Hedge microclimate impact on the qualitative and quantitative parameters of different tomato genotypes

Doctoral (PhD) dissertation by

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List of Abbreviations

TAFS	Traditional Agroforestry Systems
AFS	Agroforestry Systems
FAO	Food and Agriculture Organization of the United Nations
VAF	Vegetables Agroforestry Systems
OECD	Organisation for Economic Co-operation and Development
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
NCBGC	National Centre for Biodiversity and Gene Conservation
ARS	Agricultural Research Service
USDA	United States Department of Agriculture
ToMV	Tomato Mosaic Virus
pH	Potential of Hydrogen
°C	Degrees Celsius
GCMs	Global Climate Models
DI	Deficit Irrigation
N	Nitrogen
P	Phosphorus
K	Potassium
NRCS	Natural Resource Conservation Service
O	Oxygen
CIE	Commission International de l'Eclairage
L*	Lightness
a*	Red/Green
b*	Yellow/blue
L*a*b* (Lab)	Color model
AsA	Ascorbic Acid
HPLC	High-Performance Liquid Chromatography
TSS	Total Soluble Solids (Brix %)
IR	Infrared spectroscopy
TPC	Total Phenolic Compounds
FRAP	Ferric Reducing Antioxidant Power
TAC	Total Antioxidant Capacity
NW–SE	Northwest Southeast

RBD	Random Block Design
P	Protected side
W	Windy side
SPAD	Non-destructive measurement of leaf chlorophyll concentration
TPF	Triphenyl Formazan
TTC	Triphenyl Tetrazolium Chloride
DHA	Dehydrogenase activity
pNP	P-nitrophenyl-phosphate
SAR	Sugar - Acid Ratio
TA	Titratable Acidity
DW	Distilled Water
ANOVA	Analysis of Variance
GAE	Gallic Acid Equivalent
RH	Relative Humidity
ÖMKi	Research Institute of Organic Agriculture (Ökológiai Mezőgazdasági Kutatóintézet)
SD	Standard Deviation
NIRS	Near-Infrared Spectroscopy
SSC	Soluble Solid Content
TPTZ	Tripyridyl-s-Triazin
pNP	p-nitrophenol
POXC	Permanganate-Oxidizable Carbon
SOC	Soil Organic Carbon
GRSP	Glomalin-Related Soil Protein
CIE	Commission Internationale de l'Éclairage
TNs	Total Nitrogens
TCs	Total Carbons
LSL	Long Shelf Life
GLM	General Linear Model
ROS	Reactive Oxygen Species
BBCH	Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie

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1. INTRODUCTION

Climate change poses a significant threat to global food production systems, leading to a reduction in the yield and nutritional quality of important crops such as tomatoes (Djibrilla et al., 2024; Mustafa, et al., 2023). This environmental shift can result in harvest losses of up to 70%, drastically affecting tomato growth (Mamatha et al., 2014; Ruggieri et al., 2019). However, in 2022, the Food and Agriculture Organization of the United Nations (FAO) reported that 182 million tons of tomatoes were produced globally, with an output value of approximately 20 trillion (FAOSTAT, 2020). Extreme weather events, such as heatwaves, droughts, and floods, intensify this impact, making open field tomatoes especially vulnerable and prompting the need for climate-resilient cultivars. Stress conditions affect crop adaptability and performance, necessitating effective management for sustainable production (Rani Chandrasekaran et al., 2020; Zhou et al., 2024). Traditional agroforestry systems (TAFS) offer a potential solution, as trees and woody plants create unique microclimates, altering temperature, humidity, and wind speed that influence crop resilience (Blanca et al., 2015; Bryant et al., 2021).

Tomato (*Solanum lycopersicum* L) is ranked first among the vegetables produced globally due to its nutritional and economic importance. It belongs to the *Solanaceae* family, accounting for 16% of the total vegetable production (Costa & Heuvelink, 2005). Tomatoes are used in soup, paste, juice, and ketchup, and are a rich source of essential minerals (Bergougnoux, 2014). Tomatoes are a rich source of metabolites, including soluble solids, flavonoids, vitamins, and minerals, providing essential nutrients (Altuntas & Ozkurt, 2019; Sainju et al., 2003). However, stress factors can significantly impact the growth, yield, and quality of tomato plants, leading to substantial economic losses in open-field production, especially in challenging ecological conditions. In tomato breeding and production, programs prioritize plant yields over abiotic factors, as global climate change poses a significant threat to the biological processes and activities of plants. Among the various environmental stressors, however, high or low temperatures and drought are examples of environmental circumstances that limit plant growth and yield (Gerszberg & Hnatuszko-Konka, 2017). Climate change, with its associated hot waves and droughts, is responsible for over 40% of yield variation globally (Zampieri et al., 2017). Agroforestry systems, which incorporate trees and bushes into crop production, are increasingly being explored due to climate change, soil degradation, and erosion. Trees are used in agricultural settings as hedgerows, farm boundaries, or scattered plantings (Garrett, 2015). Plant interactions affect growth resources like nutrients, water, and light. Complementarity occurs when trees absorb nutrients from deeper soil layers, increasing farm productivity and reducing abiotic stress. This approach also reduces soil erosion and promotes environmental benefits like carbon storage and agrobiodiversity (Workman et al., 2002). However, these systems can influence microclimate conditions during the cultivation stage, including plant growth, flowering, fruit set, development, as well as post-harvest stages, such as storability and shelf life. Moreover, it is important to note that the physiological and metabolic responses to a combination of heat and drought stresses are unique and cannot be directly extrapolated from each stressor individually (Rizhsky et al., 2004).

Hedgerows have great importance in field vegetable production, especially in regions where climate and soil properties (sandy soil with 1,5% organic matter content or lower) do not meet the optimal production requirements. Hedgerows and shelterbelts decrease harmful effects mainly by reducing wind speed. The efficiency of reducing wind speed is about 10–15% on the windward side and can reach 60% on the leeward side (Bošković et al., 2010; Mustafa, Szalai, et al., 2023). By the reduction of wind speed, the microclimate can be modified in terms of relative humidity and temperature. Microclimate manipulation can optimize the microenvironment, lessen wind erosion, and protect crops from direct wind for the plants. These factors may enhance crop development, plant morphology, phenology, physiology, and productivity (Nair et al., 2021; Nair et al., 2010; Nerlich et al., 2013). Enhancing tomato plants' tolerance to abiotic stress under changing climate conditions is a key goal in modern cultivation efforts. One approach involves developing hypotheses that explore how microclimate conditions influenced by hedgerow systems on both windy and protected sides at different distances impact crop yield and quality. Such studies, carried out over multiple years, can provide valuable insights for sustainable tomato and vegetable production, guiding future strategies for resilient agroecosystems.

1.1 Hypothesis

- Hedgerow systems improve soil quality chemical and biological soil properties, such as organic carbon content and microbial activity, compared to open-field tomato systems.
- Hedgerow side and planting distance significantly affect tomato fruit yield weight and number due to variations in microclimatic conditions between windy and protected sides.
- Hedgerow systems, by stabilizing microclimatic conditions and reducing daily maximum temperatures on both windy and protected sides, enhance the resilience of tomato genotypes to climate-induced thermal stress, thereby improving their nutritional quality specifically phenolic content, antioxidant levels compared to open field cultivation.

- Tomato genotypes exhibit varying susceptibility to pests, diseases, and fungi in hedgerow systems, supporting the hypothesis of genotypic resistance.

1. 2 OBJECTIVES

1.2.1 General study aims.

The primary objective of this study is to examine the impact of different hedgerow microclimate conditions on development various tomato genotypes. Specifically, we aim to analyze the crop's phenology, physiology, and qualitative parameters of the tomato fruits. Additionally, we aim to investigate whether incorporating hedgerow into the production system can enhance tomato productivity, under organic farming conditions, focusing on the microclimatic effects across sides, windy (W1–W5) and protected (P1–P5) distances from the hedge.

1.2.2 Specific objectives

(1) Microclimate condition:

Examination of hedgerow system to mitigate climate extremities effects, by modifying microclimatic conditions across windy sides (W1–W5) and protected sides (P1–P5) distances, allowing assessment of its impact within a tomato cultivation.

(2) Plant growth and nutritional contents:

- To compare the performance of different tomato genotypes in terms of plant growth, morphological development, including plant height, stem diameter, and leaf area.
- SPAD, chlorophyll A, B content, N, P, K, and carotenoid on tomato plant leaves.

(3) Productivity of three tomato genotypes:

- Yield traits (fruit number and weight per plant and per plot) were evaluated to determine which side of the hedgerow system produced higher final yields.
- To identify the most productive and high-quality tomato genotypes that are well-suited.

(4) Quality contents of three tomato genotype fruits:

- To assess the impact of hedgerow microclimate modulation effects on open field tomato fruit quality, employing three genotypes (Roma, Ace55, Szentlőrinckáta). Key quality traits: Chroma (C*), and hue (h°), Total soluble solids (TSS), Titratable Acid (TA), Sugar Acid Ratio (SAR).
- To evaluate the levels of Ferric Reducing Antioxidant Power (FRAP), Total Phenolic Content (TPC), as well to identify the most effective positions relative to the hedgerow and the microclimate conditions that promote the development of tomato genotypes.

2. LITERATURE REVIEW

1.2 Background and history of the tomato

Tomato (*Solanum lycopersicum* L.) belongs to the Solanaceae family, which contains more than 3000 species, mostly economically important, such as potatoes (Weese et al., 2007). Tomatoes, originally considered a garden vegetable, are native to tropical South America, specifically along the coasts and high Andes spanning from central Ecuador through Peru to northern Chile and the Galapagos Islands. The first recorded cultivation of present-day tomato varieties occurred in the Galapagos Islands (Costa & Heuvelink, 2005). In the early 16th century, tomatoes were introduced to Europe and later spread to the Mediterranean region, although they were already extensively cultivated in southern Mexico during this period. The Spanish conquest of Mexico played a significant role in the spread of tomato cultivation. Although tomatoes are tropical plants, they are grown worldwide, from the tropics to areas a few degrees north of the Arctic Circle. In unfavourable climatic regions, tomatoes are cultivated in greenhouses rather than open fields. The top tomato-producing countries, in order of importance, are China, the United States, India, Turkey, Egypt, and Italy (Foolad, 2007).

The tomato fruit, which the Spanish referred to as *tomate* after translating the Aztec word xitomatl, played an essential role in pre-Columbian cuisine and was mentioned in various Spanish reports. The Spanish exported the tomato fruit across the Spanish Empire and to other European nations, the Caribbean, and regions of Asia. The first recorded consumption of tomato fruit in Seville, Italy, occurred in 1608 when it was used in a salad with cucumbers. In Italy, the tomato is known as pomo d'oro or golden apple (Smith, 1994). The tomato plant was also widely grown in France, where it was referred to as tomate and love apple, or pomme d'amour. The first commercial tomato production in Europe, which started in the 1800s, included four red and two yellow varieties: Big, Little, Large Yellow, Pear-Shaped, Cherry, and Yellow Cherry Love apples (Costa & Heuvelink, 2005; Kaundal et al., 2024; Smith, 1994).

2.2 Classification of tomato (*Solanum lycopersicum* L.)

The description of tomato (*Solanum lycopersicum* var. *lycopersicum*) includes the cultivated tomato and its 12 wild relatives, which can be categorized into two complexes, the *esculuntum* complex and the *peruvianum* complex based on their ability to be crossed with the cultivated cultivar, that are indigenous to South America, particularly regions of Ecuador, Peru, and northern Chile, where they have adapted to diverse environmental conditions. The binomial nomenclature of the crop is still up for question (Bergougnoux, 2014). Phylogenetic connections, molecular sequences, and morphological evidence, however, strongly support its inclusion in the genus *Solanum* L. (Knapp & Peralta, 2016b). Nevertheless, tomato landraces that have been adapted to their specific habitats are viable genetic sources for adding beneficial features to cultivated varieties (Csambalik et al., 2014; Peralta & Spooner, 2005). Furthermore, the *esculentum* and *peruvianum* complexes, which may hybridize with the cultivated tomato and represent potential sources of resistance to biotic and abiotic stressors as well as other desirable traits, were presented as two primary groupings in an early study's categorization of tomato species (Bergougnoux, 2014). However, *Solanum* is the largest genus in the *Solanaceae* family, encompassing 1250 to 1700 species have some of the most varied growth patterns from trees to tiny annual herbs, habitats from deserts to the wettest tropical rainforests, and morphologies of any plant family (Weese et al., 2007). Numerous *solanaceous* plants have served as significant model plants. A revised taxonomic classification of tomatoes was proposed in the early 2000s, reinstating S. *lycopersicum* has been reinstated as the species name for the cultivated tomato according to extensive genetic and morphological evidence (Peralta & Spooner, 2001).

2.2.1 Taxonomy and botanical characterizations

Traditionally, the examination of genetic variation in plant species has relied heavily on morphological traits, such as leaf shape, flower structure, and fruit characteristics, as in the Scientific classification and Figure 1. However, these morphological characters are often influenced by ecological and environmental interactions, which may obscure true genetic differences; hence, such studies require careful replication and environmental control to ensure reliability (Knapp & Peralta, 2016a; Olaniran & Odelade., 2014). Modern taxonomy and genetic evaluation now integrate multiple approaches beyond traditional morphology. These include evolutionary taxonomy based on phylogenetic relationships, numerical taxonomy or phenetics quantitative analysis of overall similarity, chemotaxonomy (use of biochemical markers such as secondary metabolites), and molecular taxonomy using DNA-based genetic data. Together, these methods provide a more comprehensive and objective framework for classifying Solanum species and understanding their genetic diversity and evolutionary relationships, which are essential for breeding and conservation efforts (Khan et al., 2013; Olaniran and Odelade., 2014).

Scientific classification

Kingdom: Plantae
Clade: Tracheophytes
Clade: Angiosperms
Clade: Eudicots
Clade: Asterids
Order: *Solanales*
Family: *Solanaceae*
Genus: *Solanum*
Species: *S. lycopersicum*
Binomial name: *Solanum lycopersicum* L.
Synonyms:
Lycopersicon lycopersicum (L. H. Karst.)
Lycopersicon esculentum (Mill.)

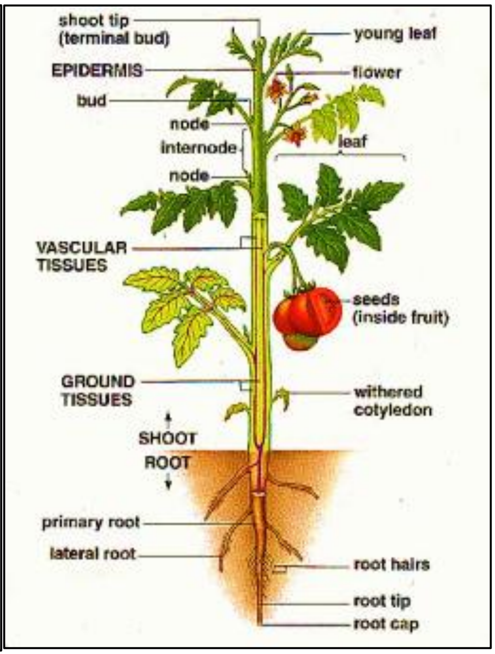


Figure 1: Morphology of tomato plant organs (CLIFF, 2005).

2.2.2 Morphology of tomato (*Solanum lycopersicum* L.)

Roots: The tomato plant's root system is classified as primary and secondary, and it is crucial for plant growth (Figure 1). Due to its critical roles as a physical support structure, an organ of storage, a selective barrier against pathogens, and a regulator of various stress responses (Alaguero-cordovilla et al., 2018; Courtois et al., 2010). Plants often have either a fibrous root system or a taproot system for their roots. The core taproot, which is bigger in diameter than the lateral roots, makes up the taproot system. Lateral roots split out from the tap root, and they can also split off additional lateral roots. The fibrous rooting system is made up of thin, stringy roots with an average diameter of approximately the same, whereas taproots often penetrate the soil relatively deeply. And tomato plants can have a range of root systems depending on how they are raised. If the plant were produced from a seed, it would display taproot organization (Orman-ligeza et al., 2013; Tuylu, 2018).

Leaves: leaves are classified as being unit-pinnately complex, which is made up of leaflets growing along the leaf rachis. Each leaflet has a petiole that connects it to the rachis, which is then fastened to the plant's stem (Tuylu, 2018), as illustrated in (Figure 1**)**. The adult leaves of tomatoes typically feature three pairs of strongly lobed, sizable lateral leaflets spread along the rachis. These leaflets grow in a basipetal sequence, with the youngest pair emerging from the leaf's base. Between the big lateral leaflets, pairs of tiny, less-lobbed, evenly spaced leaflets also develop (Li et al., 2013). Finding and analysing mutants has helped researchers learn more about the genes and pathways responsible for the shape and colour of leaves. However, studies on photosynthesis and plant growth have made extensive use of mutants lacking chlorophyll, and significant advancements have been made in our understanding of the processes underlying leaf shape. In addition to affecting how the aerial component looks, changes in leaf size and shape also have an impact on photosynthesis rate by altering light absorption (Kessler et al., 2001; Vicente et al., 2015). However, Dixon et al., (2020) reported, the trichomes, or hair-like structures, that develop on the epidermal layer of tomato leaves constitute one of its distinctive characteristics. These structures can be either polymeric hairs or glandular trichomes.

Stem: There are several morphological, physiological, and biochemical tomato plant stem variations that have been documented to be associated with effects on the environment. Tomato plants with a characterized stem and length. First, determine the length of the stem. Tomato plants are compact plants that stop growing once fruit sets on the top bud and ripen within a short time frame, providing a consistent supply of ripe tomatoes for canning. Second indeterminate growth, plants grow and produce fruit until slew by frost, usually reaching heights of up to 12 m (Vicente et al., 2015). Nonetheless, there have been reports of the influence of anatomical tomato stem characteristics. While seasons and decades pass, anatomical traits remain constant. Osmotic changes were connected to the tomato's root and shoot growing differently (Kulkarni & Deshpande, 2005), as presented in (Figure 1). Reportedly, the tomato (2n = 2x = 24) is an autogenous species with a high degree of homozygosity (Foolad, 2007). While often grown as an annual plant, it is a perennial. Since frost or drought destroys the plants after the first growing season, wild tomatoes most likely act as annuals in their native Andes highlands and deserts (Rick & Smith, 1953). Depending on the plant's ability to establish secondary growth in basal stems and roots, wild tomatoes can act as biennials or perennials under suitable climatic circumstances (Liedl et al., 2013).

Flower: At full bloom, tomato flowers often have a yellow colour and measure less than 2.5 cm in diameter. The stamen, one of its component elements, is located inside the petals. It consists of two elongated sections that fit together individually. The single stamens then joined forces to create a cylinder-shaped structure that encircled the carpels (Helyes, 2004). On the other hand, tomato carpels are said to be green in colour, vary in number depending on the cultivar, and are fused to create a single structure that resembles a bulb. The number of fruit locules and the number of carpels in a flower are correlated, and the stem (Figure 2-A). At the carpels, where the ovules transform into seeds, fertilization takes place. However, in flowering plants, the shift from vegetative growth to reproductive development is a significant morphogenetic occurrence that entails a notable alteration in the shoot apical meristem's development. When the shoot apical meristem develops reproductive capacity, it generates an inflorescence meristem, which in turn produces floral meristems that give rise to flowers. Initially, this meristem generates leaves, buds (Foolad, 2007).

Fruit: The tomato fruit has characteristics of a berry, and, as a true fruit, it develops from the ovary of the plant after fertilization, its flesh constituting the pericarp walls. And the fruits are globular, or ovoid biologically (Figure 2-B). The fruit has all the characteristics of berries, and it is simple. Fleshy fruit with seeds enclosed in the pulp. In addition to the placenta, the outer skin is a thin, fleshy tissue, and cells within the fleshy tissue give the fruit its colour. The epicarp and subepidermal tissues' pigments work together to give the fruit its colour. Since the pericarp of certain species contains chlorophyll, their fruits are green (DIXON, 2020; Figás Moreno et al., 2024). It is possible for tomato fruits to be bilocular or multilocular. Each locular cavity contains between 50 and 200 seeds enclosed in a gelatinous membrane. After fertilization, the fruit takes seven to nine weeks to develop. The Organisation for Economic Co-operation and Development (OECD) consensus document on compositional considerations for new tomato varieties details the many end uses of tomato fruit as well as food and feed safety considerations, such as the composition of key nutrients for food and feed, antinutrients, allergens, and toxicants (OECD, 2008). In the cultivated tomato, a wide range of varieties with fruits of different colours, shapes, and sizes are currently commercialized (Figás Moreno et al., 2024). Quantities of carotenoids, such as lycopene and beta-carotene, and chlorophyll govern the fruit's colour, which ranges from green to yellow to orange to red, which is the most prevalent (Kimura et al., 2008). Pollination, fertilisation Tomato plant is a self-pollinating plant that requires warm temperatures and sunlight to grow and produce fruit. It thrives in well-drained, fertile soil with a pH between 6.0 and 6.8.

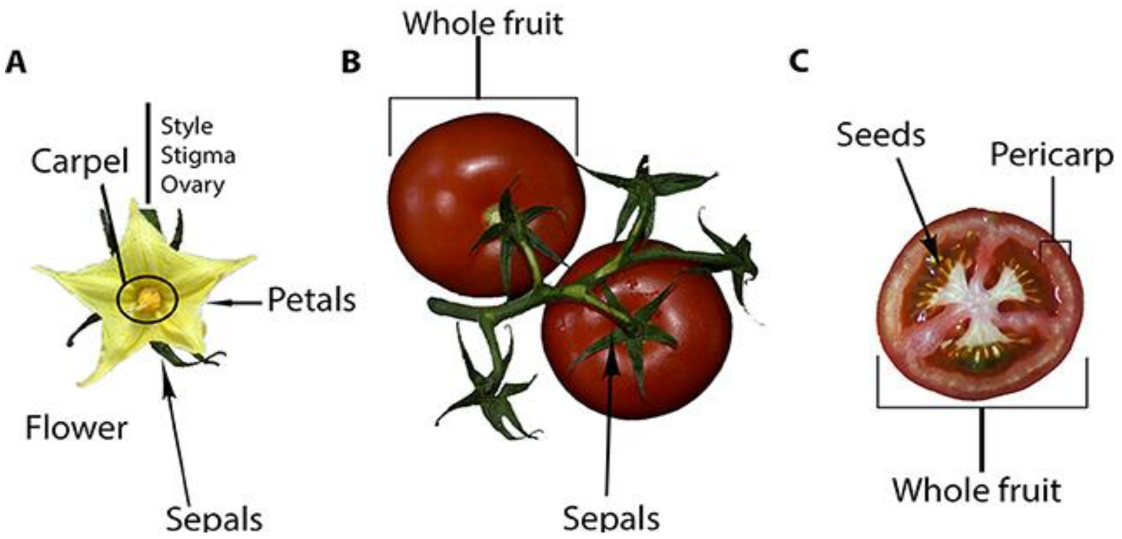
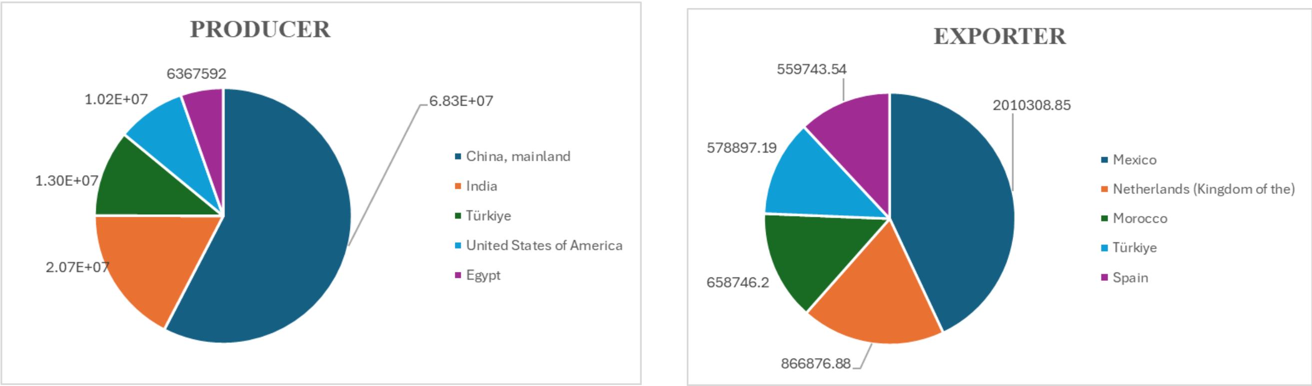


Figure 2: The (A) flower, (B) fruit, and cross section of the tomato fruit (C) (DIXON, 2020).

