pod and seed number as well as overall seed yield (Kumar et al., 2009). Similarly, in oilseed rape, the reduction in seed yield associated with a 5 °C increase in temperature could not be compensated for by elevated CO_2, indicating that heat stress may constrain or override potential beneficial effects associated with increased atmospheric CO_2 concentrations (Frenck et al., 2011).

Information regarding the direct effects of elevated atmospheric CO_2 on seed vigor remains relatively limited. In contrast, exposure to high temperatures before or after physiological maturity can result in substantial reductions in seed vigor (Hampton et al., 2013). High temperature is also known to accelerate physiological ageing and deterioration processes in seeds, thereby potentially reducing their storage performance and subsequent field establishment capacity (Powell, 2006). Moreover, even short-term exposure to high temperature during critical stages of seed development can adversely affect seed vigor, highlighting the sensitivity of seed quality to thermal stress during seed formation

and maturation (Hampton et al., 2013). Thus, climate-induced temperature increases may affect not only seed yield but also the physiological quality and subsequent longevity of harvested seed lots.

The effects of climate change on seed production extend beyond yield and physiological quality and may also pose important challenges to the genetic integrity and varietal purity of seed crops. In particular, elevated temperature and atmospheric CO_2 concentrations may influence reproductive processes in open-pollinated and F1 hybrid seed production systems. Alterations in reproductive synchrony, pollen viability, pollen–stigma interactions, or the expression of self-incompatibility and male-sterility systems may increase the risk of unintended self-pollination or undesired pollen-mediated fertilization under stressful environmental conditions. Such disturbances may compromise genetic purity and, in hybrid seed production, reduce the uniformity and expected heterotic performance of the resulting seed lots. These concerns are particularly relevant for crops in which self-incompatibility or male sterility is deliberately exploited to control pollination and maintain genetic identity (Hampton et al., 2016).

In crops relying on self-incompatibility systems, environmental disruption of reproductive processes may increase the probability of unintended self-fertilization and consequently contribute to increased inbreeding over successive generations. In forage crops such as alfalfa and perennial ryegrass, where reproductive systems are important for maintaining genetic diversity and population performance, such changes could potentially influence long-term varietal stability and productivity. Similarly, in vegetable crops in which male sterility is exploited for F1 hybrid seed production, temperature-induced changes in male fertility could compromise the effectiveness of the sterility system and increase the occurrence of undesired selfed seeds. Even a relatively small

proportion of off-type or selfed seeds may be important commercially because hybrid seed production depends on high genetic purity and uniformity to ensure the expression of the expected heterosis and agronomic performance (Simmonds, 1991).

Under climate change conditions, maintaining genetic purity and identifying undesirable seeds will become increasingly important in seed production systems. Genetic markers and selectable traits may be used to improve the control of genetic purity in hybrid seed production.

Climate change can affect not only seed yield but also seed quality, vigour, longevity, and genetic purity. High temperatures may accelerate seed ageing and reduce seed quality and vigour, while the effects of temperature and atmospheric CO_2 levels may vary depending on species and developmental stage. Therefore, maintaining seed quality under future climatic conditions will require the combined consideration of suitable production environments, stress-tolerant genotypes, effective production practices, and appropriate storage conditions.

Effects of Climate Change on Seed Weight

The effects of elevated atmospheric CO_2 concentrations on seed weight vary considerably among plant species and genotypes (Hikosaka, 2011). This response may be more pronounced in legumes, whereas in some non-leguminous species, increases in seed weight under elevated CO_2 may be accompanied by reductions in seed nitrogen concentration (Hampton, 2013).

High temperature is another important environmental factor affecting seed weight. Elevated temperatures can accelerate seed development and shorten the duration of seed filling, thereby limiting dry matter accumulation and ultimately reducing final seed weight (Gibson et al., 1999; Young et al., 2004). However, reductions in seed weight do not necessarily result in corresponding

losses in germination capacity or seed vigor, indicating that seed weight and physiological quality may respond differently to environmental stress (Hampton et al., 2013).

Effects of Climate Change on Seed Germination

The effects of elevated atmospheric CO_2 concentrations on seed germination vary among plant species (Ziska & Bunce, 1997). Changes in the carbon-to-nitrogen ratio associated with elevated CO_2 may alter seed protein content and consequently reduce seed viability, whereas increased ethylene production may promote germination in some species (Hampton et al., 2013). High temperature stress occurring before physiological maturity may reduce germination capacity by limiting the accumulation of essential storage reserves or causing physiological damage to developing seeds (Powell, 2006).