Phenological stages: The plant undergoes several stages of growth, including seed germination, vegetative growth, flowering, fruit development, and maturation (Dingley et al., 2022). Tomato seeds germinate best in warm soil, taking 5-10 days. During the vegetative growth stage, the plant produces leaves, stems, and roots, which last for 6-8 weeks. Once mature, the plant begins to produce flowers, which develop on the ends of branches, followed by fruit development. The tomato plant requires warm temperatures and ample sunlight for optimal growth. The plant's growth and development are facilitated by cotyledons, which provide initial energy (Dingley et al., 2022; Sobarzo-Bernal et al., 2021).

2.2.3 Economic importance

Tomato is a crucial vegetable globally, accounting for 16% of total vegetable production. It experienced the fastest growth rate of 49% from 2000 to 2022.With 132 million tons produced annually, 90 million tons are used in fresh form, and 42 million tons are processed, making it the leading vegetable for processing. Tomato-processed products, including paste, canned tomatoes, sauces, and ketchup, produced approximately 6.00 million tons in 2022, averaging EUR 5.9 billion. The tomato's economic importance is evident in its significant role in both international and local markets (FAOSTAT 2025). In 2022, the top five major tomato producers in the European Union were China, India, Turkey, the United States of America, and Egypt. Tomatoes make up 19% of total vegetable production in the European Union, with Germany's per capita consumption of 25 kg over the last decade. Mexico, the world's largest tomato exporter, supplies and consumes over 52% of its total production in the United States. China produced about 60.00 million tons of tomatoes in 2022, representing one-third of global production. However, most of the production is used for domestic consumption. Other significant producers include North Africa, Sweden, Russia, Turkey, Jordan, the US, Spain, and France, which is the largest tomato-producing country in Europe (Figure 3) (FAOSTAT, 2025).



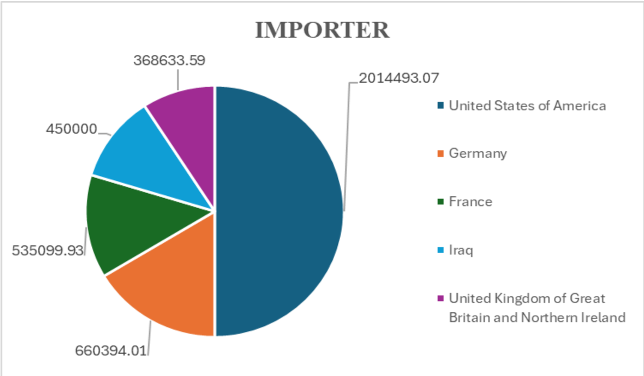


Figure 3: Top 5 Global production, export, and import of tomato in 2022 (FAOSTAT, 2025). (https://www.wifss.ucdavis.edu/).

The production overview described above indeed demonstrates the size and significance of tomatoes in the global market. Numerous varieties are developed based on their intended uses, which may include processing into tomato products or using them fresh, to support the industry's ongoing expansion. Approximately 7,500 tomato cultivars are currently grown for various culinary purposes worldwide (FAOSTAT, 2025). These varieties are categorized into five groups based on their size and shape: (1) slicing, globe, or round, which are used for processing or fresh consumption; (2) beefsteak, large tomatoes best suited for sandwiches; (3) plum, which are more fleshy and ideal for tomato sauce and paste; (4) cherry, small, sweet tomatoes meant primarily for salads; and (5) grape tomatoes, recently developed varieties described as a smaller type of plum, also used in salads (Bosland et al., 2005; Ferreira et al., 2004; Smith, 1994).

2.3 Tomato varieties applied in the experiment

Tomato varieties Szentlőrinckáta, Roma VF, and Ace55 were chosen based on their genetic diversity, adaptability to local and international conditions, disease resistance, and relevance to both fresh consumption and processing. Szentlőrinckáta represents a Hungarian landrace with strong regional significance, while Roma VF and Ace55 offer globally recognized traits suitable for comparative analysis under open field conditions.

2.3.1 Szentlőrinckáta

The genotype of Szentlőrinckáta is a Hungarian landrace variety and cultivated plant with a historical heritage and a distinct character. It was added to the national gene bank collection inin 2011 for systematic genetic improvement or breeding by the National Centre for Biodiversity and Gene Conservation (NCBGC) in Tápiószele, Hungary. The traits of Szentlőrinckáta were collected from a gene bank accession with the code number RCAT078726. This variety is typically utilized for both fresh consumption and processing, aligning with the distinct consumption types of worldwide tomato varieties (Boziné-Pullai et al., 2021). The average single fruit weighs between 50 and 55 grams, has an oval shape, is medium in size, and is red (Figure 4 -A). The growing type has been determined as bush-type with a determinate growth habit. This variety demonstrated competitive results in terms of both yield and resistance compared to commercial tomato varieties, making it suitable for use as a control in research experiments. Szentlőrinckáta varieties exhibited adequate yields and better resistance against tomato blight than the control cultivars. Additionally, among bush tomatoes (*Alternaria solanii*), their extended growing season and exceptional yield surpassed the results of commercial varieties (Boziné-Pullai et al., 2021). The accession was studied by both the Hungarian University of Agricultural and Life Sciences and Research Institute of Organic Agriculture (Ökológiai Mezőgazdasági Kutatóintézet) ÖMKI.

(A) Szentlőrinckáta | **(B) Ace 5** | **(C) Roma VF**

Figure 4: Important Tomato Hungarian Landrace and International Genotypes.

2.3.2 Roma VF

The Roma VF is an international tomato variety that is extensively planted in most tomato-producing countries and has global appeal and consumer acceptance, especially in Europe, Asia, and the United States. The Roma VF tomato variety was developed in the 1950s by USDA Agricultural Research Service (ARS) scientists in Beltsville, Maryland, USA. According to the study of Ogwulumba et al., (2011), tomato cv. Roma VF showed a notable response to *M. javanica* infestation when treated with bitter leaf and mango extracts, supporting its known resilience and varietal characteristics. Roma determinate, open pollinated tomato variety with high leaf cover; the Roma VF character is a very high plant quality in fruit; and it has a physiological character of hardy skin and a rugged stage to maturity between 75 and 95 days. However, according to open-field research by (Kathimba et al., 2021), the weight of a single fruit is between 57 and 85 g, and the colour of the fruit is red (Figure 4 – B). The growth habit is determinate, and the plant has a good ability to resist disease (for example, Fusarium wilt, Verticillium wilt, nematodes, and ToMV (*Tomato Mosaic Virus*)) and pests (Kathimba et al., 2021).

2.3.3 Ace55

The tomato Ace55 variety (Figure 4 – C) produced at the University of California, Los Angeles, is one of the few low-acid red fruit tomato plants and is an open-pollinated type (Hassan et al., 2020). The plant produces numerous bright red fruits. It has a few seeds and is meaty, juicy, and tasty. This variety is ideal for sandwiches, salads, and slicing plants and has dense foliage that protects tomatoes from sunburn. A great option for home gardeners and market producers. It is an heirloom cultivar produced in the United States in the 1950s. and registered as PI 212423, United States Department of Agriculture germplasm collection, Ace55 is a type of disease-resistant tomato with resistance common varieties Verticillium wilt, Fusarium wilt (Hassan et al., 2020). The physical character of fruits with a diameter of 5 – 6 cm and a weight approximately (340–400 g) is ideal for quartering and packing into jars, they are also resistant to cracking and bursting. The yields are extraordinary for the Ace55 determinate variety, and the bulk of the fruits mature within one month (Mustafa, Adjei, et al., 2023).

2.4 Requirements for cultivation of tomato

Tomatoes can be grown under a broader range of environmental conditions. The environment suitable for an experiment depends on the research subject and may influence the choice of an appropriate location for cultivation. While most conditions require ideal settings for growth, some require an adverse setting or a particular form of stress. However, open field tomato cultivation requires specific environmental and agronomic conditions for successful production. Key environmental requirements include appropriate temperatures, adequate light, and suitable water management, with soil preparation being fundamental for establishing healthy stands through either direct sowing or transplanting (Csizinszky & Heuvelink, 2005).

2.4.1 Soil condition

Most types of soils are suitable for tomato growth. Additionally, they prefer deep, well-drained sandy loams (Rutger et al., 1977). Tomatoes' tolerance regarding pH is relatively wide, such as the amount of acidity, but they thrive on soils with a pH between 5.5 and 6.8 when there is an appropriate supply of nutrients. In general, the presence of organic materials promotes healthy development. Tomatoes may be grown on heavy clay-type soils with deep ploughing, allowing optimal root penetration. Permeability is required for the top layer. However, the crop requires a soil depth of 15 to 20 cm. Deep ploughing promotes higher root penetration in hard clay soils. Peat soils, which have a high proportion of organic matter, are less suited because of their great propensity to retain water and nutrient deficits (Kütük et al., 2004). Under field cultivation, plants heavily rely on the soil for physical support, anchoring, water, and nutrients. Soil compaction can result in reduced total root length and surface area, lateral root growth, increased root diameter, and swollen root tips, all of which are thought to restrict the capacity of the organ to discover and utilize the plant's necessary resources (Tracy et al., 2012).

2.4.2 Nutritional application:

The tomato crop's nutritional needs are influenced by variety, productivity, and cultural techniques. The following nutritional needs might be regarded as typical In open field cultivation, tomato plants require nutrients in the following order of uptake K (Potassium) > N (Nitrogen) > Ca (Calcium) > S (Sulfur) > P (Phosphorus) > Mg (Magnesium), with maximum uptake values of 360, 206, 202, 49, 32, and 29 kg ha^{-1} respectively (Fayad et al., 2002).The fertilizer dosages can be increased in a greenhouse to boost production. Due to the high expense, fertilizer use is restricted in conventional agriculture as well as in organic agriculture (Sainju et al., 2003). The starting solution technology to meet the immediate nutritional needs of early tomato plants. The kind of culture, the tillage techniques used, and the cropping patterns all influence how much fertilizer should be administered to the plants. A goal yield of 40 tons/ha for tomatoes has a ratio of 3.3N-0.4P-4.2K (kg/tons yield) and a total hectare of 330 N-160 P-336 K. The desired yield is an essential component in estimating the nutrient need (Ma & Kalb, 2006).

2.4.3 Climatic requirement

Temperature for tomato: Tomato temperature requirements vary significantly across phenological stages and growing seasons. For optimal germination, tomato seeds require temperatures of 20-25°C, followed by a temporary reduction to 12-15°C during the day and 6-10°C at night for one week to promote strong root development. During vegetative growth and fruit development, optimal daytime temperatures range from 20-26°C with nighttime temperatures of 16-18°C (Sirieva & Daulakova, 2020). However, it may thrive in a variety of climates, from moderate to hot and moist tropics. For most types, the ideal temperature range is between 21 and 24 °C. The plant tissues are damaged below 10 °C and over 38 °C, although the plants can tolerate a broad temperature range and survive temperatures up to 40°C and down to 0°C. (Geisenberg & Stewart, 1986). Temperature changes affect tomato plant growth in several ways, including seed germination, seedling development, flower and fruit production, and fruit quality. Pollen production will be minimal if chilly or hot weather spells continue when flowers are blooming. This will affect how fruits develop, and plants will perish from frost. However, for better growth and development, postpone the sowing until winter is over to prevent frost damage. Furthermore, the colour of the leaves, fruit set, and fruit all depend on the amount of light. The soil's temperature also plays a crucial role in seed germination. According to (Shamshiri et al., 2018) recommendation, for one to two weeks, it was strongly advised to maintain a warm conditions to enhance emergence, followed by cooler temperatures and reduced soil moisture one week before transplanting to improve plant survival temperature of around 27 °C to promote high emergence, in addition to reducing soil moisture and air temperature to 13 °C to 16 °C one week before transplanting in the field to increase the likelihood that the plants will survive (Shamshiri et al., 2018).

Relative humidity (RH): The ideal relative humidity for tomato plants to develop, blossom, set fruit, and produce fruit is typically between 65 and 75% (Schwarz et al., 2014). The microclimate in tomato fields progressively shifts from extremely high maximum daily temperatures, often higher than 35°C, to relatively moderate ones, about 30°C or less (Guzman-Plazola et al., 2003). The development of tomato plants can also be influenced by the relative amount of water in the air; high humidity plays a crucial role in seed germination, together with a temperature of less than 20 °C. Thus, it is possible to have, even decades later, seeds with a high germination rate. Similar to grafted tomatoes, high humidity is required to prevent scion withering and promote graft union healing (Suzuki et al., 2015).

Wind condition: While most farmed tomatoes self-pollinate, the wind may efficiently pollinate plants growing in the field. Strong winds can have a significant impact on crops, particularly during the fruiting and flowering stages, as well as early growth (Gardiner et al., 2016). Research demonstrates that strong winds significantly impact crop production in Hungary and elsewhere, particularly during critical growth stages. Hungarian agriculture faces increasing climate variability, with rising temperatures and changing precipitation patterns affecting crop productivity (Bakucs et al., 2020; Jolankai et al., 2007). Furthermore, Previous research claimed that due to severe winds, the fruit quality and quantity had drastically decreased. It was shown that four days of exposure to a wind speed of 1,340 cm/sec (30 mph) resulted in bigger leaves, thicker midribs, and a doubling of the number of stomata. All of which have been discovered to have a detrimental effect on tomato plants' photosynthetic and respiration rates. In addition, the plants show severe wound callus and subsequent epidermal loss (Greig et al., 1974; Precheur et al., 1987).

2.5 Open field tomato cultivation technologies

Tomatoes grown in open fields are more susceptible to weather conditions than tomatoes grown in a controlled greenhouse environment, so open field tomato farming will be more affected by global warming (Bosland et al., 2005). Although it is unknown how large the possible repercussions will be, various strategies can be used to anticipate. Global Climate Models, general circulation models (GCMs), are helpful tools for examining potential effects on a plant, and the tomato species (Shabani et al., 2013). According to a recent study on assessing the impact of global warming on worldwide open-field tomato, large areas with an ideal climate will become marginal or unsuitable due to rising heat and dry stress, while similarly sized areas that are currently marginal and unsuitable will become suitable due to a decline in cold stress. The utilization of landrace germplasm to create novel tomato cultivars that are tolerant to local stress, plant geneticists and horticulturists may find this concept to be helpful (Silva et al., 2017).

Land preparation: These tillage techniques frequently fall under larger agronomic principles like residue management, continuous ground cover, and different crop rotations in conservation agriculture. Some common tillage and establishment systems are summarized in the definition of tillage systems, which differ across practitioners. However, the soil volume will be prepared for robust and wide root growth, which is subsequently required for the effective use of water and nutrients, by tillage systems employing a bottom or spinning *moldboard plow*. Before installing plastic mulch and transplanting, final soil preparation and/or bedding should be carried out with a rotary tiller, bedding disc, double disc hiller, bedding press, or levelling board (Dixon et al., 2020; Townsend et al., 2016).

Propagation: The tomato (*Solanum lycopersicum* L) was the subject of the first study to find the perfect age for transplanting tomatoes in 1929. Studies used seedlings grown in peat, plastic, wood, or Styrofoam containers, and later researchers used soilless commercial mixes, nutrition regimens, and plastic trays. The earliest transplant-age studies typically used plants that were 7 weeks old (Vavrina & Orzolek, 2018). However, according to studies, transplants are more advantageous over direct-seeded plants due to their better plant survival, quicker establishment, increased plant uniformity, earlier maturity. In tropical regions, poor environmental conditions, pests, and viral infections are among the leading causes of tomato seedlings' low development and quality. In producing areas, enhancing the crop microclimate and keeping out insects that spread viruses may increase transplant quality and production

(Gogo et al., 2012). Meanwhile, Proper seedling preparation is essential. Trays must be sterilised, elevated, and covered with a 60-mesh net to prevent pests. Chemical or biological treatments were applied to manage fungal pathogens. Seeds were sown two per hole at a 0.5 cm depth, and seedlings were transplant at the four- to five-leaf stage (Hanson et al., 2000).

Plant spacing: Yield variation in tomatoes is a complex phenomenon affected by environmental factors, plant spacing, and stem pruning. Factors like humidity, rainfall, disease, and pests can affect yield, while optimal plant spacing can help to obtain good-quality fruits (Muhammed et al., 2006). Tomatoes benefit from a wider spacing (60 cm x 50 cm) when it comes to integrated pest management technology. The crop produces a higher marketable yield (82.39 t/ha) and reduces water and light competition (Ara, Bashar, Begum, & Kakon, 2007; Ara, Bashar, Begum, et al., 2007). Determinate cultivars are recommended to be planted 45 - 60 cm apart with a row distance of 1-1.5 m, while indeterminate types can be grown with 50 - 90 cm distance between plants and 1.5 - 2 m between rows (Ara, Bashar, Begum, et al., 2007). Furthermore, better air circulation and light interception by plants result in fewer diseases and pests. Healthy, productive tomato plants need to be spaced properly. Also, fertilization, variety, and cultural practices affect tomato plant spacing. The proper spacing of plants prevents disease outbreaks and reduces air circulation, as well as allowing light to penetrate the lower leaves (Getahun & Bikis, 2015).

Irrigation: Tomato cultivation is highly sensitive to deficit irrigation (DI) management strategies, which influence growth and yield. Water represents the primary constraint for agricultural expansion (Chand et al., 2021). Research demonstrates that drip irrigation significantly outperforms conventional irrigation methods for tomato production. Drip irrigation achieved 63.8 t/ha yield compared to conventional methods, while saving 184% more water and achieving superior water productivity of 0.30 t/ha/m^3 versus 0.08-0.09 t/ha/m^3 for furrow and border irrigation (Nipa, 2020). Climate change negatively influences agricultural production, leading to rising temperatures, erratic precipitation patterns, increased droughts, and rising water demands from competing industries. These factors could pose significant challenges to crop production in the future (Chand et al., 2021). To ensure optimal growth, tomato plants need to be watered 5 to 6 mm every day. Particularly throughout the following growth stages: early plant growth, fruit set, and the fruit enlargement phase, it is essential for achieving consistent maturity in tomatoes. Irrigation is tightly managed when the fruit reaches its ideal size to prevent fruit rot and fractures (Sánchez-Rodríguez et al., 2014).

Pruning and spurting stalk: Tomato seedlings typically reach a height of 12 to 18 cm, after developing 10 to 13 true leaves during the early vegetative stage. Lateral branches are also forming currently, yielding fruit that is beginning to add to the tomato's weight, necessitating the need for structural support. Meanwhile, pruning helps plants achieve their goals of increasing their photosynthetic activity while decreasing their chance of contracting diseases as a result of mutual shadowing and dense structure (Alam et al., 2016). For determinate tomato types, only suckers below the first flower cluster need to be removed; in contrast, maintaining no more than four stems is advised for indeterminate tomato types. The second stem should develop from the first node above the first fruit, especially for multi-stemmed plants, and the same rule should be followed for the successive stems. This will lead to healthy laterals that do not dominate the main stem (Alam et al., 2016; Muhammed et al., 2006).

2.5.1 Main pests and diseases of tomato cultivation

Disease control is a critical challenge in organic agriculture (Figure 5), particularly for tomato cultivation. While organic plant protection methods exist, diseases and pests significantly impact tomato yield and quality. Disease-resistant traits are highly beneficial for growers. Four major fungal diseases affecting tomatoes are *Fusarium wilt, Fusarium crown, late blight,* and *Sclerotinia rot*. Late blight, caused by *Phytophthora infestans*, is particularly devastating, leading to losses of up to 70%. Tomatoes are susceptible to over 200 pests and diseases that directly or indirectly affect their productivity (Panthee & Chen, 2010). Pests such as *Helicoverpa armigera* (bollworm) and the potato beetle are among the most economically damaging. *Helicoverpa armigera* larvae bore into fruits, causing significant damage, while root-knot nematodes form galls in roots, restricting water and nutrient uptake, leading to stunted growth and reduced yield. Biological control methods, including parasitic wasps, predatory bugs, birds, spiders, and microbial pathogens, are effective against *Helicoverpa armigera* (Mustafa, Adjei, et al., 2023). Other notable diseases include early blight, bacterial canker, and mosaic virus, all of which contribute to substantial economic losses for farmers. Effective pest and disease management is crucial for sustainable tomato production (Ramadan et al., 2017).

	
Larva of Helicoverpa armigera	*potato beetle damage*

	
Bacterial canker	*Late blight disease*
	
Root-knot nematode	*Tomato mosaic virus disease*

Figure 5: Pests and diseases affecting tomato crops damage and Infections (Ramadan et al., 2017).

Pests and diseases control in organic farming: Organic farming employs diverse methods for pest and disease management due to restrictions on synthetic pesticides. The primary approach emphasizes preventative measures through maintaining biological diversity and soil health via balanced crop rotations, nitrogen-fixing and cover crops, intercrops, and additions of manure and compost (Kumari et al., 2020). Cultural practices include reduced soil tillage, which naturally suppresses most soil-borne diseases, though foliar diseases can remain problematic (van Bruggen et al., 2016) By 2025, the EU organic farming framework (https://agriculture.ec.europa.eu/farming/organic) based on Reg. 2018/848 and its updates enforces strict preventive pest and disease control, minimal synthetic input, and transparent certification. All exceptions are temporary, justified, and closely monitored, ensuring high environmental integrity and consumer trust in organic products.

2.6 Agroforestry systems

Agroforestry is an ancient practice, growing crops and trees on the same land area is a long-standing tradition. As part of early worldwide efforts to study integrated production systems, including crops and trees, the word agroforestry was first used in 1977 (Nair et al., 2021). However, initiatives were launched in North America, China, Australia, New Zealand,

and southern Europe after it was recognized to effectively address major environmental challenges such as soil erosion, water pollution, and biodiversity loss (Nair, 2011). The foundation of agroforestry is the expectation that both on- and off-farm tree production will contribute to the management of natural resources and sustainable land use. The system offers connections with trees and other landscape elements at the landscape and watershed levels, while the above- and below-ground variety increases the system's stability and resilience at the site level. These agroforestry systems' ecological underpinnings show themselves in the provision of environmental services such as soil protection, carbon sequestration, biodiversity preservation, and improvement of water quality (Garrett, 2015). Agroforestry is divided in various categories based on the characteristics of its products: agriculture-forestry, agriculture-fruit, agriculture-vegetables, agrosilvicultural systems, silvopastoral systems, and agrosilvopastoral systems. The system can be categorized as a sub-system based on the type of system (Chongfa et al., 2002), as shown in Table 1.

Table 1 : Commonly used classifications of agroforestry techniques and practices.

Practice Technique	Short Summary
Hedgerows	Hedgerows consist of rows or clusters of trees, shrubs, perennial herbs, and grasses established along roadsides, fences, field margins, or other uncultivated areas.
Alley cropping	Alley cropping the trees should be spaced closely within rows (~0.5 m) but with wide spacing between rows (4 m or more). To reduce the shading of crops, the woody species should be periodically pruned at low heights (1.0 m). The resulting pruning's can be used as mulch in the alleys, providing a source of organic matter and nutrients that can be utilized as crop fertiliser (Nair et al., 2021; Nair et al., 2010).
Taungya	Raising crops during the initial phases of establishing forestry (timber) plantations; cropping is done for two or three years, depending on the rate of tree canopy development (causing crops to be shaded by trees) and soil fertility (Nair et al., 2021; Nair et al., 2010).
Trees with several uses for farms and rangelands	Fruit trees and other multifunctional trees are dispersed or planted in various methodical configurations. Trees produce goods like fruits, fuelwood, fodder, and lumber.
Techniques of cut-and-carry method systems with shady perennial crops	Cultivating shade-tolerant plants under or between overstory shade-, timber-, or other commercial tree crops, such as cacao (*Theobroma cacao* L.) and Coffea sp.
Improved fallow practice	Fast-growing, preferably leguminous, woody species planted and allowed to develop during brief fallow intervals of no more than three years between cultivating years contribute to the improvement of the land and may produce profitable goods.
Homegardens systems	Intimate multistorey arrangements of various trees, particularly fruit- and nut-producing species, as well as crops on homesteads; animals may or may not be present; the garden is tiny (less than 1 hectare), and it is actively tended, often by family work.

The cultivation of vegetables with trees simultaneously, whose components are arranged spatially to achieve both the economic and environmental benefits of the farming system (Wang et al., 2014). On the agricultural scale, the combination of agroforestry plots with ephemeral crops like vegetables, such as tomato crops, can certainly act as a haven and a source of beneficial insects. As a result, agroforestry systems could be a good option that supports ecosystem services and aids producers in making the switch to agroecological agriculture. Natural enemies that protect the horticultural crops by eliminating insect pests when herbivores are present can be found in agroforestry systems. Natural enemies can develop a numerical response to herbivore abundance, but their populations are also impacted by random elements associated with climate circumstances. As a result, agroecological systems and practices may promote agriculture based on the preservation and maintenance of ecosystem services (Harterreiten-Souza et al., 2014a).

2.6.1 Hedgerow systems

In modern agricultural systems, hedgerows, windbreaks, filter strips, complex plant communities that function as small ecosystems are becoming increasingly common. For thousands of years, farmers and rural dwellers have planted hedgerows. Hedgerows date back to 547 A.D., and fields were enclosed as early as the Bronze Age, 3000 B.C.–1000 B.C (Jones, 1992). Hedgerows are lines or groupings of trees, shrubs, perennial forbs, and grasses planted along roadways, fences, field edges, or other non-cropped areas. However, windbreaks and other agroforestry systems can benefit sustainable agriculture systems in a variety of ways. It does, however, require a thorough study of all parts of the agricultural system, as well as a working knowledge of local conditions and basic ecological principles (Brandle et al., 2004a). The name hedge comes from the old English word Hegg, which means closely grown bushes or dead plant debris (Earnshaw, 2004). In other name, hedgerows can be called as windbreaks, which are natural barriers composed of trees or bushes that reduce and redirect wind, producing microclimate changes in the protected zone (Chaudhary, 2000). Also known as filter strips, vegetation-covered regions control soil erosion, slow runoff, and capture and prevent sediments and nutrients from entering waterways.

Tree shelterbelts represent a crucial agroforestry practice for sustainable agriculture, offering multiple environmental and economic benefits. Research demonstrates that shelterbelts effectively protect crops from wind damage, reduce soil erosion, and improve field microclimates while providing opportunities for production diversification (Szigeti et al., 2020a). Tree shelterbelts significantly improve crop micro-climate by reducing wind and evaporation, which can boost yields by up to ~50 %. However, the actual benefit depends strongly on site, crop, and shelter design. They are a promising agroforestry strategy for sustainable production and ecosystem resilience (Suratman & Brandle, 2023). However, farmer adoption faces challenges, with over half of surveyed farmers in Kyrgyzstan expressing negative perceptions due to concerns about crop shading, reduced yields, and small field sizes. Despite these barriers, shelterbelts remain essential tools for climate adaptation and environmentally sustainable agriculture (Ruppert et al., 2020).

Intercropping in agroforestry systems offers significant benefits for agricultural productivity and economic viability. Research demonstrates that intercropping increases cropping intensity through temporal and spatial complementarity between crops, with advantages under moisture stress conditions (Willey et al., 1987). Integrate vegetables with woody components in various spatial arrangements across agricultural landscapes. Horticulture based alley cropping systems combine perennial woody crops with vegetables, providing economic and environmental benefits while maintaining higher output and improving farmers' livelihoods (Pandey & Tiwari, 2022). Horticulture-based alley cropping systems maintain higher output while improving farmers' livelihoods and providing year-round employment (Pandey & Tiwari, 2022). Research on vegetable production in agroforestry systems shows mixed results. A study comparing cabbage production found equivalent yields between agroforestry and conventional systems (66.08 vs 66.76 t/ha), but the agroforestry system proved more economically profitable and showed different pest dynamics (Essomo et al., 2024). However, another study by Kovács and Vityi, (2022) examined the effects of intercropping poplar (*Populus* × *euramericana* cv. I-214) with maize in Hungary's traditional Vákáncsos forestry system. Results showed that the agroforestry plots significantly reduced soil temperatures by 1–14 °C, improved humidity, and lowered wind speed compared to monoculture stands in the warmest period of the year. These microclimate benefits enhance the stress tolerance and growth of young poplar seedlings. The research concludes that intercropping can increase afforestation efficiency, land-use optimization, and climate resilience in Hungarian forestry (Kovács & Vityi, 2022).

2.6.2 The benefits of hedgerows and sustainability goals.

Hedgerows can perform several functions, including supplying habitat for beneficial insects and pollinators. Other benefits include wildlife habitat creation (Heath et al. 2017), water quality protection (Long et al. 2010), erosion protection and weed control, stabilizing waterways, limiting non-point source water pollution and groundwater pollution, increasing surface water infiltration, buffering pesticide drift, noise, odors, and dust, responding as living fences and boundary lines, increasing biodiversity, and supplying an aesthetic resource (UC IPM 2017). Hedgerow species diversity, especially when utilizing indigenous species, ensures a variety of benefits, including attracting a range of insects and wildlife and increasing pollination and pest control by beneficial insects (Morandin et al. 2016), enhancing soil and water resources, and ensuring individual plant viability under site-specific climatic and other environmental conditions (Ghazavi et al., 2008).

Hedgerow intercropping systems using mulberry combined with vetiver or alfalfa have been shown to enhance soil fertility, reduce erosion, and support higher overall crop performance on sloping lands in Southwestern China. These hedgerow systems enhanced soil organic carbon and nitrogen while lowering bulk density, showing that crop hedgerow intercropping effectively stabilizes soils and boosts productivity in fragile hilly regions (Lei et al., 2021). Hedgerow intercropping systems in Europe and other regions show varied effects on agricultural sustainability and productivity. In Europe, cereal-grain legume intercropping has gained renewed interest for sustainable intensification, particularly in organic farming, with over 50 field experiments conducted across 13 sites in France and Denmark demonstrating effects on yields, quality, and agronomical performance (Bedoussac et al., 2018). Furthermore, study in maize systems in western Kenya was evaluated. Farmers managed hedges well but faced high labour demands, especially during busy seasons, and women rarely pruned. Profitability required 10–17% higher maize yields to break even. Although some farmers noted yield and soil improvements, only about 20% expanded hedges, showing limited adoption due to labour intensity and low short-term returns (Swinkels et al., 1997). However, small woody features such as hedgerows, field boundaries, and riparian buffers represent overlooked agroforestry systems of significant importance in European agricultural landscapes, with managed and unmanaged hedgerows being dominant in France, Great Britain, and Ireland (Rubio-Delgado et al., 2024). Furthermore, in South Asia show mixed results for crop productivity and sustainability. Research in Indonesia demonstrated that hedgerow intercropping with peltophorum and mixed peltophorum-gliricidia systems maintained similar yields to monoculture while improving soil fertility, though gliricidia alone showed negative interactions (Suprayogo et al., 2010).

2.6.3 Windbreak concept and consequences on ecosystems.

Windbreaks significantly modify airflow patterns and provide substantial agricultural benefits. The effectiveness of windbreaks is primarily determined by their porosity, with low-porosity barriers producing maximum wind reductions extending up to 50 times the windbreak height (h), though reductions of 20% or more typically extend to about 25h (Heisler & Dewalle, 1988). Windbreaks represent crucial agroforestry systems in Hungarian agricultural landscapes, providing significant climate and ecosystem benefits. Research demonstrates that doubling

Hungary's windbreak plantations by adding 14,256 hectares could sequester 913 kt C by 2050, achieving an annual climate mitigation potential of 144 kt CO^2 equivalent (Király et al., 2024). In Hungary's intensively managed agricultural systems, shelterbelts serve multifunctional roles, protecting crops from wind damage while addressing environmental problems like soil erosion and deflation that emerged when windbreak systems declined. These systems represent effective tools for sustainable agriculture and climate adaptation (Szigeti et al., 2020b). Successful agricultural systems often include windbreaks because they improve both producer profitability and the environment. They provide a habitat for numerous wildlife species and can significantly improve the carbon balance equation, reducing the financial costs of climate change. A windbreak must be created with the demands of the landowner in mind, and both the interior and exterior structures, as well as the shape, orientation, and dimensions of the building, should be taken into consideration. The capacity to use changes in microclimate to increase agricultural sustainability and profitability is possible, but the two largest obstacles are figuring out why farmers are hesitant to use windbreak technology and defining the function of woody plants in the agricultural ecosystem (Brandle et al., 2004b).

Windbreaks function by impeding wind flow and changing flow patterns, which affects wind efficiency and speed. They are directly applicable to farming operations and agricultural production systems, including field and animal farming as well as regenerative agriculture, which utilizes resources from the entire farm. The design, management, and advantages of windbreaks, as their influence on the regenerative agricultural landscape, are examined. Plants respond to wind protection through improved physiological stability, reduced transpiration rates, enhanced leaf retention, and increased biomass accumulation (Brandle et al., 2022).

2.6.4 Design of contour hedgerow-intercropping

The requirement for ancient cultures with growing populations to cultivate trees and food crops on a limited land base, as well as the peaceful coexistence of numerous species in natural forested ecosystems that produced many goods, are the driving forces behind agroforestry methods. Yet, as listed below, four essential characteristics describe and set agroforestry methods apart from others. Agroforestry systems (1) are intentionally designed and managed to maintain the functional interactions between trees, crops, and soil, using practices such as cultivation, fertilization, irrigation, pruning, and thinning to support their productivity. (2) They form a single integrated management unit, maximizing the land's potential for production. Additionally, (3) they actively control and make use of the biophysical interactions between component species, and (4) they produce a variety of goods and provide other ecosystem services (Jose & Gordon, 2008).

A contour hedgerow-intercropping system is a farming system comprised of two parts: contour hedgerows and the agricultural activities that run between them. Planting trees or bushes closely and along a contour line on sloping terrain creates a contour hedgerow, often known as an „active hedge." This farming system is called contour farming. In comparison to pure plantation agriculture and shifting agriculture, this design provides a significant potential for soil and water conservation. The hedgerow intercropping system is classified as a system, sub-system, or structure based on the relationship between the crops and the hedgerows (Chongfa et al., 2002).

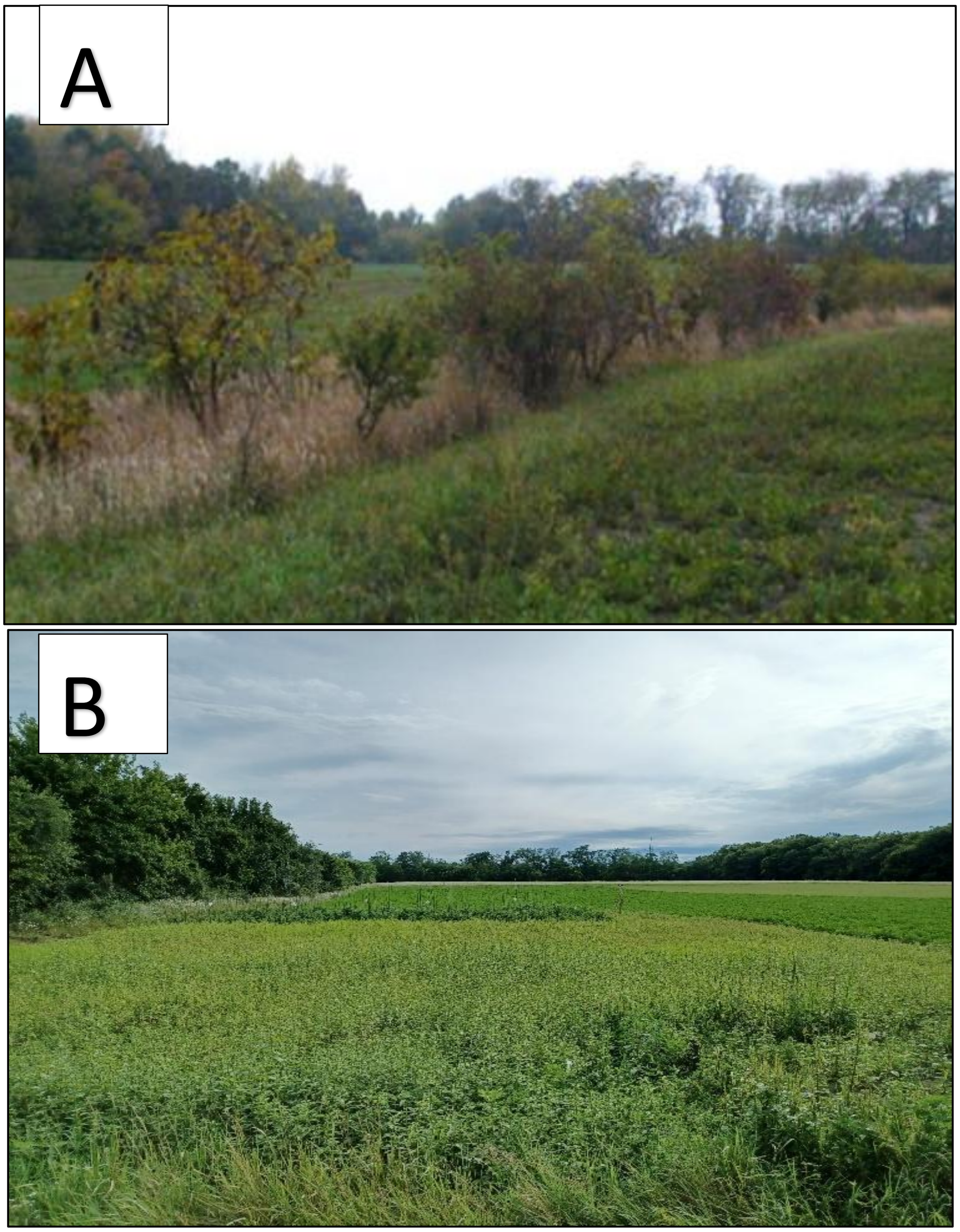


Figure 6: Hedge in the research and experiment field of the organic unit in soroksár research and experiment station (A) (Szalai, 2010), and (B) (Mustafa, Adjei, et al., 2023).

A practical example of wind mitigation in regenerative agriculture can be observed at the Research and Experiment Field of the Organic Unit in Soroksár, part of the previously named Hungarian University of Agriculture and Life Sciences Research and Experiment Station. As shown in Figure A, the site is bordered by an older, pre-existing woodland belt that has been in place for many years. To further reduce wind impact, an additional hedgerow composed of local woody species was established later, in two phases during 1999 and 2000. Figure B shows the same site in 2025. (Szalai, 2010; Mustafa, Szalai, et al., 2023).

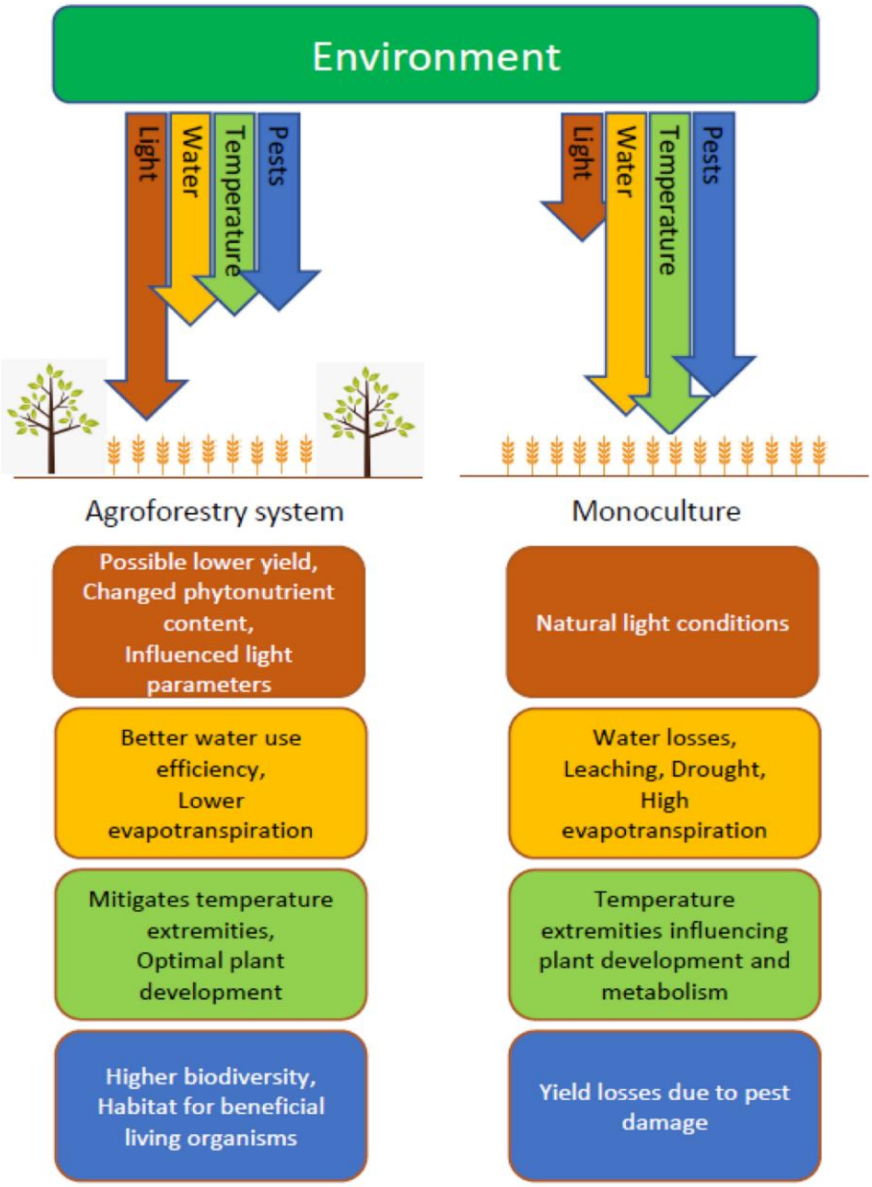


Figure 7: Stress elements are crucial in arable farming and agroforestry systems, with severity indicated by the length of arrows (Mustafa et al., 2022).

The arrows in the (Figure 7) are illustrative and not scaled to indicate quantitative importance. Their purpose is to visually represent the qualitative influence of environmental factors (light, water, temperature, and pests) on agroforestry and monoculture systems, rather than their relative magnitudes (Mustafa et al., 2022).

2.6.5 Carbon sequestration and climate change

Agroforestry systems are thought to be better able to collect and exploit growth resources (light, nutrients, and water) than single-species crop or pasture systems, and they are thought to have a higher potential to store carbon. Estimates of the amount of carbon held in AFS range from 0.29 to 15.21 t/ hectare/year above ground and from 30 to 300 t hectare^{-1} and below ground up to a depth of 1 m. Research by Nair et al., (2010), found that tree-based agricultural systems retained more carbon in deeper soil layers close to the tree than away from the tree, and that higher organic soil content was related to higher species diversity and tree density, relative to treeless agricultural systems. Also, in deeper soil profiles, C3 plants (trees) provided more carbon to the silt and clay fractions (<53 μm) than bahi agrass, which are more stable carbon sources than C4 plants (Haile et al., 2010). The quantity of carbon that AFS was able to sequester was heavily influenced by system management and environmental factors (Nair, 2011).

2.7 Organic farming and tomato cultivation

Organic farming: The EU adopted Regulation (EC) No 2018/848 in 2022 to protect the environment and consumer health through organic agricultural production (Argyropoulos et al., 2013). Organic farms have higher biodiversity in the soil, crops, fields, entire rotation or polyculture, and landscape levels (Mäder et al., 2002; Lammerts Van Bueren et al., 2011). Although organic systems apply fertilizers derived from organic matter, the availability of macronutrients particularly nitrogen (N) and phosphorus (P) can be limited due to the slow and variable rates of mineralization. Unlike synthetic fertilizers, which provide immediately available nutrients, organic inputs depend on microbial activity and environmental conditions to release nutrients, potentially leading to temporary nutrient restrictions during critical crop growth stage (Baresel et al., 2008). Crop genotypes with strong root systems, active mycorrhizal linkages, decreased root losses from diseases, and the capacity to recover from the topsoil is needed to enhance nutrient-use efficiency (Ghorbani et al., 2008).

Organic fertilizers: Plants require energy for proper development, and sixteen essential elements are required in vastly different amounts. Carbon, hydrogen (H), and oxygen (O) are derived from the atmosphere and soil water, while the remaining thirteen elements are supplied either from soil minerals and soil organic matter or by organic or inorganic fertilizers (Mengel et al., 2001). Organic fertilizers such as farmyard manure, slurries, and green manure have most plant nutrients in an inorganic form, while other nutrients, such as nitrogen and sulfur, are converted to inorganic forms by soil microorganisms before the absorption by plant roots takes place. Inorganic and organic fertilizers do, however, differ in the availability of the plant nutrients they contain. Nutrients in inorganic fertilizers are directly available to plant roots, whereas nutrients in organic materials must first be processed by soil microorganisms. These organic nutrients primarily support microbial activity, which in turn enhances nutrient cycling, soil health, and resilience (Ntim Amedor et al., 2015).