Effects of Climate Change on Seed Quality

Temperature is one of the primary environmental factors determining the duration of plant developmental stages and shaping the geographical limits of crop production. Exposure of the mother plant to suitable temperature conditions throughout its development contributes to the favorable physiological and biological characteristics of the seeds produced. Although the effects of high temperature on plant growth, metabolic processes, hormonal regulation, and yield have been extensively investigated, studies addressing the quality and planting performance of seeds produced under such conditions during subsequent production cycles remain relatively limited (Nautiyal et al., 2001; Bita & Gerats, 2013; Zhao et al., 2017; Moore et al., 2021; Xu et al., 2021). Therefore, the evaluation of seed quality should consider not only the intrinsic characteristics of the seed but also the environmental conditions experienced by the mother plant during seed development.

Prolonged exposure to high temperature during germination and seedling development can reduce germination percentage and emergence uniformity, thereby adversely affecting plant stand establishment under field conditions. In particular, prolonged heat stress accompanied by increased water loss may result in restricted seedling growth, wilting, and impaired root system development, and, under severe conditions, may lead to seedling mortality (Liu et al., 2019; Xu et al., 2021). The reproductive stage, however, is considered particularly sensitive to high temperature stress. During this stage, heat stress can reduce pollen viability and germination, impair pollen tube development, and limit fertilization success. Consequently, disturbances in embryo and ovule development, reproductive abortion, and reductions in seed formation may occur (Liu et al., 2019; Lamichaney et al., 2021). These findings demonstrate that high temperature can affect not only the development of the current crop but also the quality of seeds that serve as the starting material for the subsequent production cycle.

Effects of Climate Change on the Post-Harvest Period and Seed Storage

Inadequate drying and inappropriate storage conditions during the post-harvest period can result in substantial losses in seed quality and viability. Globally, such losses have been reported to range from 10% to 40%, depending on the species and storage conditions (Halmer et al., 2006).

Elevated atmospheric CO_2 concentrations are not expected to substantially reduce the viability of stored seeds, and CO_2 accumulation in enclosed storage environments may help control certain seed pests. In contrast, rising temperatures can negatively affect seed quality during harvesting and storage. Seeds exposed to direct solar radiation may reach temperatures 10–12 °C above ambient air temperature, increasing the risk of heat injury. Excessive heating during sun-drying may also reduce germination capacity,

whereas rapid cooling and protection from direct sunlight can help limit these effects. Storage temperature and relative humidity are key factors influencing seed longevity and deterioration. Under appropriate moisture conditions, a 5 °C reduction in storage temperature may approximately double seed storage life. Therefore, climate change may threaten long-term seed viability, particularly in storage systems without controlled environmental conditions (Hill, 1999).

Conclusion

The impacts of climate change on seeds extend far beyond yield losses; they manifest as a decline in biological performance throughout the continuum from seed formation to storage. Increasing temperatures, drought, and irregular water availability can simultaneously affect seed filling, germination, vigor, biochemical homeostasis, and aging processes, thereby accelerating the deterioration of seed quality.

Accordingly, seed quality and longevity should be regarded as complementary components of the same physiological continuum. Stress experienced during seed production can compromise subsequent storage potential, while high temperatures and inappropriate storage conditions after harvest may rapidly accelerate the deterioration of the quality already established. Thus, seed quality losses should be considered within a "stress–aging continuum" extending from production through storage.

From a climate-change adaptation perspective, the development of stress-tolerant cultivars alone is insufficient. Future seed systems will require seeds capable of maintaining high vigor, germinating rapidly and uniformly under fluctuating environmental conditions, producing robust seedlings, and retaining viability throughout storage. In this context, integrating genetic improvement with advanced seed technologies is increasingly important.

Approaches such as priming, stress memory, imaging-based phenotyping, single-seed oxygen consumption analysis, and artificial intelligence–based assessment offer promising opportunities for developing more resilient seed systems.

Ultimately, the goal should shift from "producing more seeds" to "producing seeds capable of delivering more reliable performance under variable environmental conditions." In this way, seeds can move beyond their conventional role as agricultural inputs and become active components of sustainable agriculture and climate-change adaptation.

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