Research on organic manure applications in agroforestry systems reveals varying optimal rates and limitations, the study found that organic fertilizers applied at 5 tons/ha in teak-based agroforestry systems enhanced soybean nutrient uptake and yields compared to inorganic fertilizers, with peanut green manure producing the highest yield of 1.6 tons/ha (Setyaningrum et al., 2024). However, (Sudharta et al., 2022) identified nitrogen limitation as a key constraint in coffee-pine agroforestry systems, requiring nitrogen fertilizer supplementation to achieve yield increases up to 3.9 times compared to no-management treatments.

Organic tomato cultivation: Organic tomato cultivation can achieve 80% of the total productivity in terms of volume kg obtained in the conventional system (Seufert et al., 2012). The organic system may significantly enhance productivity with better management and greater soil fertility. Furthermore, a study found that growing tomatoes using organic methods is lucrative and can be up to 113.6% more profitable than conventional goods, compared to other herbaceous plants (Santos Neto et al., 2017). Nevertheless, research investigations by Jalpa &Mylavarapu, (2023), into the best soil conditions for improving tomato productivity in an organic agricultural system is the total carbons (TCs) of 30,000-36,000 mg/kg, the total nitrogen (TNs) of 1600-1900 mg/kg, and a C/N ratio of 18-21. Compost and cover crops are used to improve the soil and encourage strong plant development, while companion planting is used to ward off pests. This encourages a more ecologically responsible and sustainable method of agriculture (Adhikari et al., 2018).

2.7.1 Tomato on EU organic regulation

The EU's organic laws and production methods provide unique challenges for the development of organic tomatoes. Reducing the use of conventional untreated seeds is the goal of the new EU organic rule that went into effect in 2022, highlighting the significance of organic seed supply (Schwitter et al., 2022). Different harvesting practices and fruit maturity levels had no discernible effects on seed quality and germination rates, according to research on organic seed production (Schwitter et al., 2022). Although production methodologies have varying effects on fruit quality features among cultivars, comparative studies show that organic tomato yields are generally around 63% of conventional yields (Riahi et al., 2009). demands consideration of crop rotation techniques, soil fertility management, variety selection, and site selection (Baglieri et al., 2014; Diver et al., 2014). The need for cultivars suited to organic conditions has surged as a result of the EU's goal of having 25% of agricultural land be organic by 2030 (Paull, 2024).

2.8 Tomato fruits' physico-chemical characteristics

Tomatoes are a widely consumed fruit and vegetable known for their nutritional benefits. Studies have been conducted to understand the chemical composition, nutritional value, and antioxidant content of both fresh and processed tomato-based products. It is important to consider preharvest and postharvest variables to optimize the quality and nutritional value of the products. (Acharya et al., 2010; Opara et al., 2012). On the other hand, tomatoes are a great source of trace elements, including copper, manganese, zinc, selenium, and vitamins C, B6, E, and folic acid, which are essential for human immune defence systems. An important chemical component of tomatoes is ascorbic acid, which is necessary for plant nutrition and contains sugars that affect tomato quality and customer preferences (Felföldi et al., 2022). Fruit quality is a broad notion that encompasses all aspects of agronomy, commerce, nutrition, and gustation. The physiological functions of the fruit cells continue even after harvest, and maturity affects the quality and post-harvest storage life. The best quality and sensory standards are found in mature fruits (Harker et al., 2003). Ethylene controls the distinctive physico-chemical processes of ripening in the tomato fruit's climacteric ripening. Nevertheless, long shelf-life (LSL) cultivars represent a distinct category of fruit varieties characterized by reduced ethylene production and extended storage capability. In tomatoes, LSL phenotypes can maintain fruit quality for up to ten months after harvest without deterioration symptoms (Juan-Cabot et al., 2022).

In the Rambla et al. (2014) study, the rate of fruit development and non-volatile chemical production in tomato fruit are correlated. In the same way, organic acids (mg/100 g) and water-soluble pectins (%) are volatile reducing chemicals. Particularly, it was shown that total pectic materials (%) and total titratable acidity (%) increased in concentration at the beginning of maturation but decreased toward the conclusion of the ripening stage (Rambla et al., 2014). Additionally, it was noted that ascorbic acid levels (mg/100 g) rose to the beginning of maturity. Through the various phases of development, the concentrations of the chemicals that impact fruit colour alter. These substances consist of lycopene (mg/100 g), carotene (mg/100 g), and chlorophyll (mg/100 g). While this was going on, other research looked at how various agronomic factors affected certain fruits' physical and chemical characteristics (Dabesor et al., 2022; Rambla et al., 2014).

2.8.1 Tomato fruit colour

Tomatoes are at their best organoleptic quality and ready for consumption when they reach their full red colour stage. This is because lycopene and other carotenoids are created when chlorophyll is broken down, giving fruit skin their characteristic red shade. To distinguish between different levels of ripeness, the USDA has established six ripening stages: green, breaker, turning, pink, pale red, and red (Table 2). However, these categories are intended for research and quality control purposes, not for consumers, who typically seek fully ripe (red) fruits, here, the focus is limited to nature tomato varieties. (López Camelo & Gómez, 2004).

The most significant antioxidant present in tomatoes is lycopene, which is an acyclic carotenoid. Lycopene is the cause of the mature fruit's crimson hue, and it is employed in production techniques as one of the markers of quality and maturity. When tomatoes are still in the immature stage, they contain chlorophyll, which gives them their green colour. However, during the ripening period, this pigment is broken down, and yellow pigments like xanthophylls and beta-carotene are enhanced. As a result, lycopene accumulates more due to the enhanced synthesis of the two pigments previously discussed. The ratio of lycopene to β-carotene affects how brightly coloured red fruits are. The concentration of these chemicals is significantly impacted by the ripening, maturity, variety, and growing circumstances of the tomatoes (Duma et al., 2015; Jiang et al., 2020).

Table 2: USDA Tomato fruit colour identification (Jiang et al., 2020).

Colour type	**A percentage is used to describe the colour of the tomato.**
Red	Over 90% of the colour is red.
Light red	The colour ranges from reddish, between 60% to 90%.
Pink	The surface contains a reddish colour that ranges from 30% to 60%.
Turning	The aggregate colour, excluding green, falls within the range of 10% to 30%.
Breaker	There is an observable shift in colour with less than 10% of non-green hues present.
Green	Green 100%

Though the technique of classifying colours has long been in use, more precise colorimeter systems are now becoming increasingly common. CIELAB which quantifies colour, is one of the most widely used techniques for evaluating the colour of tomato fruit. This offers an objective numeric assessment of this external characteristic, which serves as a helpful supplement to the visual colour categorization, which mostly depends on human perception and is, in turn, highly complex owing to variations in brightness, light, intensity, and other factors (Duma et al., 2015; López Camelo & Gómez, 2004). The CIE Lab* colour space was created in 1976 by the Commission International de l'Eclairage (CIE). It is divided into six stages, which are defined by the amount of non-green or reddish colour present in the material being described. The L* axis measures the achromatic component of the colour, which corresponds to the relative lightness or darkness of the material. It runs vertically, with a maximum L* value of 100, indicating white, and a minimum value of 0, indicating black (Viscarra Rossel et al., 2006).

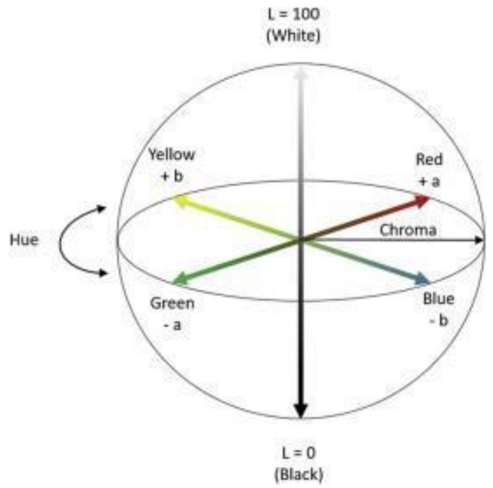


Figure 8: The CIELAB colour space diagram (Ly et al., 2020; Viscarra Rossel et al., 2006).

The a* and b* values in the CIELAB colour space are used to measure the chromatic characteristics of a material. Unlike the L* axis, these values theoretically do not have specific numerical limits, most practical systems limit their values between -127 and 128. Positive a* values indicate redness and negative values indicate greenness. Positive b* values indicate yellowness and negative values indicate blueness (Figure 8), so these measurements can be utilized in other analyses, such as determining the lycopene content of a material (López Camelo &Gómez, 2004).

2.8.2 Vitamin C, ascorbic acid (AsA)

Tomatoes are a significant dietary vitamin C, primarily as ascorbic acid (AsA), with smaller amounts of dehydroascorbic acid. The vitamin C content varies depending on the tomato cultivar and growing conditions, with red tomatoes typically containing about 23 mg of ascorbic acid per 100 grams of fresh fruit. The production and accumulation of ascorbic acid are closely linked to the fruit's maturation stage. In comparison to fresh tomatoes, stored or processed tomatoes can lose up to 50% or more of their ascorbic acid content due to thermal degradation during processing and prolonged storage. Proper environmental adjustments, such as temperature control, can help preserve vitamin C in fresh tomatoes (Ntagkas et al., 2016; Valšíková-Frey et al., 2017). Tomatoes have a high concentration of vitamin C early in their maturation, which decreases gradually as the fruit grows. However, vitamin C levels typically increase again as the fruit ripens, reaching their peak during the overripe stage (Ntagkas et al., 2016). AsA is a water-soluble antioxidant that plays a crucial role in plant development. It impacts several vital physiological functions, including the removal of reactive oxygen species (ROS), which are essential regulators of cellular processes in aerobic organisms, as well as growth regulation, cell metabolism, cell division, wall expansion, and the synthesis of other metabolites. It is also essential for human nutrition (Mellidou et al., 2021).

2.8.3 Tomato fruit lycopene

The pigment lycopene is primarily in charge of giving tomato fruit its distinctive red hue. The amount of lycopene in several tomato fruit fractions, including the skin, water-soluble, water-insoluble, fiber rich pulp, and soluble solids fractions, was estimated using High-Performance Liquid Chromatography HPLC and a spectrophotometric technique. The findings showed that the epidermis and the water-insoluble fraction accounted for 72–92% of the lycopene. Lycopene levels were higher in the fiber-rich tomato pulp fraction (42.3 mg/100 g) than in the water-soluble fraction (4.0 mg/100 g). According to the results, lycopene may be precisely measured using the spectrophotometric technique or HPLC (Chandra et al., 2012; Marković et al., 2010). Lycopene is a ~~crucial~~ key biological compound that has been linked to preventing atherosclerosis, skin cancer, prostate cancer, and cardiovascular diseases. It is a primary antioxidant found in both fresh and processed tomatoes, and it is stable even after harsh processing techniques. Lycopene is the most abundant and economically accessible carotenoid, accounting for 80–90% of the total carotenoids in popular tomato varieties (Agarwal & Rao, 2000). Lycopene is a powerful antioxidant with antibacterial, photoprotective, anti-hypercholesterolemic, antioxidant, and cardioprotective properties. It is essential for protecting cells from oxidative damage to proteins, lipids, and DNA. Lycopene's molecular makeup is C40H5, making it a valuable nutraceutical. The red-coloured carotenoid pigment is essential for protecting cells from oxidative damage (Carvalho et al., 2021; Rajoria et al., 2010).

2.8.4 Total soluble solids (TSS, °Brix)

Tomatoes are widely valued for their rich nutritional profile, including vitamins, minerals, dietary fiber, and antioxidants (Arah, Amaglo, et al., 2015; Olaniyi et al., 2010). Their composition has been extensively studied in both fresh and processed forms. To maintain quality and nutrient density, careful management of preharvest and postharvest factors is essential (Table 3). A tomato’s composition consists mainly of water, tomato solids (soluble and insoluble), organic acids, primarily citric acid, and trace minerals including carotenoids and vitamins A and C. Soluble solids, which are mainly composed of salts and sugars, are measured in degrees Brix (°Brix). The tomato’s total solids, including seeds and peel, range from 4.5% to 8.5%, depending on the variety, soil, and environment. The flavour of tomato concentrate is mainly determined by its sugar-to-acid ratio, which shapes its sweetness and tanginess in the final processed product (Pedro & Ferreira, 2007).

Table 3: The fifteen primary nutrients obtained from tomatoes (Arah, Kumah, et al., 2015).

Nutrient	Pantothenic acid (mg)		Vitamin C (mg)	Mg (mg)	Dietary fiber (g)	P (mg)	Fe (mg)	Total sugars (g)
Amount	0.109		16.9	1.4	1.5	3	0.33	3.23
Nutrient	Niacin (mg)	Fat (g)	Copper (mg)	K (mg)	Protein (g)	Thiamin (mg)	Ca (mg)	Carbohydrate (g)
Amount	0.731	0.2	0.073	292	1.0	0.046	1.2	4.7

2.8.5 Titratable acidity (TA, ACID) and sugar acid ratio (SAR)

High nitrogen supplies, such as total soluble glucose, fructose, and pH, can harm tomato quality characteristics. Decreased nitrogen sources can improve fruit taste, but variations in phosphorus content cannot affect quality attributes like solids, pH, the acidity of tomato juice, and fruit colour (Arah et al., 2015). Concentrations of total pectic materials and titratable acidity increased at the start of maturation (Rambla et al., 2014). Tomatoes are thought to be rather acidic, with a pH range of 4.0 to 4.5 or 4.3 to 4.4 in most cultivars. The "tartness" of the fruit is greatly influenced by acidity, which also has a significant impact on the fruit's overall quality and flavour. It is a well-known fact that fruit with lower acidity tastes less intense flavour. The degree of ripeness, climate, growth media, as well as cultural practices, are typically found to have an impact on this parameter (Tyl. & Sadler, 2017). The quantity of these substances in the fruit may be determined using conventional techniques like titration, chromatography and enzymatic kits. Nevertheless, these elements and other substances contained in the fruit are being measured using more contemporary techniques, including infrared (IR) spectroscopy (Wilkerson et al., 2013). These approaches enable the study of various juice constituents from a single sample and are less complicated, time-consuming, and expensive than conventional approaches (Thorne & Efiuvwevwere, 1988).

2.8.6 Carotenoids

Carotenoids, found in tomatoes, are natural compounds that reduce the risk of various diseases and have anticancer properties, especially against prostate, lung, and stomach cancers (Ali et al., 2021). Tomatoes are rich in carotenoids like lutein, phytoene, phytofluene, neurosporene, α-carotene, β-carotene, γ-carotene, δ-carotene, and lycopene. According to (Martínez-Blanco et al., 2011) measured the concentrations of these pigments in tomatoes, found lycopene levels ranging from 7.8-18.1 mg/100 g FW. Lutein, a carotene found in ripe tomatoes, becomes detectable as the fruit matures. High-Performance Liquid Chromatography (HPLC) is the most precise method for detecting and quantifying lycopene in fresh, canned, and juice samples. Other methods, like colorimetric and spectrophotometric, are also used. The accuracy of results depends on the required skill, time, and precision (Chaudhary et al., 2018). However, research indicates that carotenoids are vital for plants, protecting the photosynthetic apparatus from excess light and aiding in fruit colour development (Cui, 2021; Felföldi et al., 2022).

2.8.7 Total phenolic compounds (TPC)

Tomatoes are an important source of antioxidants, including phenolic compounds, flavonoids, and carotenoids. Research indicates significant differences in the levels of these compounds across various tomato cultivars and species (Figure 9). Among them, quercetin stands out as the most abundant flavonoid, while chlorogenic acid is the dominant hydroxycinnamic acid, with its concentrations varying across commercial tomato varieties (Periago et al., 2002a). Phenolic compounds, a group of secondary metabolites in plants, are distinguished by their structure, which includes one or more hydroxyl groups attached to a benzene ring. Various factors, including genotype, storage conditions, extraction methods, and environmental influences shape the levels and composition of these compounds in foods (Chaudhary et al., 2018).

Ripe tomatoes are particularly rich in phenolic compounds, which play essential biological roles. They help plants recover from injuries caused by insects, attract pollinators, and function as pigments in plant tissues. Additionally, phenolic compounds benefit human health due to their antioxidant properties, which can help prevent chronic diseases and may slow the aging process. Tomatoes contain a diverse range of phenolic compounds, with over 8,000 identified in plant materials (Periago et al., 2002a). These compounds are categorized into phenolic acids including caffeic, chlorogenic, sinapic, p-coumaric, and ferulic acids, and flavonoids like quercetin, rutin, kaempferol, and naringenin. As tomatoes mature, their chlorophyll content decreases, while the accumulation of flavonoids increases (Jafari et al., 2017). Reversed phase HPLC is frequently used to assess organic acids in fruits, juices, and other biological fluids. UV absorbance at 210 nm is used for detection; for major acids, mild chromophore detection is sufficient (Marconi et al., 2007). However, it can be challenging to measure molecules containing conjugated double bonds, including phenolics and nucleotide phosphates, due to the limited selectivity of UV detectors at 210 nm. Anion exchange columns manufactured to order have been utilized to get rid of interfering substances (Cen et al., 2007).

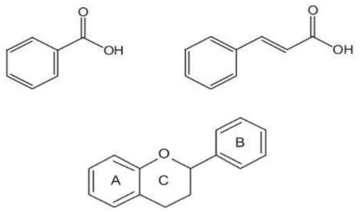


Figure 9. Total phenolic compounds (TPC) chemical structure (Rosa-Martínez et al., 2023).

2.8.8 Ferric reducing antioxidant power (FRAP)

Tomatoes are versatile fruits with antioxidant properties, including carotenoids, ascorbic acid, and phenolic compounds. Regular consumption can reduce cancer and cardiovascular disease risk due to its positive effect on health (Borguini & da Silva Torres, 2009), as shown in (Figure 10). In addition, tomatoes have high antioxidant activity due to the variety of bioactive compounds they contain. However, it acts synergistically, scavenging peroxyl radicals and singlet molecular oxygen. All parts of the tomato fruit have antioxidant activity, with skin and seeds having almost equal antioxidant activity to pulp (Dumas et al., 2003b). Research on tomato antioxidant capacity using the Ferric Reducing Antioxidant Power (FRAP) assay demonstrates significant variability across cultivars and processing methods (Marcu et al., 2025). Antioxidants (FRAP) are crucial because they scavenge oxygen-active species that are produced during ripening, under extreme heat or cold, and intense radiation. As the ripening process progresses, total carotenoids continuously climb, while ascorbic acid and some phenolics tend to build from the green to the midrise stage (Dumas et al., 2003a; Jimenez et al., 2002). However, according to (Moco et al., 2006) total antioxidant capacity (TAC) is influenced by several factors, including the fruit ripening stage, and the cultivation methods such as water availability, mineral nutrients, and the climate, mainly light and temperature. Furthermore, investigations have demonstrated that the tomato's antioxidant profile and, consequently, its nutritional value may be greatly influenced by genotype and agronomic techniques, including fertilization and crop protection methods (Gautier et al., 2008).

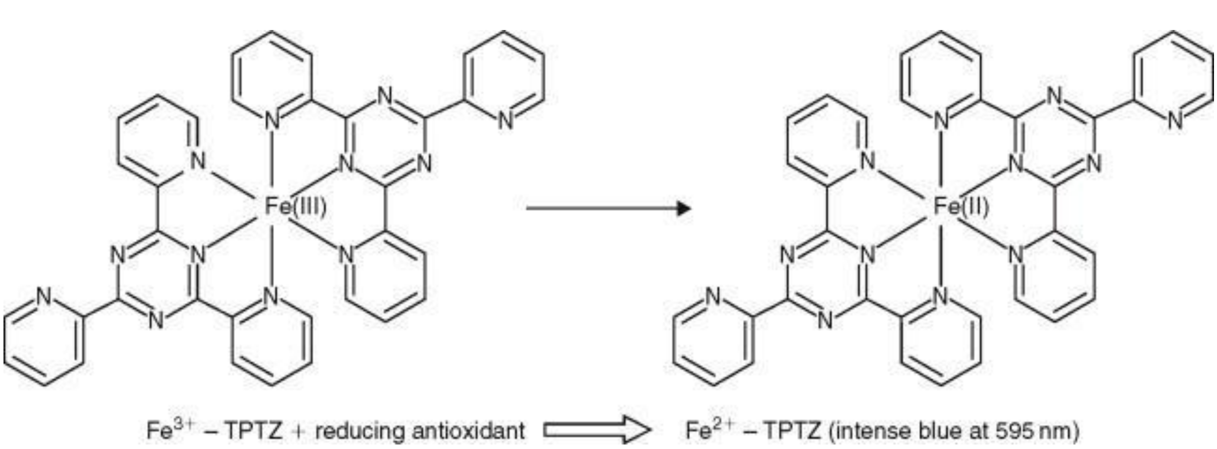


Figure 10. Ferric reducing antioxidant power assay methods (Vijayalakshmi et al., 2016).

3. MATERIALS AND METHODS

3.1 Study area and microclimatic conditions

The experiment was conducted over three consecutive years (2022, 2023, and 2024) at the Soroksár Experimental and Research Station of the Hungarian University of Agriculture and Life Sciences (47.392897, 19.148496, 150 m above sea level), specifically at a certified organic unit, with a focus on utilizing a hedgerow system to mitigate climate extremities effects, employing five-five gradually ascending distances from the hedge (W1 to W5 = Windy, P1 to P5 = Protected position). The soil type is sandy loam with a relatively low organic matter content. Weather data (temperature and humidity reported) were collected using Voltcraft DL-121TH and DL-210TH data logger instruments (Voltcraft, Conrad Electronic SE, Hirschau, Germany) to assess microclimatic differences. Loggers were positioned in the middle of each distance block, on both sides, while one logger was installed within the hedge (Figure 11). The hedgerow, in a Northeast Southwest position, is considered narrow with an average width of 5 m and a height of 5 m, and its alignment corresponds to the prevailing north westerly wind. The hedge is composed of a diverse mix of native species, creating a closed plantation (1,5 m x1,5 m in three rows), including Blackthorn (*Prunus spinosa* L.), Elder (*Sambucus nigra* L.), Common Hazel (*Corylus avellana* L.), Dog Rose (*Rosa canina* L.), Wild Privet (*Ligustrum vulgare* L.), Cornelian Cherry (*Cornus mas* L.), Common Dogwood (*Cornus sanguinea* L.), Spindle (*Euonymus europaeus* L.), Common Hawthorn (*Crataegus monogyna* Jacq.), Field Maple (*Acer campestre* L.), European Wild Apple (*Malus sylvestris* (L.) Mill.), and European Wild Pear (*Pyrus pyraster* (L.) Burgsd.) (Mustafa, Adjei, et al., 2023).

Figure 11: Satellite view of the Soroksár Experimental and Research Station of the Hungarian University of Agriculture and Life Sciences organic farming unit (Google Maps, 2025).

3.2 Plant material and experimental design layout

The experiment involved three tomato genotypes, two international varieties (Ace55, Roma), and Szentlőrinckáta (RCAT078726), a Hungarian tomato landrace, named after its place of origin. The propagation material of the landrace was provided by the Center for National Biodiversity and Gene preservation (Nemzeti Biodiverzitás- és Génmegőrzési Központ NBGK), Tápiószele, Hungary (Table 4). Tomato seeds were sown annually on April 10th in the glasshouse at the Hungarian University of Agriculture and Life Sciences, Buda Campus. Seedlings were transplanted into open field conditions on May 10th each year. This schedule was consistently followed across three growing seasons: 2022, 2023, and 2024. The experimental blocks were oriented Northwest Southeast (NE–SW), designed to reduce wind speed and enhance microclimatic conditions (Figure 12). The plots were 3 meters long, arranged in 3 rows, and 5 distances both sides of the hedge, perpendicular to the hedge. The Windy side (W) of the hedgerow experiences direct exposure to prevailing winds characteristic in Hungary (Rácz & Környei, 2023), while the Protected side (P) benefits from milder wind intensity, with wind speed reductions estimated at 10–15% based on literature data, rather than direct measurements (Bošković et al., 2010). Plots were placed at three-meter intervals from the hedge (Figure 12). P1 and W1 were the closest to the hedgerows, while P5 and W5 were the farthest ones. The design was a random block design (RBD), consisting of five replicates of three genotypes on both sides, Windy and Protected, resulting in 2 × 15 plots. Each plot had 8 plants in two rows, 120 plants on each side, and 240 plants on both sides of the hedgerow strip.

Table 4: Three tomato genotypes' properties used in the experiment.

Genotype	Use, Fresh Processing	Fruit Weight (g)	Shape	Growing Type	GenBank Code	Origin
Szentlőrinckáta	Processing (P)	50–55	Ovate	Determinate	RCAT078726	Hungary
Ace55	Fresh, (P)	95 – 120	Round	Determinate	Commercial variety	USA
Roma VF	Fresh, (P)	57-85	Oblong	Determinate	Commercial variety	France

Szentlőrinckáta

Ace55

Roma

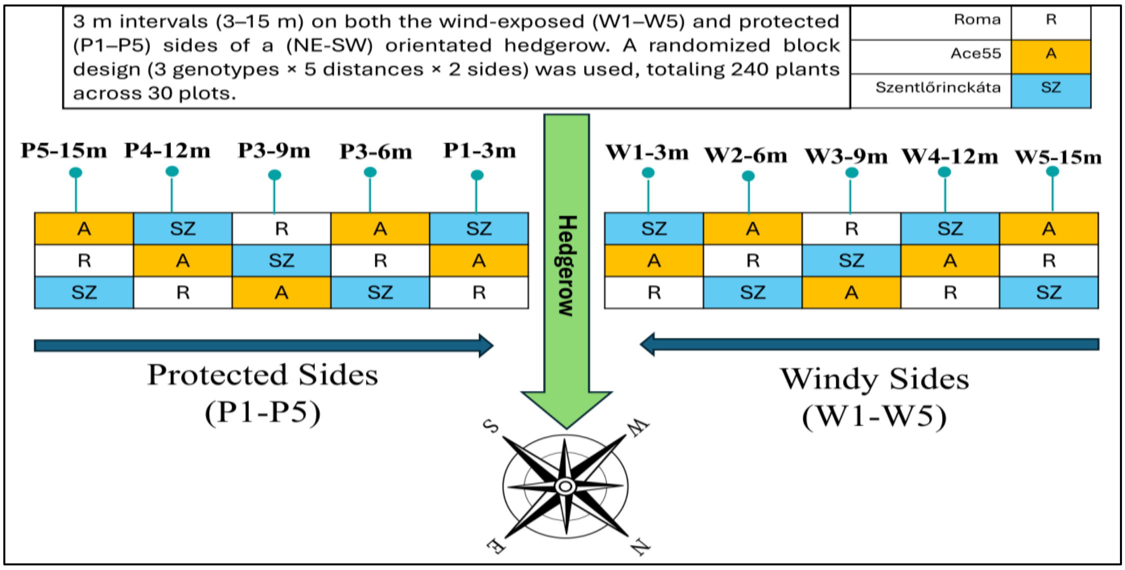


Figure 12: Experimental design of tomato plants on the Windy and Protected sides of a hedge, located in the organic land of soroksár experimental research farm, Budapest, Hungary, Northeast-southwest orientation.

3.3 Land preparation

During the cultivation period from May to September over three consecutive years, the preparation of the land and soil has been completed, including clearing, disking, and smoothing the soil. Agrotextile and plastic mulch was used to cover the soil surface, enhance moisture retention, providing weed management and improve the organic matter layer as presented in table 5. Additionally, technical support was provided to the plants tying and timely drip irrigation was used, delivering water directly to the tomato roots through emitters for efficient, consistent watering while reducing disease and improving plant growth. Fertilizer was applied at the time of tomato seedling transplanting as a top dressing in May, using TRIBÚ fertilizer containing 65% organic matter derived from natural pelleted manure were applied during the experiment, and weed control was performed manually within and between plots. Chemical pesticides were not used, as the field was managed under certified organic conditions

Table 5: Field operations, timing, and location during the experimental period (2022–2024)

Operation	Timing	Location
Land clearing	Early May (each year)	Entire experimental field
Disking	Early May (each year)	Entire experimental field
Soil smoothing/levelling	Early May (each year)	Entire experimental field
Installation of agrotextile and plastic mulch	Before transplanting (May)	Plots along both sides of the hedgerow
Tomato transplanting	May (each year)	Experimental plots at defined distances from the hedgerow
Pre-planting soil sampling	Before transplanting (May)	3, 6, 9, 12, and 15 m from the hedgerow
Plant tying, technical support	May–September	Within tomato plots

Drip irrigation	May–September	Tomato root zone within plots
Manual weed control	As needed (May–September)	Within and between plots
Fertiliser was applied at transplanting to seedlings	May	As topdressing in all plots
No chemical pesticide application	Entire experiment	Entire experimental field
Final harvesting and plant removal	September (each year)	Tomato plots
Post-harvest soil sampling	After harvest (September)	5, 10, and 15 m from the hedgerow

Table 6: Measured parameters during the experiment from (2022, 2023, and 2024)

Microclimatic condition	**Soil physico-chemical**	**Nutritional contents on tomato plant leaf**
• Temperature (°C) • Relative Humidity (RH) • Distances from a Hedgerow in Protected (P1 – P5) and Windy (W1 – W5).	• Soil moisture • Soil pH • Organic matter stability quality • Phosphorus, Potassium • Phosphatase activities • Dehydrogenase activity • Glucosidase activity	• Chlorophyll A and B • Carotene • Nitrogen (N) • Phosphorus (P) • Potassium (K)
Plant morphological traits	**Tomato fruit yield**	**Tomato fruit quality**
• Plant height (cm) • Stem diameter (mm) • Leaf length (cm) • SPAD Chlorophyll Measurement	• Fruit Weight / Plant • Fruit Weight / Plot • Fruit Number / Plant, Plot and Sides • Fruit Diameter (mm) • Pest and disease	• Colour attributes (Chroma (C*), Hue (h°)) • Total Soluble Solids (TSS) • Titratable acidity (TA) • Sugar acid ratio (SAR) • Antioxidant (FRAP) • Total phenolic content (TPC)

3.4 Microclimatic condition (Protected and Windy Sides)

Over three consecutive years 2022, 2023 and 2024 from May to October, a field experiment was conducted to evaluate the impact of a hedgerow system on the nutritional quality parameters of a tomato cultivation system through microclimate modulation of a hedgerow. The study area was established on certified organic land with sandy loam soil and relatively low organic matter content. A continuous transect line perpendicular to the hedgerow aligned in a northeast southwest orientation was delineated for systematic observation. To examine the influence of wind protection, microclimatic conditions were compared between two distinct zones along this transect: the wind-exposed blocks (W1 to W5) and the protected blocks (P1 to P5). Weather data, specifically temperature and humidity, were recorded every 30 minutes during the cultivation season using Voltcraft DL-121TH and DL-210TH sensors. These data were used to quantify the hedgerow's capacity to buffer climatic extremes.

Microclimatological observations were further contextualized by integrating sensor data with the surrounding landscape features to improve the spatial interpretation of temperature variations across the experimental site. This approach allowed for a detailed analysis of how differential exposure due to hedgerow positioning modulates local microclimates in a heterogeneous tomato cropping system.

3.5 Soil analysis measurements

Soil sampling was conducted over three consecutive years (2022, 2023, and 2024), yielding a total of 18 composite samples per side of the hedgerow (six per year). Sampling was performed twice annually, before transplanting and after harvest, to assess baseline soil conditions and seasonal changes induced by crop growth and management. Each composite sample represented a representative soil sample, formed by mixing 20 subsamples collected from the 0–20 cm depth following EU sampling guidelines (Sastre et al., 2001). Samples collected before planting were stored under refrigerated conditions and analysed together with post-harvest samples to ensure consistent temporal comparison. Although sampling distances from the hedgerow did not exactly coincide with treatment distances, the design captured overall spatial and temporal variability in soil properties rather than point-specific treatment effects: R1 (5 m), R2 (10 m), R3 (15 m), and a control point at 7.5 m. These distances were assessed on both the Windy (W), Windy Control (WC), as well as on the Protected (P), and Protected Control (PC) sides of the hedgerow. The samples were analysed for Soil physical (moisture), chemical (pH, organic matter stability, phosphorus, potassium), and biological properties (phosphatase, dehydrogenase, glucosidase activities) were chosen because they directly influence nutrient availability, root development, and microbial activity, all of which are closely linked to tomato yield and fruit quality at the Soil Department Laboratory of the Hungarian University of Agriculture and Life Sciences, Buda Campus. The results provided insights into diversity and composition of soil components (Figure 13**)**.

Figure 13: (A) Sample collection (B) pH, biological activities measurements (C) Dehydrogenase Activity and organic matter quality (Mohammed Mustafa, 2024).

3.5.1 Soil physico-chemical properties measurements

Soil samples were collected for laboratory analysis from three positions on both Windy (W1, W2, W3) and Protected (P1, P2, P3) sides, with WC and PC serving as respective controls. Sampling was conducted at distances of 5 m (R1), 10 m (R2), 15 m (R3), and a control point at 7.5 m from the hedgerow, over three consecutive years. Average values were used for analysis.

Soil moisture: After homogenization, the samples were stored at 4°C. The moisture content of the soil was determined after drying the samples at 105°C according to (Smith & Mullins, 2000), formulae (1)

$$\% \text{ of soil water content} = w(\%) = ((W2 - W3) / (W3 - W1)) \times 100 \quad (1)$$

W_1 = Weight of empty container	W_3 = Weight of container + dry soil
W_2 = Weight of container + wet soil	w (%) = Moisture content percentage

3.5.2 Soil chemical properties

Soil pH: The pH of the A horizon soils was measured annually. The pH of the soil samples was determined from an aqueous extract. 12.5 ml of distilled water was added to 5 g of a dry soil sample, which was mixed well, and the mixture was determined after 24 hours using an Adwa AD1020 device (Shober et al., 2019), formulae (2).

$$pH = -\log_{10} [H+] \quad (2)$$

Organic matter fractions:_The total organic carbon (TOC) content of the soil was determined using potassium dichromate oxidation Tyurin method modified by (Nikitin, 1999). The soil organic matter content (SOM %) was calculated by multiplying the TOC values by 1.724.

Soil quality and stability: To investigate the fractional composition, the two-solvent method developed by Hargitai (1966) was applied (Pabar et al. 2025). This method is based on extracting soil organic matter using different reagents (NaOH and NaF) and measuring the extracts at specific wavelengths, which provides information on humic substances with different degrees of humification and thus different qualities. In addition to the absolute amounts of the individual fractions, their ratios can also be evaluated, allowing conclusions to be drawn regarding rapid changes occurring in the soil and overall soil quality.

Larger, more stable molecular structures characterize the NaF-soluble organic matter fraction: these are organic compounds bound to Ca, more highly condensed, and typically higher in nitrogen content. In contrast, the NaOH-soluble fractions represent more “raw,” less transformed organic material in the early stages of humification (Hargitai, 1966).

Using the above-described Hargitai two-solvent method, the NaOH- (0.5%) and NaF- (1%) soluble organic matter contents of the soil samples were determined spectrophotometrically at 400, 480, 540, and 670 nm, and the obtained values were averaged. These data are informative on their own; moreover, together with SOM content (calculated as TOC × 1.724), they allow the calculation of the organic matter quality (Q) and stability (K) indices, where $Q = E_{na}F / E_{na}OH$ and $K = Q / H\%$ (Pabar et al. 2025).

Phosphorus and potasium: in the case of P and K, 100 ml of ammonium lactate solution was added to 5 g of soil sample, then the samples were filtered after shaking for 1 hour. The K content was measured directly from the filtrate using a flame photometer. To measure the P content, 15 ml of ammonium molybdenate and 1 ml of ascorbic acid stannous chloride were added to 10 ml of filtrate. After standing for 15 minutes, the transmittance was measured with a spectrophotometer at 438 nm. The P concentration (mg/L) was calculated from the obtained values using the equation of a standard straight line.

3.5.3 Soil biological properties

Soil samples were stored at 4°C until used for soil enzyme assays. Permanganate-oxidizable organic fraction (POXC) and Glomalin Related Soil Protein (GRSP) assays were performed on samples dried at room temperature.

Phosphatase (PHOS) and ß-Glucosidase (ß-GLU) enzyme activity: PHOS procedure is based on the determination of the coloured product (p- nitrophenol) released during the enzymatic hydrolysis of the synthetic substrate (p- nitrophenol phosphate), (Tabatabai & Bremner, 1969). The ß-GLU method, similar to the determination of phosphatase activity, is based on measuring the p-nitrophenol released upon enzymatic hydrolysis of a synthetic substrate. In this case, the artificial substrate is p-nitrophenyl-β-glucopyranoside (Sinsabaugh et al., 1999).

Dehydrogenase enzyme activity (DHA): DHA was determined using the modified 2,3,5-triphenyltetrazolium chloride reduction method (TTC) of Thalmann on 1968 (Kotroczó et al., 2023).

3.6 Plant physical and mechanical properties

The physical and mechanical properties of mature tomato plants were evaluated over three consecutive years (2022, 2023, and 2024) under two different environmental conditions: protected and windy sides. The experiment involved three tomato genotypes: Roma, Ace55, and Szentlőrinckáta. Data were collected from four tagged middle plants per plot, while the outer rows were used as border plants. The measured parameters included leaf area, leaf length, stem length, and stem diameter which were used to estimate the physical and yield attributes (Figure 14**).**

Figure 14: Plant height, leaf area, The length of the leaf (Mohammed Mustafa, 2024).

The growth and development of tomato plants were evaluated through several morphological parameters. Plant height (cm) was measured using a ruler from the base of the plant above the ground up to the tip of the main stem. The physical attributes of tomato plants were measured at two key phenological stages according to the BBCH (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) scale: the first measurement eight weeks after the seedling stage (BBCH 14–16, leaf development) and the second just before fruiting (BBCH 51–55, inflorescence emergence and flower development). The average of these measurements was used for evaluation. Stem diameter (mm) was recorded two months after seedling establishment (BBCH 14–16, leaf development stage). Using a caliper, stem diameter was measured at a height of 10 cm above the ground on four marked plants per plot. Leaf area was determined by selecting four fully expanded mature leaves from the middle part of the shoot in each plot; leaf length was measured with a ruler from the insertion point of the first leaflet on the rachis to the distal end of the leaf. Root length and root diameter were measured at harvest on the same plants after careful uprooting, using a ruler and caliper, respectively. Flowering and branching data were collected from the two central rows of each plot, and the number and length of branches were recorded as morphological and phenological traits, as presented in Table 6. Four tagged plants per plot were measured using a ruler, with branch length recorded from its origin on the main stem to the tip

3.6.1 SPAD-502 plus chlorophyll content measurement

Chlorophyll content in tomato leaves was measured non-destructively over three consecutive years (2022, 2023, and 2024) using the SPAD-502 Plus meter, which calculates a numerical SPAD value based on light absorbance at red (650 nm) and near-infrared (940 nm) wavelengths, proportional to leaf chlorophyll content (Ling et al., 2011a). Measurements were conducted at key phenological stages, including flowering and fruit development, on 3–5 representative plants per plot, sampling 2–3 fully expanded leaves from the upper and middle canopy, and on both sides of the leaves (Figure 15). The first measurements were taken two months after the experiment started, followed by a second set three weeks later to monitor changes. Each measurement was repeated three times per plot, and the average values were used for statistical analysis. This approach allowed accurate monitoring of plant nitrogen status and photosynthetic activity, providing guidance for optimized fertilizer management to enhance yield while minimizing environmental impact.

Figure 15: SPAD Chlorophyll measurement (Mohammed Omer, 2024)

3.7.1 Chlorophyll A and B and carotene spectrophotometric analyses

The tomato plant's leaves were meticulously selected based on their health and maturity. Four samples were collected from each variety per plot, with a total of 4 samples x 3 species x 5 plots x 3 replications x 2 sides. The samples were transported from the experimental research farm (MATE) to the university laboratory at the Department of Vegetable and Mushroom Growing for chlorophyll spectrophotometric analyses while being stored frozen in storage bags with ice. Sample preparation involved crushing the samples in a grinder, after which extractions were performed using pre-refrigerated acetone. An aliquot of this extract was then subjected to spectrophotometric analysis to determine the total chlorophyll and chlorophylls A and B , as shown in (Figure 16). The results were expressed as mg of chlorophyll per g of fresh tissue and determined using the formula outlined (Ling et al., 2011b; Neață, 2012). The absorbance readings were taken at 480, 644, and 663 nm as shown in Formula (3).

$$\text{Chlorophyll A (mg/mL)} = 3.95 \times A_{665} - 6.88 \times A_{649} \quad (3)$$
$$\text{Chlorophyll B (mg/mL)} = 24.94 \times A_{649} - 7.32 \times A_{665}$$
$$\text{Total Chlorophyll (mg/mL)} = \text{Chlorophyll A} + \text{Chlorophyll B}$$
$$\text{Total Chlorophyll (mg)} = \text{Total Chlorophyll (mg/mL)} \times \text{Final Volume (mL)}$$
$$\text{Chlorophyll A (mg)} = \text{Chlorophyll A (mg/mL)} \times \text{Final Volume (mL)}$$

A_{645} = Absorbance at a wavelength of 649 nm.

A_{663} = Absorbance at a wavelength of 665 nm.

Figure 16: Distractive analysis of chlorophyll determination (Mohammed Mustafa, 2024).

3.7.2 NPK Content determination of tomato plant leaves

Nitrogen (N): The Kjeldahl (AOAC, 1995), as shown in (Figure 17) was used to assess the total nitrogen (N) content of a sample, including the concentration of the sulfuric acid standard titration solution, the volume of the standard acid solution consumed by the sample, the sample cluster M, and the volume of liquid A to be tested during distillation, formulae (4).

$$1\frac{(V_2-V_0)\times C\times O.0140}{M\times(\frac{V1}{V})}\times 100 \quad (4)$$

Where: V_2 = sample titration volume, V0 = blank titration volume, C= acid concentration, M = sample mass, V1 = total digest volume, V = aliquot volume, and 0.0140 = N equivalent factor.

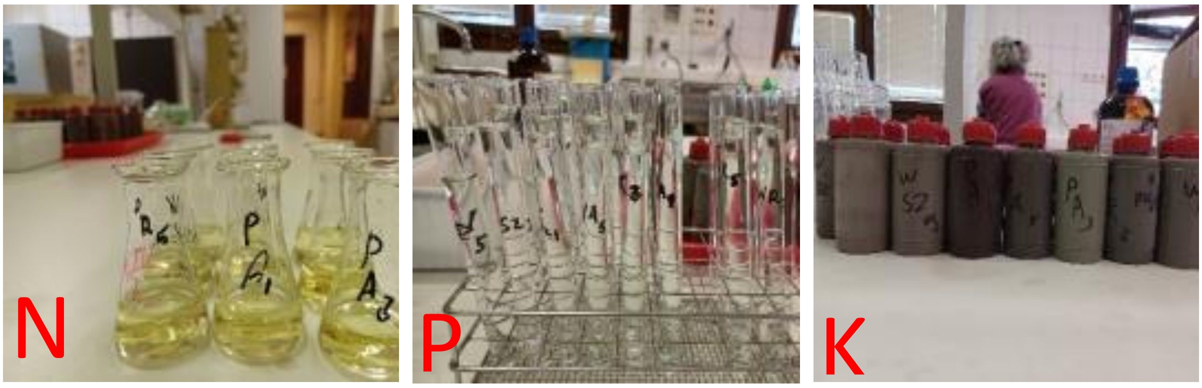


Figure 17: NPK Content determination of tomato plant leaf (Mohammed Mustafa, 2024).

Phosphorus (P): Molybdenum-antimony anti-absorption spectrophotometry (Liu et al., 2015), as presented in figure 17. It was used to evaluate the concentration of phosphorus in tomato plant leaves. Tomato plant leaves were extracted and placed in a solution containing ammonium molybdate and sulfuric acid. Data were analysed based on calibration, formulae (5).

The total P content was calculated:

P = (C x V1 x V2) / (V x m)

$$w_2 = \frac{p \times V}{m} \times \frac{1}{V2} \times 10^{-4} \quad (5)$$

Where: w2 = phosphorus content (%), p = phosphorus concentration from calibration (µg/mL), V = extract volume (mL), m = sample mass (g), V1 = total digest volume (mL), and V2 = aliquot volume (mL).

Potassium (K): Flame atomic absorption spectrophotometry (Sun et al., 2019), Was used to determine the potassium content of a plant sample, expressed as a mass fraction (w2) in g/100 g. formula (6).

The total K content was determined by applying:

K = (V - V1) x K / (V2 x m) – (V0 x K / V2)

$$w_2 = \frac{(p - p_0) \times V}{m} \times \frac{V1}{V2} \times 10^{-4} \quad (6)$$

Where: w3 = potassium content (%), p = K concentration from calibration (µg/mL), p0 = blank value (µg/mL), V = extract volume (mL), mmm = sample mass (g), V1 = total digest volume (mL), and V2 = aliquot volume (mL).

3.8 Harvesting and yield parameters measurements

To evaluate the yield performance of tomato plants and harvesting and yield measurements were conducted in 2022, 2023, and 2024 at the Soroksár Experimental and Research Station, with fruits sampled at the mature breaker, pink, and red-ripe stages. The first harvest typically occurred between early July and mid-August, and the second harvest in late August and early September., fruit yield was evaluated per plant and per plot (kg/plant and kg/plot) across five planting distances (3, 6, 9, 12, and 15 m) on both the protected and windy sides. For statistical analysis, only healthy red-ripe fruits were counted for each plant, and their weight was measured using a precision balance. In addition, the equatorial diameter of the fruits was measured using an analog caliper gauge. The obtained data were used to estimate the physical and yield attributes of the plants (Figure 18 A, B, and C).

3.8.1 Fruit weight and number

Tomato fruit yield was assessed over three growing seasons by recording both fruit number and weight for each tomato variety. Measurements were taken at two harvests during the growing season, early July to mid-August and late August to early September, using a digital precision scale, with only healthy, fully mature fruits counted and weighed. Data were collected separately for plants on the windy and protected sides of the hedgerow system, considering different distances from the hedgerow to capture microclimatic effects. Fruits were manually counted and categorized by maturity stage (green or red), and total fruit number and weight were calculated per plant total fruit per plots, per variety, and per side.

3.8.2 Fruit diameter (mm)

Random fruits from the three tomato varieties were sampled from each planting distance on both the protected and windy sides, and their diameters were measured using a digital caliper. (Figure 18). The fruit diameter was determined following the methodology described by Quispe Choque et al. (2022),. Using the maximal equatorial diameter was used to determine the size of the tomatoes (data not reported).

Figure 18: Data collection from red tomato fruit ripening in physiological stage (A) Szentlőrinckáta fruit (B) Roma fruit (C) Ace55 fruit (Mohammed Omer, 2024).

3.8.3 Pest and disease data collection first year experiment (2022)

Pest and disease assessments included visual quantification of leaf damage by Colorado potato beetle *Leptinotarsa decemlineata* (18 June 2022) fruit damage by cotton bollworm *Helicoverpa armigera* (23 - 30 August) fungal infection by *Phytophthora infestans* (10 August) and physical damage by wild animals (10 August). However, harvested fruits were categorized by damage type and weighed post-harvest (5 October) using a digital spring balance.

3.9 Tomato fruit quality traits measurement and sample preparation

Tomato fruits that had reached the ripening stage were meticulously selected based on their quality parameters at the Soroksár experimental research farm, located at the Hungarian University of Agriculture and Life Sciences, Organic Farming Unit. These fruits were then transported to the lab of the Department of Fruit and Vegetable Processing, Institute of Food Sciences, Hungarian University of Agriculture and Life Sciences for nutritional content analyses. The tomatoes underwent a thorough examination to determine their nutritional value and other chemical components to identify the best varieties for future cultivation from both sides of the experiment.

For the consecutive years 2023 and 2024, 5–6 fruits from each plot were sampled at each of the two harvests (early July to mid-August and late August to early September)., 1.5 to 2 kg of fully mature intact tomato fruits without any sign of infection were collected from each distance (W1- W5, P1- P5) relative to the hedgerow, separately from the 3 varieties. After washing, samples were randomly chopped into pieces using the toss-and-chop method to ensure representative tissue homogenization for analysis (Kilambi et al., 2016). The fruit pieces were then processed into puree using homogenizer blender model (Dsp set 41,China). Approximately a total of 45 mL of homogenate for each variety × year × harvest × side × distance combination was filled into centrifuge tubes and kept frozen at -18 ºC until further measurements.

3.9.1 Determination of colour parameters for chroma (C*), and hue (h°) calculation

Fruit homogenate colour analysis was investigated by using a Konica Minolta CR-410 tristimulus colorimeter. (Konica-Minolta, Osaka, Japan) as shown in (Figure 19). Measurements were done in triplicate. Colour was expressed as L*, a*, and b* according to the Commission Internationale de l'Éclairage (CIE), and chromaticity (Chroma C*) and hue angle (°h) were calculated after McGuire (Durmus, 2020; Horváth-Mezőfi et al., 2024; Mcguire, 1992), following formulae (7,8).

$$\text{Chroma } (C^*) = \sqrt{(a^{*2} + b^{*2})} \quad (7)$$

$$\text{Hue angle } (h°) = \text{arctang } (b^*/a^*) \quad (8)$$

where a*: Red-green axis, b*: Yellow-blue axis

Figure 19: Hand-held Model: CR-410T Tomato colorimeter (Horváth-Mezőfi et al., 2024)**.**

3.9.2 Total soluble solids content of tomato fruits (°Brix)

A refractometer measures light refracted in a liquid, determining the flavour and quality of fruits and vegetables. It has built-in temperature compensation and is only valid for fruit juice solutions. The refractometer uses a light source filtered to a single wavelength, directed towards the prism-sample interface (Ugwu et al., 2018), as shown in (Figure 20).

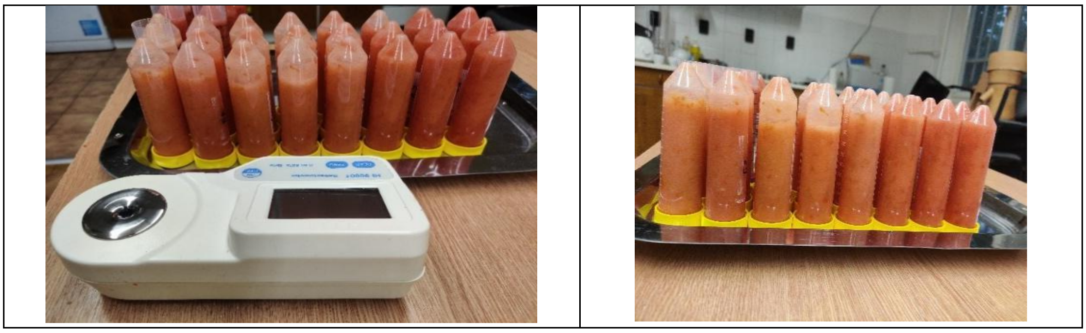


Figure 20: Atago Pocket Brix Refractometer (Mohammed Mustafa, 2024).

3.9.3 Determination of TSS, TA, and SAR

Instrumental analyses were performed at the Institute of Food Science and Technology at the Hungarian University of Agriculture and Life Sciences, Hungary. Total soluble solids (TSS) were measured using a Hanna HI96801 digital refractometer (Hanna Instruments Magyarország, Szeged, Hungary) following ISO 2173:2003 (Divéky-Ertsey et al., 2022) (Figure 21) and expressed in degrees (°Bx). Titratable acidity (TA) was determined via titration with 0.1 N NaOH using phenolphthalein as an indicator and expressed as % citric acid equivalent (ISO 750:1998). The sugar–acid ratio (SAR) was calculated by dividing (TSS) by (TA), using ISO methods (Alamo et al., 1993). All measurements were done in three technical repetitions.

Figure 21: Titratable acid measurements for tomato juice (Mohammed Mustafa, 2024).

3.9.5 Determination of ferric-reducing antioxidant power (FRAP)

The FRAP determination was performed following the method of Benzie and Strain (Benzie & Strain, 1996), to assess the total antioxidant content. The FRAP reagent was prepared by blending 3.1 g of sodium acetate trihydrate (Na-acetate $3H_2O$) and hydrochloric acid (Riel-de Oberderdingen, Haen, Germany), with 16 mL of acetic acid (1 L) to form a 300 mM acetate buffer (pH 3.6), and ferric chloride hexahydrate ($FeCl_3 \cdot 6H_2O$) was dissolved in distilled water at a concentration of 5.4 mg/mL. Additionally, a 2,4,6-tripyridyl-s-triazine (TPTZ) solution was mixed in a 10:1:1 (v/v/v) ratio were used for FRAP analysis. This solution was then heated to 37 °C for 5 minutes in a water bath. For the measurement, 1500 µL of the prepared FRAP reagent was placed into a test tube, and a blank reading was recorded at 593 nm. Subsequently, 1500 µL of FRAP reagent, 50 µL of the prepared selected extracts, and 50 µL of distilled water were added to a cuvette. The second reading was recorded at 593 nm after a 5-minute reaction time (Divéky-Ertsey et al., 2022). The measurements were done in three technical repetitions, and the results were expressed in ascorbic acid equivalence using mg AAE 100 mg^{-1} dimensions based on the reaction the method.

$$Fe^{3+} - TPTZ <> Fe^{2+} - TPTZ \text{ - Colourless blue}$$

The FRAP assay evaluates antioxidant capacity by measuring the reduction of ferric (Fe^{3+}) to ferrous (Fe^{2+}) ions using a ferric tripyridyl triazine (Fe^{3+}-TPTZ) complex, which generates a colorimetric change detected spectrophotometrically. As calculated using the formula (9).

$$\text{FRAP value } (\mu\text{mol } Fe^{2+}/\text{g sample}) = (C \times V \times D) / m \qquad (9)$$

Where: C = Fe^{2+} concentration from calibration (µmol/mL), V = extract volume (mL), D = dilution factor, and m = sample mass (g).

3.9.6 Determination of total phenolic content (TPC)

The colorimetric technique was employed to quantify the total polyphenol content, with the absorbance of the samples measured using a Hitachi U-2900 spectrophotometer (Hitachi

High Technologies Europe GmbH, Krefeld, Germany) and compared to a blank solution (Singleton & Rossi, 1965), as presented in (Figure 22). The Folin-Ciocalteu reagent (Sigma Aldrich, St. Louis, MO, USA), adapted from Singleton and Rossi, was prepared by blending 50 mL of Folin's solution with 500 mL of distilled water to create the Folin solution. Methanol was diluted with distilled water (DW) in a ratio of 80:20 mL, while 31.1g of sodium carbonate Na_2CO_3 (Riel-de Haen, Oberderdingen, Germany) was dissolved in 500 mL of DW. Additionally, 5.1 mg of gallic acid (Merck KGaA, Darmstadt, Germany) was dissolved in methanol and distilled water in a ratio of 80:20 mL. To prepare the samples, 1250 µL of the Folin solution and 200 µL of the MeOH: DW mixture were added to test tubes, which were then placed in a 50 °C water bath for five minutes. The absorbance at 750 nm was measured for the blank sample, followed by the addition of 50 µL of gallic acid and 10 mL of blended tomato juice. Each sample, with a final volume of 2500 mL, was measured in triplicate to ensure accuracy (Bobo-García et al., 2015; Singleton & Rossi, 1965). Results were expressed in gallic acid equivalence using mg GAE 100 g^{-1} dimension. was calculated using (10).

$$\text{TPC} = \frac{A}{tg\alpha} * \frac{V\ all}{V\ sample} * D \tag{10}$$

Where: A = absorbance of the sample, tgα = slope of the calibration curve, V_{all} = total (final) Volume (µL)V_{sample} = sample volume used (µL), and D = dilution factor.

Figure 22: TPC and FRAP analysis by spectrophotometer (Mohammed Mustafa, 2024).

3.10 Statistical methods

3.10.1 Soil health properties analysis.

A three-way ANOVA was performed to compare soil parameter means across treatments, sides (windy vs. protected), and years (2022, 2023, and2024). A repeated measures design was applied to account for temporal variation, with measurements repeated over three consecutive years. Post-hoc Tukey's HSD tests were used to identify significant differences between groups, with results indicated by letter codes (e.g., A, B, a, b). Error bars in figures represent either standard deviation or standard error, depending on the parameter, to illustrate variability.

3.10.2 Tomato leaf nutritional properties analysis

Mineral nutritional parameters, for chlorophyll and carotene content spectrophotometric analyses and NPK on the tomato plant leaves. The experimental dataset was analysed ($n = 360$), and the statistical methods applied. The normality of data was checked using Shapiro-Wilk's test while the homogeneity of variance through Levene's test. The analysis proceeded to post hoc test for the comparison of the time effect using Tukey HSD. Two-way univariate ANOVA with factors t varieties and distances was used in analyzing the data for inner content. Post hoc test using Tukey LSD was conducted to determine the significantly different treatments.

3.10.3 Tomato fruit quality parameters analysis

A Multivariate Analysis of Variance (MANOVA) models were constructed to assess the effects of variety, distance from the hedgerow (distances 1 to 5), and side (protected and windy) on Chroma and hue in 2023 and 2024. Harvest time was included as a blocking factor. MANOVA models, employing the same fixed factors and blocking factor, were utilized to analyse Total Soluble Solids (TSS), Titratable Acidity (TA), Ferric Reducing Antioxidant Power (FRAP), Total Phenolic Content (TPC), and Soluble Solids/Titratable Acidity (SA) ratio in 2023 and 2024. Normality of model residuals was assessed based on the absolute values of skewness (<1) and kurtosis (<2). Given that the assumption of homogeneity of variances was violated in certain instances (Levene's test, $p<0.05$), Games-Howell post-hoc tests were employed to ensure robustness. Pairwise comparisons were conducted for each of the three fixed factors, holding the levels of the other two fixed factors constant. The statistical analyses were conducted using R (v 4.4.2, R Core Team, 2024).

3.10.4 Tomato yield (fruit weight and numbers) analysis

Statistical analyses were conducted using IBM SPSS Statistics (v29.0, IBM Corp., 2025). A General Linear Model (GLM) was applied to evaluate the effect of distance from the hedgerow (five levels) on fruit number and fruit weight (kg/m^2), with data split by year, variety, and sides. Residual normality was confirmed based on skewness and kurtosis values (<2). Levene's and Box's M tests were used to assess homogeneity of variances and covariance matrices. Multivariate tests (Pillai's Trace, Wilks' Lambda) evaluated in general effects, and Tukey's HSD or Gams-Howell test was used for post-hoc comparisons where appropriate.

3.10. 5 Pest and disease damages

Data were analysed using three-way MANOVA to assess the effects of genotype, hedgerow side, and planting distance. Pillai's trace was used as the test statistic. Assumptions of normality and homogeneity were verified through boxplots, Box's M-test, scatterplots, and Mahalanobis distance,

4. RESULTS

4.1 Hedgerows microclimate 2022, 2023, and 2024.

Microclimate conditions within the hedgerow system were monitored during the 2022, 2023, and 2024 seasons, focusing on average air temperature and relative humidity across windy and protected sites data logging was set to 30-minute intervals; datasets were averaged for calculating daily data.

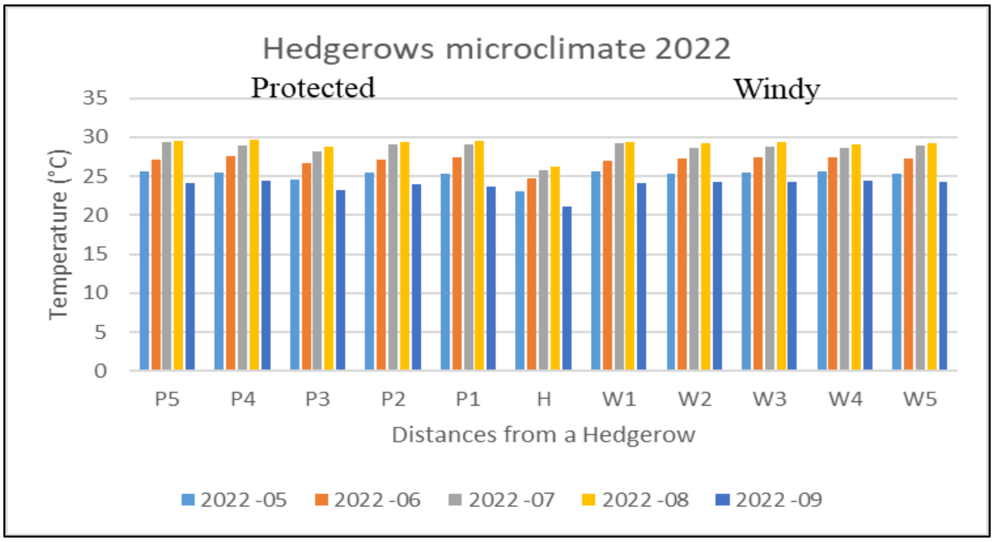
Temperature (°C): Considerable differences were found between the average temperatures of the windy and the protected sides. Using the average temperature of the hedge as a reference value throughout the period May- last September, the average temperatures measured at different distances on the Windy and Protected sides of a hedgerow over three consecutive years (2022, 2023, and 2024) are presented in Table 7. In the first year (2022), the Windy side (W1–W5) recorded an average deviation of +2.18°C, while the Protected side (P1–P5) demonstrated a higher deviation of +3.31°C compared to the reference air temperature measured within the hedgerow (H). At a distance of 15 meters from the hedgerow, the Protected side (P5) showed a marked microclimatic effect, resulting in an average increase of +1.87°C in temperature relative to the hedgerow conditions (Figure 23).

During the second year (2023), the Windy side had an average deviation of +2.07°C, whereas the Protected side reached a deviation of +3.54°C. In the third year (2024), the Windy side exhibited an average deviation of +2.49°C, while the Protected side maintained a slightly lower deviation of +3.02°C compared to hedgerow conditions. Throughout both 2023 and 2024 growing seasons, the overall average temperature on the Protected side remained +0.38°C higher than on the Windy side. Across all years, May emerged as the coldest month, with the lowest temperature recorded at P3 (18.29°C in May 2024) and W2 (18.29°C in May 2023, 18.29°C in May 2024). Conversely, July and august consistently registered the highest average temperatures, with P1 peaking at 29.08°C in 2022, 27.49°C in 2023, and 28.94°C in 2024, and W2 reaching 28.66°C in 2022, 27.18°C in 2023, and 27.68°C in 2024. The most pronounced temperature gradients were observed at P4 and W5, reflecting significant microclimatic variation influenced by hedge proximity. Temperature increases were more substantial on the Protected side with increasing distance from the hedgerow, while the Windy side exhibited more moderate changes due to exposure and ambient airflow, suggesting reduced hedgerow-induced thermal regulation (Figure 23).

Table 7. Result recorded at increasing distance from the hedgerow in protected and wind sides during the 2022, 2023, and 2024 vegetation seasons at soroksár experimental and research farm, Budapest, Hungary.

Year /Month	P5	P4	P3	P2	P1	H	W1	W2	W3	W4	W5
2022 -05	25.55	25.42	24.58	25.47	25.28	23.02	25.58	25.29	25.52	25.63	25.37
2022 -06	27.13	27.58	26.65	27.08	27.36	24.67	27.03	27.22	27.41	27.46	27.24
2022 -07	29.37	28.96	28.24	29.13	29.08	25.78	29.27	28.66	28.78	28.64	28.89
2022 -08	29.58	29.67	28.83	29.36	29.51	26.24	29.42	29.19	29.33	29.01	29.22
2022 -09	24.04	24.41	23.17	23.92	23.64	21.06	24.17	24.25	24.19	24.36	24.28
2023 - 05	22.03	24.42	21.41	21.18	21.53	19.35	21.41	22.02	22.14	21.83	21.92
2023 -06	24.74	24.31	24.02	23.64	23.86	19.97	23.64	23.75	23.8	23.31	23.88
2023 -07	27.13	22.15	25.94	25.94	27.49	22.95	23.05	27.18	27.08	26.8	22.69
2023 -08	27.98	28.38	24.05	25.1	26.61	22.58	24.22	25.66	25.43	24.54	24.42
2023 -09	19.82	19.46	21.87	21.31	21.61	19.75	20.8	21.2	20.51	20.34	19.66
2024 - 05	18.46	18.8	18.29	19.62	20.26	18.25	19.62	18.29	19.37	19.51	19.46
2024 -06	26.02	25.81	25.31	25.31	26.53	21.12	25.51	25.75	25.78	24.62	25.64
2024 -07	28.98	28.57	28.09	28.63	28.94	24.88	26.27	27.68	26.99	27.36	26.89
2024 -08	26.23	26.01	25.32	25.85	26.12	23.66	23.97	25.99	25.88	25.85	25.52
2024 -09	24.23	24.66	22.71	23.4	23.77	21.12	20.49	23.14	22.63	22.61	22.89
						Relative humidity (RH)					
2022 -05	62.13	64.04	57.47	59.04	61.62	66.9	64.04	61.29	62.67	73.51	62.12
2022 -06	59.41	62.88	50.77	52.86	58.74	58.96	62.88	60.27	61.73	72.46	60.76
2022 -07	41.93	48.63	42.14	46.94	58.1	42.14	48.63	49.23	51.94	61.45	50.05
2022 -08	44.07	47.92	40.7	42.75	56.53	43.77	47.92	48.31	52.35	60.21	49.81
2022 -09	67.9	66.14	76.9	74.29	72.77	69.79	66.14	68.12	65.7	83.91	67.96
2023 - 05	58.62	59.31	58.89	59.3	63.85	58.28	54.88	60.02	61.24	61.13	53.31
2023 -06	50.13	52.02	50.41	51.77	56.23	48.03	60.03	56.23	57.76	56.71	54.91
2023 -07	51.99	53.13	53.91	52.6	52.79	50.04	58.24	52.28	52.29	52.29	54.91
2023 -08	55.37	58.47	59.43	60.21	64.24	54.77	66.29	61.85	61.27	61.05	60.87
2023 -09	54.77	54.31	58.59	59.08	61.52	54.88	63.85	59.7	57.54	58.59	56.82
2024 - 05	42.13	42.07	42.31	42.47	43.39	43.76	44.71	47.37	41.97	42.92	44.97
2024 -06	42.55	42.3	44.3	46.14	47.37	44.34	49.11	51.7	41.97	41.97	46.14
2024 -07	52.5	52.53	54.63	57.11	51.7	52.86	59.84	60.4	51.7	51.7	57.11
2024 -08	56.71	58.47	57.83	55.7	60.41	54.77	63.29	63.29	58.62	58.62	60.87
2024 -09	71.39	72.28	72.27	72.84	69.9	71.94	76.63	75.04	74.27	73.79	74.87

Legend: White colouring indicates lower temperature, while red indicates higher values. White color indicates lower relative humidity, while blue indicates higher values.



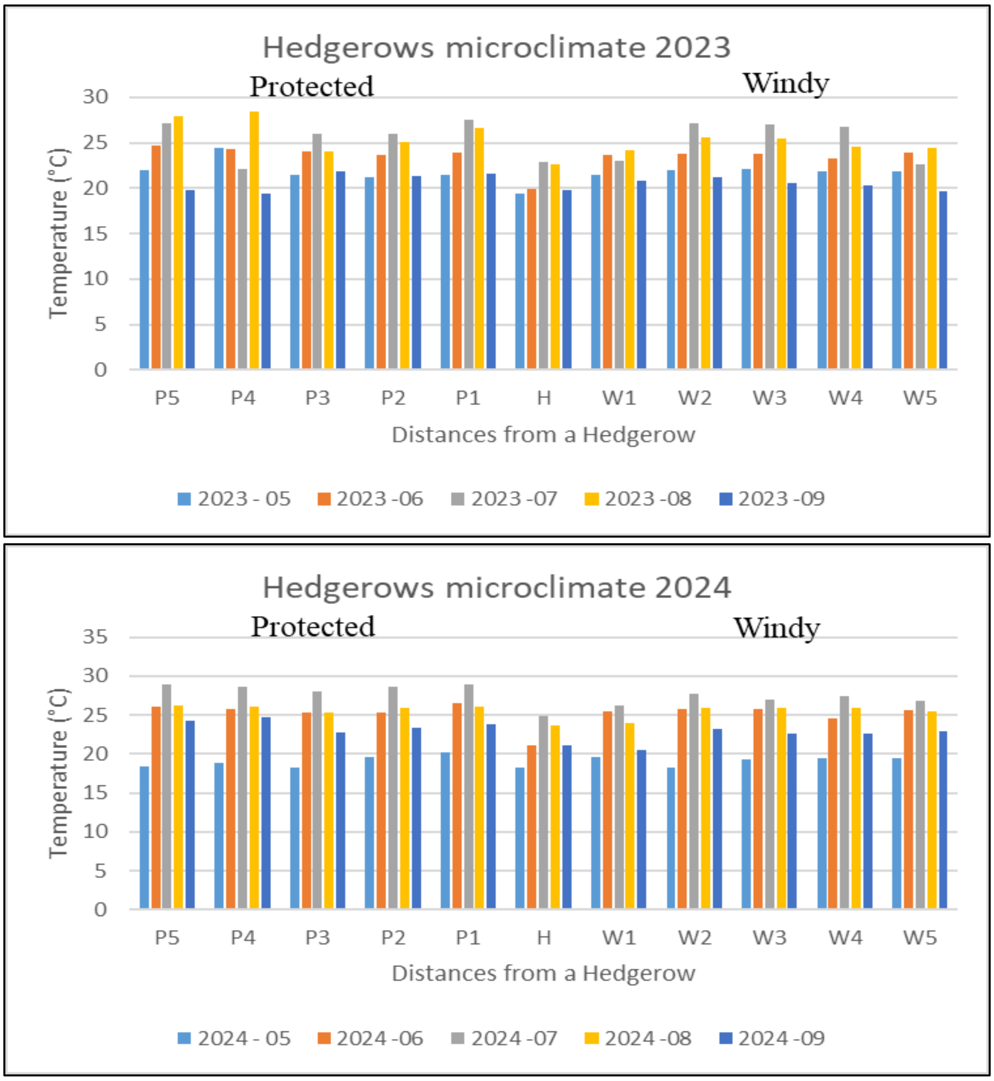


Figure 23. Hedgerows microclimate temperature (°C) at increasing distances from a hedgerow in protected and windy sides during the 2022, 2023, and 2024 vegetation seasons at soroksár experimental and research farm, Budapest, Hungary.

Relative humidity (RH)**:** Humidity trends followed an inverse relationship to temperature, with RH levels generally decreasing on the warmer Protected side and increasing on the cooler Windy side (Figure 23). Using hedgerow RH as the baseline, the Windy side displayed stronger humidity retention. In the first year, 2022, the average RH was +6.12% on the Windy side and +5.47% on the Protected side. In 2023, the average deviation from hedgerow RH was +5.97% on the Windy side and +3.74% on the Protected side. These differences increased slightly in 2024, reaching +7.44% Windy and +6.26% Protected, Table 7. Humidity was lowest in May, aligned with early-season dryness, notably at P4 (42.07% RH in May 2024) and W1 (54.88% RH in May 2023). By September, moisture levels peaked across all zones, with the highest RH recorded at W1 (76.63% in September 2024) for windy sides, and P2 (72.27% in September 2024) for protected sides. This seasonal increase reflects reduced evapotranspiration rates and cooler late-season air temperatures. Microclimatic interpretation together, the thermal and humidity analyses reinforce the hedgerow's modifying effect: The Protected side warms more with distance yet retains less ambient moisture. The Windy side, though cooler, benefits from higher and more stable RH, particularly in zones further from the hedge.

4.2 Soil physical, chemical, and biological parameters 2022, 2023, and 2024.

This study examines the impact of hedgerows on soil health over three years (2022–2024). Soil samples were systematically collected before transplanting and after harvest, following EU protocols (Schwitter et al., 2022), at varying distances (5, 10, 15 m, and control) from hedgerows on both windy sides in Windy (W), Windy Control (WC), as well as on the Protected (P), and Protected Control (PC) (Figure 24). The analysis focused on physical (Moisture and pH), chemical (Organic matter and quality, phosphorus, and potassium), and biological (Phosphatase activity, dehydrogenase, and glycosidase activity) soil properties (Appendix table 1). Sampling and analysis were conducted at the Soil lab at the Hungarian University of Agriculture and Life Sciences, Department of Agro-Environmental Studies, Budapest.

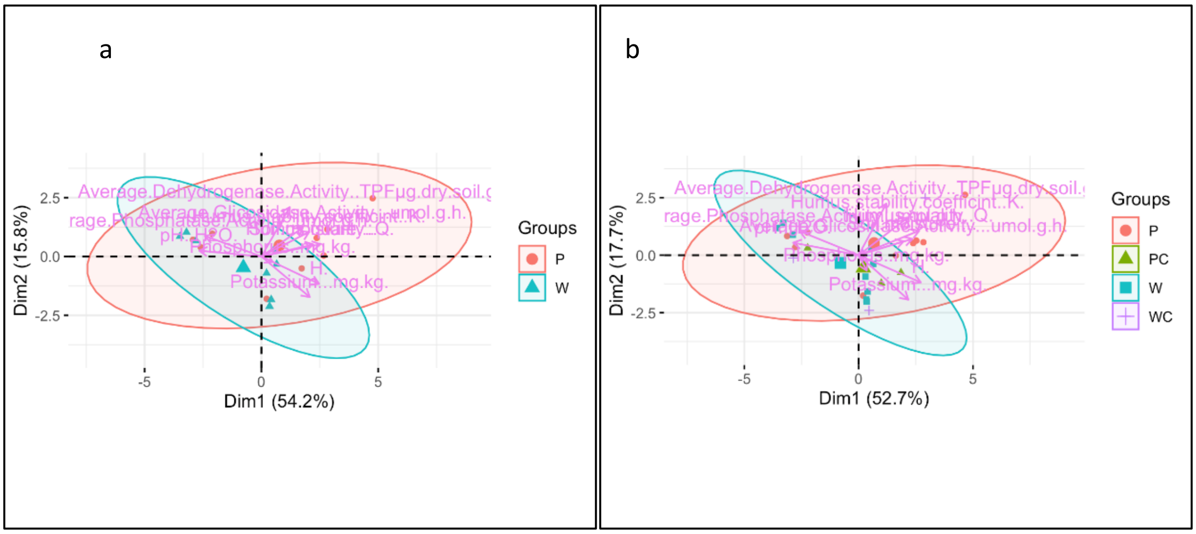


Figure 24. PCA biplot showing the distribution of soil physical, chemical, and biochemical variables across Windy (W), and Protected (P) groups, without (a) and with (b) Windy Control (WC), and Protected Control (PC) groups during 2022–2024. Dim1 (PC1) represents side-related variation, while Dim2 (PC2) reflects parcel effects across years. Together, Dim1 and Dim2 explain 70% and 70.4% of the total variance (a and b, respectively).

4.2.1 Soil physico-chemical indicators

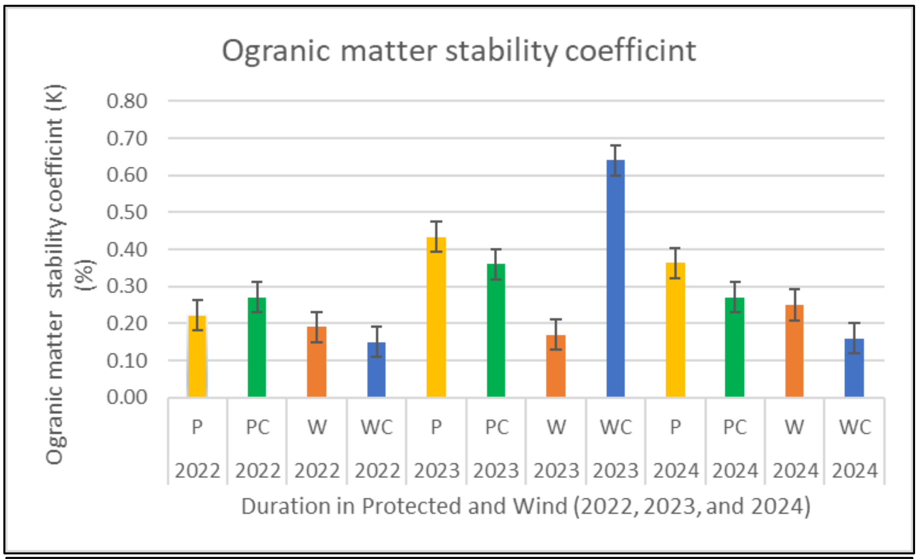
soil moisture demonstrated within each year, differed among parcels. In the first year, 2022, values were lowest at the Windy position (W) by (12.7%) and higher at the Protected position (P) by (14.3%), with control parcels (PC and WC) showing higher moisture than their respective distances. In 2023, control parcels PC and WC recorded the highest soil moisture, while P and W remained lower. In the final session, 2024, P (19.4%) had significantly higher soil moisture than W (15.4%), whereas differences among parcels in 2022 and 2023 were not significant (Figure 25).

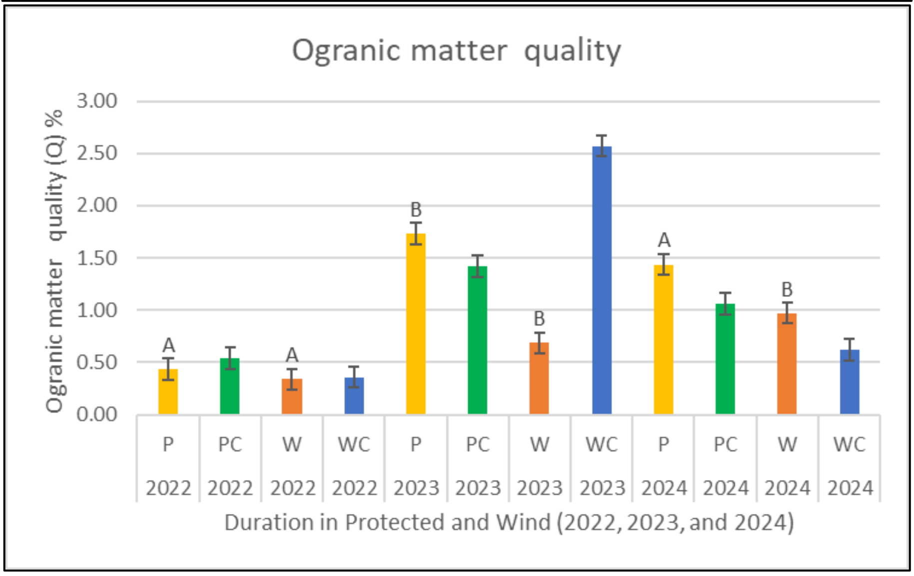
4.2.2 Soil chemical properties

Furthermore, in 2022 and 2024, all parcels. in both sides, protected sides P, PC, and windy sides W, WC showed identical pH levels of 8.50, indicating stable alkaline conditions. However, the result in 2023 shows, only the protected side (P) dropped to 7.50, while all others remained at 8.50, suggesting a temporary acidification likely due to localized organic contents or microbial activity. The protected sides control (PC) maintained consistent pH across all years, highlighting its buffering capacity (Figure 25**)**. However, the soil pH remained alkaline, with only a brief dip on the windy side, implying minimal short -term pH fluctuation.

Figure 25. Soil physico-chemical indicators Comparison of (Mean ± SD) soil moisture and PH measurements across parcels: P (Protected), PC (Protected Control), W (Windy), and WC (Windy Control) on the hedgerow sides for the years 2022, 2023, and 2024. Values represent annual treatment means, with error bars showing standard deviations. Different capital letters indicate significant differences between samples within a year and side ($p < 0.05$). Different lowercase letters mean significant differences between sides within a year.

The organic matter stability coefficient increased across all sampling on both sides of the hedgerow conditions, P, PC, W, and WC, varied among parcels within each year. In the first year, 2022, values were generally low, ranging from 0.15 at WC and 0.19 at W to 0.22 at P and 0.27 at PC. In the second year, 2023, organic matter stability increased at all parcels, with the highest value recorded at WC (0.64), followed by P (0.43) and PC (0.36), while W remained lowest (0.17). In the final year, 2024, values declined compared to 2023 but remained higher than in 2022, with PC and P maintaining higher coefficients than W and WC. No statistically significant differences in the organic matter stability coefficient were observed among parcels or between years (Figure 26).





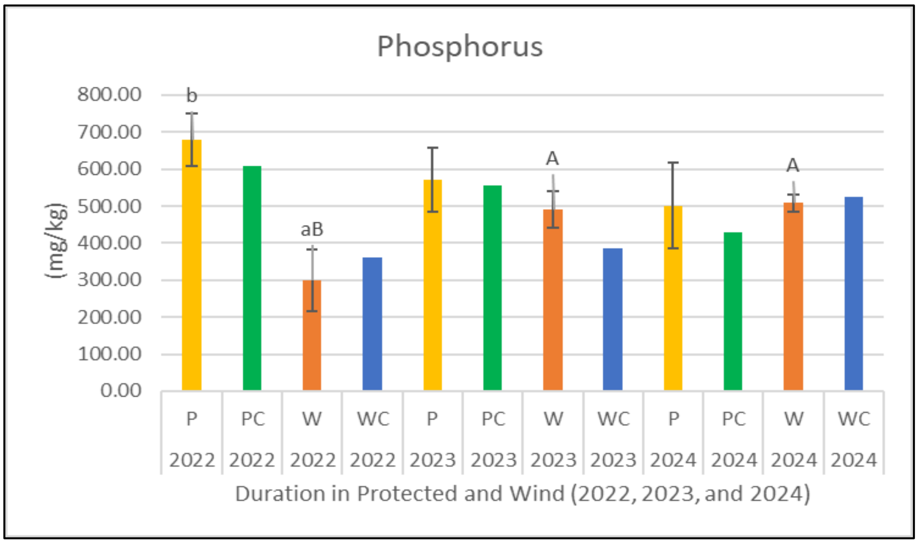


Figure 26. Soil chemical (organic matter and quality, potassium and phosphorus levels) (Mean ± SD) Variations across parcels: P (Protected), PC (Protected Control), W (Windy), and WC (Windy Control) on the hedgerow sides for the years 2022, 2023, and 2024. Values represent annual treatment means, with error bars showing standard deviations. Different capital letters indicate significant differences between samples within a year and side ($p < 0.05$). Different lowercase letters mean significant differences between sides within a year.

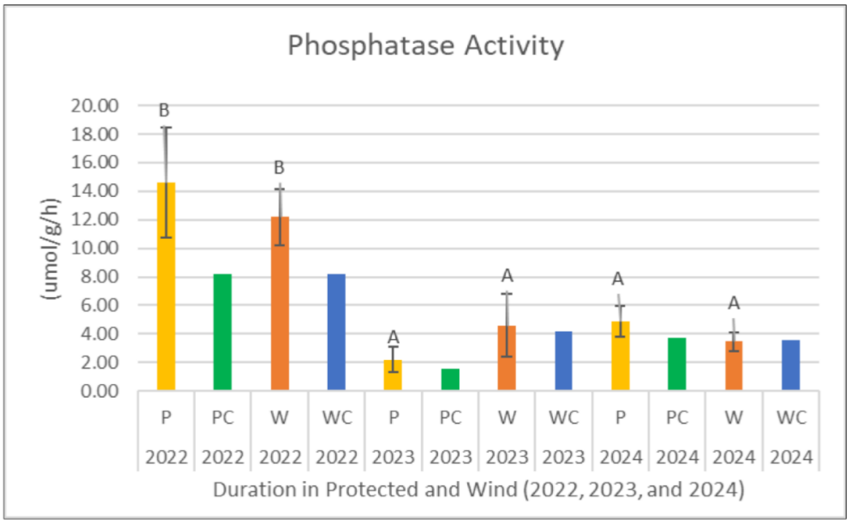
Organic matter quality altered among parcels within each year under hedgerow influence. In the first year, 2022, organic matter quality was highest at the protected control sites (0.54%), followed by the protected parcel (0.44%), while lower values were observed at the windy control (WC: 0.36) and the windy parcel (W: 0.34%). However, in the second year, 2023, WC showed the highest organic matter quality (2.57%), exceeding P (1.73%), PC (1.42%), and W (0.69%). Furthermore, in 2024, P (1.44) and PC (1.06) maintained higher organic matter quality values than W (0.97%) and WC (0.62%). Statistically significant differences among parcels were observed in 2023 and 2024, whereas no significant differences were recorded in 2022 (Figure 26). The results suggest that hedgerow-associated conditions can influence organic matter quality, although the magnitude and direction of the effect depend on parcel type and year.

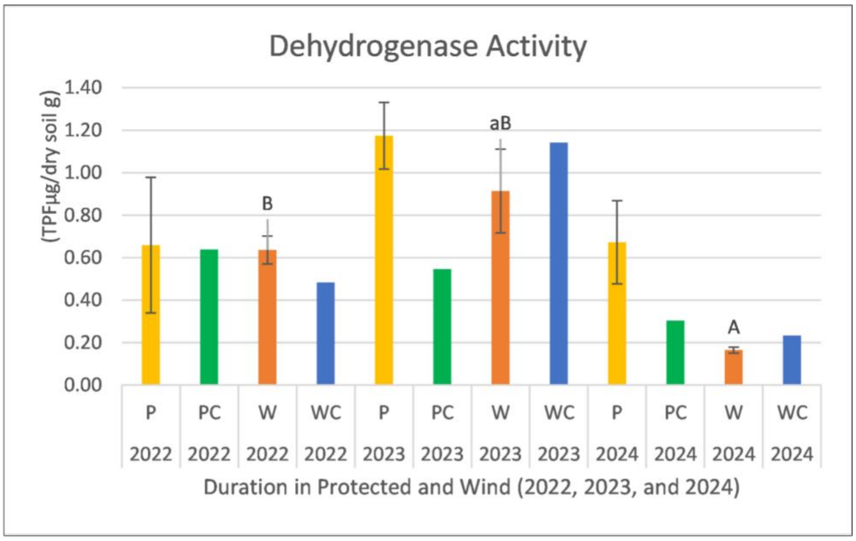
In terms of potassium and phosphorus concentrations varied among parcels located on different sides and at different distances from the hedgerow (P, W, PC, WC). In 2022, potassium was highest at the protected control PC (229 mg/kg), followed by the windy control WC (201 mg/kg) and the protected side of the hedgerow P (199 mg/kg), while the windy side at a comparable distance W (97 mg/kg) showed the lowest concentration. In the following year, 2023, potassium increased across all hedgerow-related positions, with higher values at PC (511 mg/kg) and P (435 mg/kg) than at WC (368 mg/kg) and W (338 mg/kg). In the final year, 2024, the highest potassium concentration was recorded at WC (676 mg/kg), followed by P (588 mg/kg), W (556 mg/kg), and PC (531 mg/kg), indicating variation related to both hedgerow side and distance (Figure 26).

Phosphorus also varied demonstrated with hedgerow position. In the first year, 2022, the protected side of the hedgerow P (678 mg/kg) showed the highest concentration of phosphorus, followed by the protected control PC (609 mg/kg), while lower values were observed at the windy control WC (360 mg/kg) and the windy side W (299 mg/kg). However, in the following year, 2023, phosphorus concentrations became more evenly distributed among sides at different parcels from the hedgerow, with P (571 mg/kg) and PC (557 mg/kg) remaining higher than WC (385 mg/kg) and W (490 mg/kg). Furthermore, in the final year, 2024, higher phosphorus levels were observed at the windy side W (509 mg/kg) and windy control WC (525 mg/kg) compared with the protected side P (501 mg/kg) and protected control PC (428 mg/kg). The nutrient availability varied with both hedgerow side and parcels, without a consistent dominance of a single position across years (Figure 26).

4.2.3 Soil biological properties

Phosphatase activity demonstrated contrasted among parcels located at different sides and distances from the hedgerow within each year. However, in the first sampling year (2022), activity was highest at the protected side P (14.61 µmol g^{-1} h^{-1}) and the windy side W (12.19), while lower values were observed at the control positions PC (8.18) and WC (8.22). Furthermore, in the following year (2023), phosphatase activity declined across all parcels, with slightly higher values at W (4.60) and WC (4.18) than at P (2.21) and PC (1.52). In the final year (2024), activity remained low and comparable among parcels, with the protected side showing the highest value (P 4.89), followed by PC (3.72), WC (3.55), and W (3.46). However, across all years, phosphatase activity varied among parcels at different sides and distance from the hedgerow, without showing a consistent enhancement at the protected side (Figure 27).





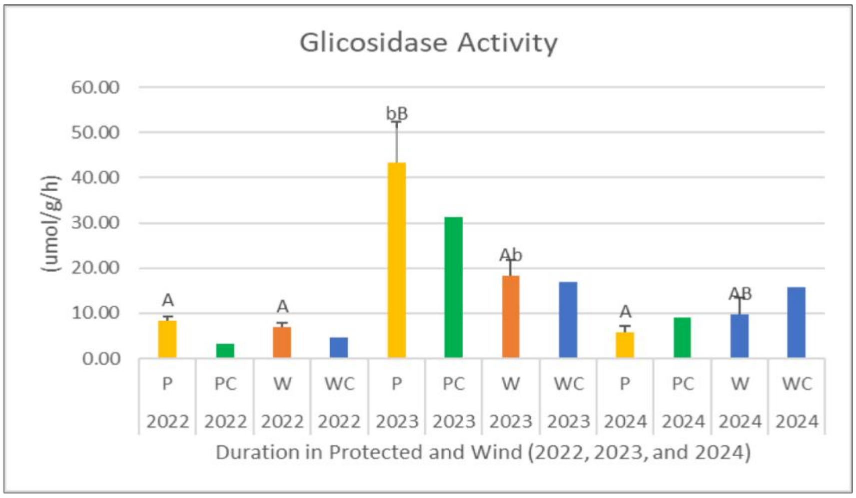


Figure 27. Soil biological properties, phosphatase, dehydrogenase, and glucosidase activity (Mean ± SD) variations in soil measured across different parcels: P (Protected), PC (Protected Control), W (Windy), and WC (Windy Control), and their respective controls over the years 2022, 2023, and 2024. Values represent annual treatment means, with error bars showing standard deviations. Different capital letters indicate significant differences between samples within a year and side ($p < 0.05$).

Examining dehydrogenase activity across the parcels at different sides and distances from the hedgerow (Figure 27). In 2022, values were relatively low and similar, ranging from 0.48 µg g^{-1} (WC) to 0.66 µg g^{-1} (P). A clear increase was observed in 2023, with the highest activity at the protected parcel P (1.17 µg g^{-1}) and the windy control WC (1.14 µg g^{-1}), while W (0.91 µg g^{-1}) and PC (0.55 µg g^{-1}) remained lower. In 2024, activity declined across all parcels, with higher values at P (0.67 µg g^{-1}) compared to W (0.17 µg g^{-1}), indicating a more favourable microbial response near the hedgerow**.** These trends confirm that protected sides and organic P significantly boost soil biological activity over time.

Glycosidase activity was demonstrated parcels within each year (Figure 27). In the first year, 2022, activity was generally low across all hedgerow sides and distances, with higher values at the protected parcel P (8.24 µmol/g/h) and windy parcel W (7.02 µmol/g/h), while lower activity was observed at PC (3.26 µmol/g/h) and WC (4.57 µmol/g/h). In the following year, 2023, a strong increase was recorded, especially at the protected side of the hedgerow P (43.31 µmol/g/h), followed by PC (31.30 µmol/g/h), whereas W (18.34 µmol/g/h) and WC (16.93 µmol/g/h) remained lower. In the last year 2024, glycosidase activity declined across all parcels, with values at P and PC (Figure 27). These results suggest that glycosidase activity is highly sensitive to environmental conditions and may a noticeable rise under the best protected conditions of the hedgerow systems, resulting in a Mean ± SD of the soil health properties (See Appendix Table 1).

4.3 Nutritional quality parameters of tomato genotypes in a hedgerow System

4.3.1 Nitrogen content determination of tomato leaves

Nitrogen content of tomato leaves was measured across all sample treatments on both the protected and windy sides of the hedgerow (Figure 28). On the windy side, the Roma variety exhibited the highest nitrogen contents, reaching 59.51 mg/100 g at W5 and 57.48 mg/100 g at W3, exceeding Ace55 (51.88 mg/100 g at W5) and Szentlőrinckáta (55.95 mg/100 g at W5). At W1, Roma also maintained a higher nitrogen level (59.51 mg/100 g) compared with Ace55 (33.06 mg/100 g) and Szentlőrinckáta (29.50 mg/100 g). However, on the protected side, no statistically significant differences among varieties were observed; however, Roma showed numerically higher nitrogen values at P5 (48.83 mg/100 g) and P1 (46.29 mg/100 g). The lowest nitrogen contents were recorded for Szentlőrinckáta at P5 (31.03 mg/100 g) and P1 (31.54 mg/100 g). A statistically significant interaction between variety and hedgerow position ($p < 0.05$) indicates varietal differences in nitrogen uptake in response to protected versus wind-exposed sample treatments (Appendix table 2).

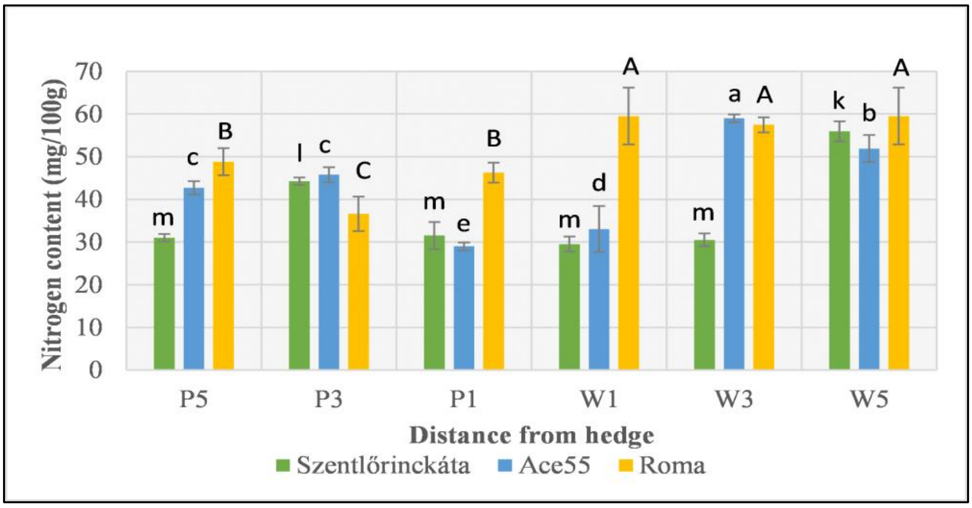


Figure 28. Nitrogen content (mean and SD) of tomato plant leaf samples produced on the protected and the windy side of a hedge, at various distances in (2023). Ascending numbers mean higher/distances from hedge. Differing letters mean a significant difference ($p < 0.05$) among samples of the same variety (Mustafa, Szalai, et al., 2023).

4.3.2 Phosphorus content determination of tomato leaves

Regarding phosphorus content, no significant difference was observed between the protected and windy sides of the hedgerow (Figure 29). However, significant variation occurred among tomato genotypes and sample treatments at different distances from the hedge ($p < 0.05$). The Szentlőrinckáta variety showed the highest phosphorus concentration at P5 on the protected side (5.48 mg/100 g), which was significantly higher than all other sample treatments across both sides. In contrast, the lowest phosphorus content was recorded for the Ace55 variety at P5 on the protected side (2.07 mg/100 g). These results indicate that phosphorus accumulation was primarily influenced by genotype and distance from the hedgerow rather than by hedge-side exposure. This treatment was significantly lower than most other groups. Szentlőrinckáta showed consistently higher phosphorus levels across distances than Ace55 and Roma, indicating that both genotype and microenvironment strongly influence phosphorus uptake in tomato fruits.

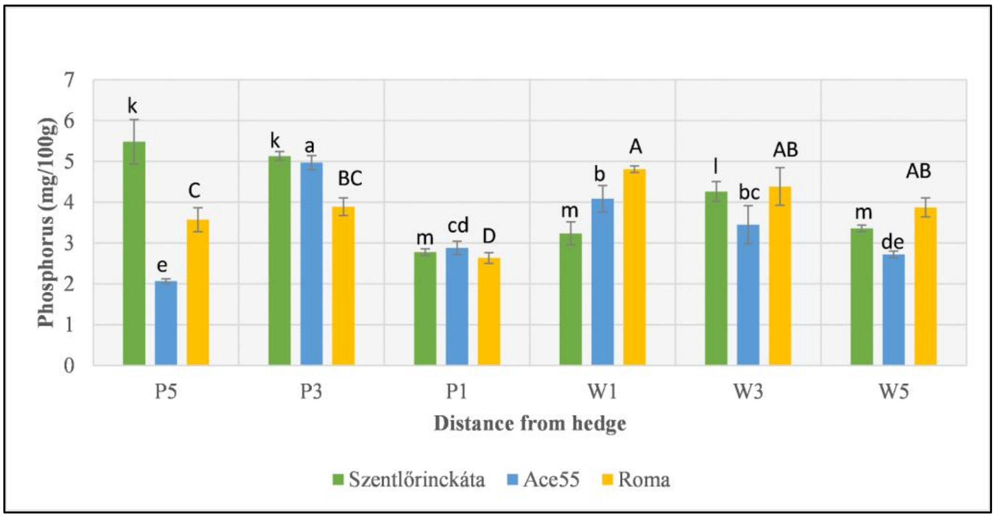


Figure 29. Phosphorus content (mean and SD) of tomato plant leaf samples produced on the protected and the windy side of a hedge, at various distances in (2023). Ascending numbers mean higher distances. Differing letters mean significant difference ($p < 0.05$) among samples of the same variety (Mustafa, Szalai, et al., 2023).

4.3.3 Potassium content determination of tomato leaves

Based on the analysis of potassium content, significant differences were observed between the protected and windy sides of the hedgerow among sample treatments and tomato varieties (Figure 30). The highest potassium concentration was recorded for the Roma variety at P5 (26.33 mg/100 g), followed closely by Ace55 at P3 (26.00 mg/100 g) and at W1 (24.67 mg/100 g). On the windy side, Roma also showed high values at W1 (26.00 mg/100 g). The lowest potassium content was found in Ace55 at P1 (15.83 mg/100 g), confirming significant differences among sample treatments and cultivars ($p < 0.05$).

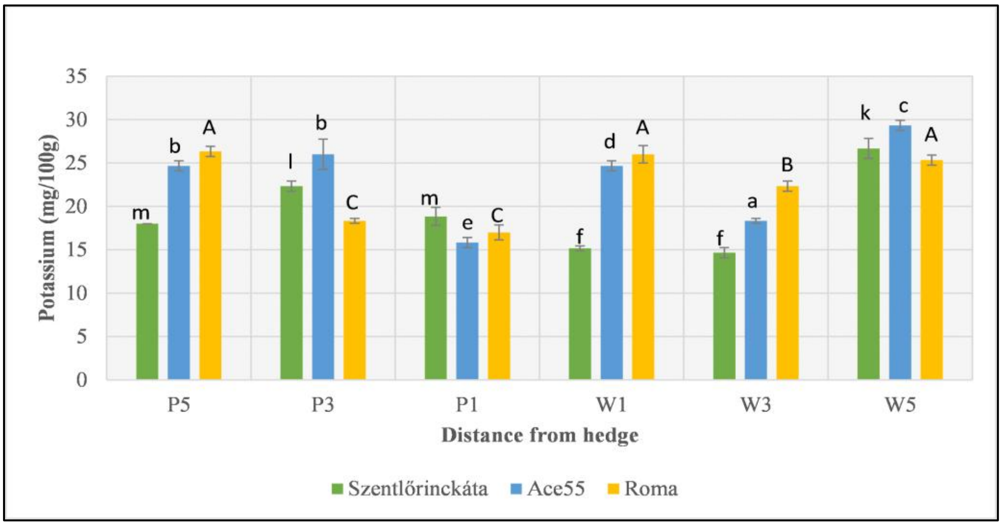
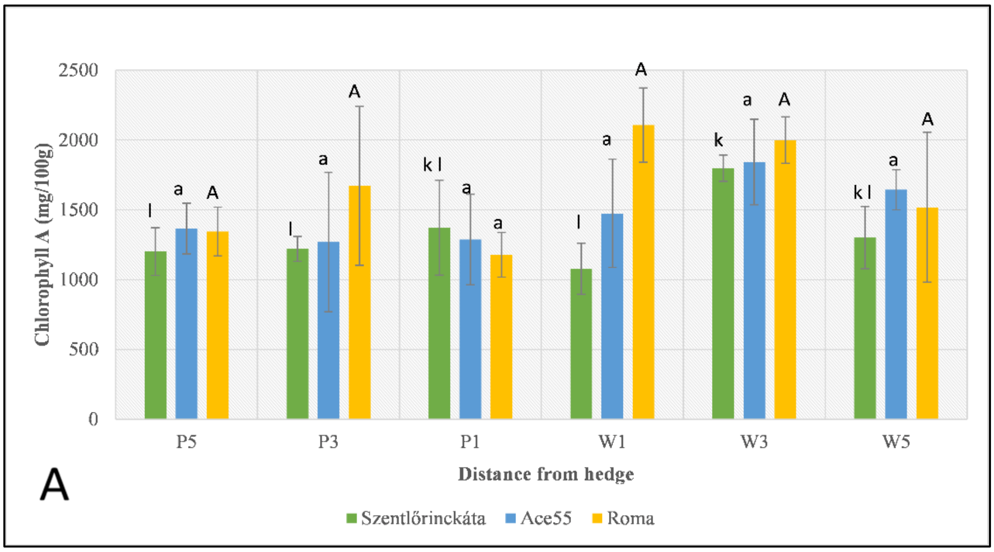


Figure 30. Potassium content (mean and SD) of tomato plant leaf samples produced on the protected and the windy side of a hedge, at various distances in (2023). Ascending numbers mean higher distances. Differing letters mean a significant difference ($P < 0.05$) among samples of the same variety (Mustafa, Szalai, et al., 2023).

4.3.4 Chlorophyll A and B determination of tomato leaves

Chlorophyll is an important factor for plant growth due to its role in photosynthetic activity, which is responsible for the green coloration of plants (Figure 31A). Based on the analysis of chlorophyll A content, values varied across sample treatments on both sides of the hedgerow. On the windy side, the Roma variety exhibited the highest chlorophyll A content, reaching 2106.98 mg/100 g at W1 and 1999.08 mg/100 g at W3, which were significantly higher than the other varieties ($p < 0.05$). On the protected side, Roma also showed the highest chlorophyll A value at P3 (1671.12 mg/100 g). In contrast, the Szentlőrinckáta variety consistently recorded lower chlorophyll A concentrations, particularly at W1 (1077.03 mg/100 g) and P5 (1201.13 mg/100 g), confirming significant differences among cultivars and sample treatments.



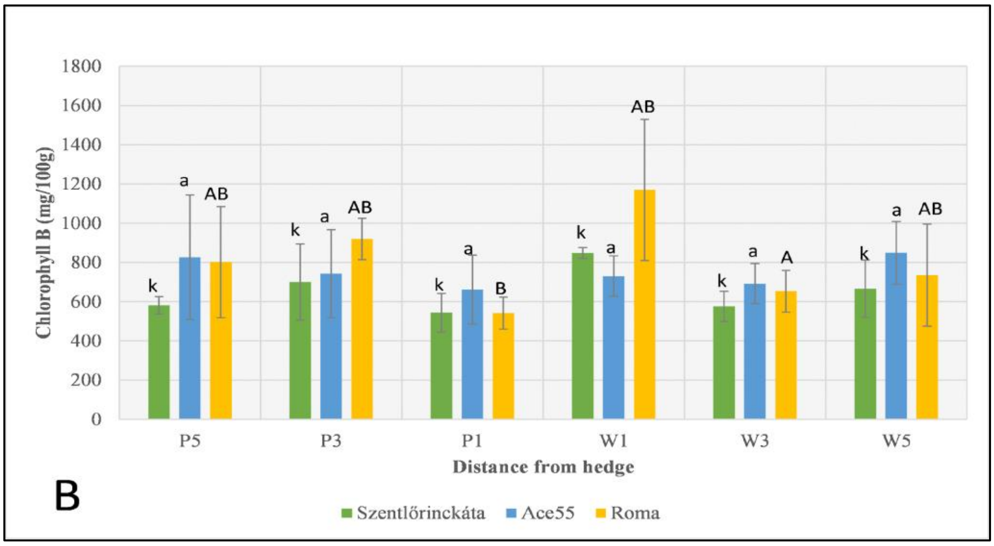


Figure 31 A and B. Chlorophyll A and B content (mean and SD) of tomato plant leaf samples produced on the protected and the windy side of a hedge, at three distances for each side in (2023). Ascending numbers mean higher distances from the hedgerow. Differing letters mean a significant difference ($p < 0.05$) among samples of the same variety (Mustafa, Szalai, et al., 2023).

4.3.5 Carotene content determination of tomato leaves

Carotene content, an important antioxidant and precursor of vitamin A, varied significantly among tomato varieties and sample treatments at different distances from the hedgerow (Figure 32). The Roma variety exhibited the highest carotene content on the windy side at W3 (485.62 mg/100 g), which was significantly higher than most other sample treatments. A similar trend was observed on the protected side at P3 (481.29 mg/100 g), indicating a consistent capacity of Roma for carotene accumulation across both hedgerow sides.

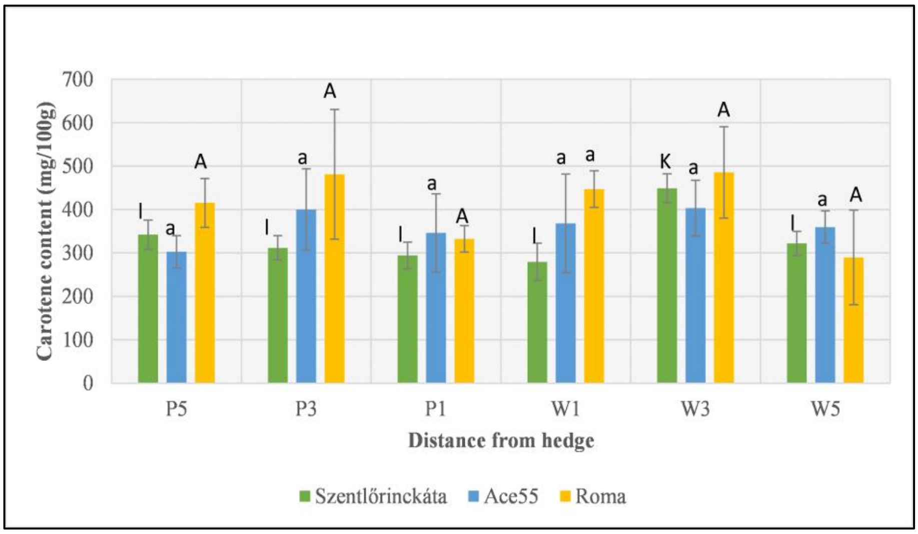


Figure 32. Carotene content (mean and SD) of tomato plant leaf samples produced on the protected and the windyside of a hedge, at three distances for each side in (2023). Ascending numbers mean higher distances. Differing letters mean a significant difference ($p < 0.05$) among samples of the same variety (Mustafa, Szalai, et al., 2023).

The Ace55 variety showed moderate carotene levels, with its highest value recorded at P3 (400.16 mg/100 g). In contrast, the Szentlőrinckáta variety consistently recorded lower carotene contents, particularly at P1 (294.33 mg/100 g) and W1 (279.68 mg/100 g), with limited variation across distances. These results highlight a significant effect of genotype and hedgerow-related positioning on carotene accumulation in tomato fruits ($p < 0.05$).

4.4 Tomato fruit yield across hedgerow sides and distances

4.4.1 Tomato fruit average weight

Total tomato fruit weight differed significantly ($p \leq 0.05$) across planting distances and hedgerow windy and protected sides in the first year (2022). Windy side enhanced yield performance, with higher fruit weights observed compared to the protected side, indicating that fruit weight variation was closely associated to genotype adaptability and microclimatic conditions. Roma resulted in the highest average fruit weight at the windy side distance at W5 (2.81 kg), which was exceptional compared to all protected side distances. Moderate weights were achieved at W1 (2.08 kg) and P4 (2.11 kg), while the lowest occurred at W3 (0.92 kg) and P2 (1.18 kg).

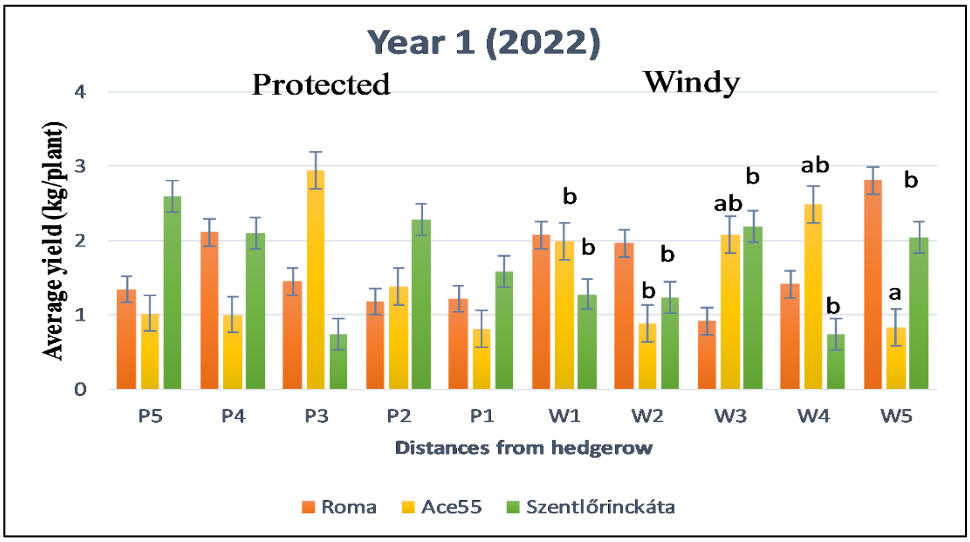


Figure 33. Tomato average yield results (mean ± SD) from the first year (2022). Interaction plots show the effects of distance from a hedgerow (W1–W5: Windy side; P1–P5: Protected side) in Soroksár, Hungary. Differing letters denote significant differences between values within side, harvest and variety ($p < 0.05$).

Ace55 also presented significant variation across distances, with the highest fruit yield at P3 (2.94 kg). Windy side distances W4 (2.48 kg) and W3 (2.08 kg) yielded relatively well, though not exceeding the protected side. The lowest weights were observed at P1 (0.81 kg) and W5 (0.83 kg). However, Szentlőrinckáta demonstrated consistent performance across both hedgerow sides (Figure 33). On the protected side, P5 (2.59 kg) and P2 (2.28 kg) resulted in high fruit weight. The windy side, W3 (2.19 kg) and W5 (2.05 kg), showed higher yield than

W4 (0.74 kg) and W1 (1.28 kg). These findings suggest that Szentlőrinckáta maintains stable productivity under variable conditions when planted at optimal distances. The windy side, particularly at distances W3 to W5, was associated with increased fruit weight in Roma and Szentlőrinckáta, while Ace55 favoured more sheltered conditions, indicating genotype responses to microclimatic factors influencing fruit development, in contrast to the protected side.

In the second year (2023), the windy side generally demonstrated higher fruit weights, particularly at the outer positions. Roma achieved its highest average fruit yield on the windy side at W4 (5.98 kg), followed by W3 (5.13 kg) and W5 (5.10 kg). These values exceeded those on the protected side, where P3 (5.79 kg) recorded high tomato fruit weight. W1 (3.60 kg) resulted in the lowest fruit weight, indicating that balanced to distal windy positions were most favorable for Roma's fruit development and yield potential (Figure 34).

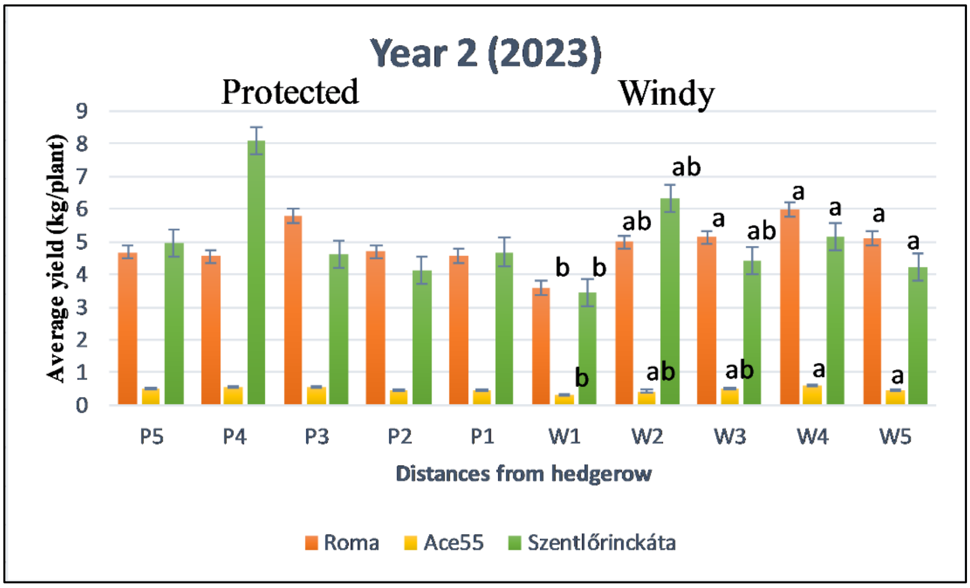


Figure 34. Tomato average yield results (mean ± SD) from the second year (2023). Interaction plots show the effects of distance from a hedgerow (W1–W5: Windy side; P1–P5: Protected side) in Soroksár, Hungary. Differing letters denote significant differences between values within side, harvest and variety ($p < 0.05$).

Ace55 had comparatively lower fruit weights across all treatments. The greatest value was observed at W3 (0.62 kg), and distances W4 and W5 exhibited the lowest fruit weight. Protected side, P3 (0.54 kg) represented the highest yield. These results suggest that Ace55 exhibited limited productivity and was less responsive to hedgerow conditions. Furthermore, Szentlőrinckáta continued to perform strongly under hedgerow systems. Windy side, W2 (8.11 kg) yielded the highest tomato fruit weight, followed by distances W3 (6.34 kg) and W5 (5.17 kg). Meanwhile, Protected side, P5 (4.95 kg) and P3 (4.62 kg) produced the highest yields. This variety appeared well adapted to balanced wind exposure and distances, contributing to its superior productivity. Szentlőrinckáta and Roma, when exposed to windy conditions, consistently resulted higher fruit weights, while Ace55 exhibited low performance, highlighting the importance of planting distance and environmental factors in tomato yield.

Interestingly, the trend of the weight in the third year (2024), tomato fruit weight continued to vary significantly across planting distances and hedgerows (Figure 35). The windy side generally produced more fruits, particularly for the Roma and Szentlőrinckáta, while Ace55 maintained comparatively lower yields with limited variability between sides and distances. Roma presented relatively low fruit weights across all protected side distances, ranging from P5 (0.56 kg) to P3 (0.75 kg). However, fruit weight increased substantially under windy side conditions, with the highest observed at W5 (1.98 kg), followed by W3 (1.66 kg) and W4 (1.16 kg).

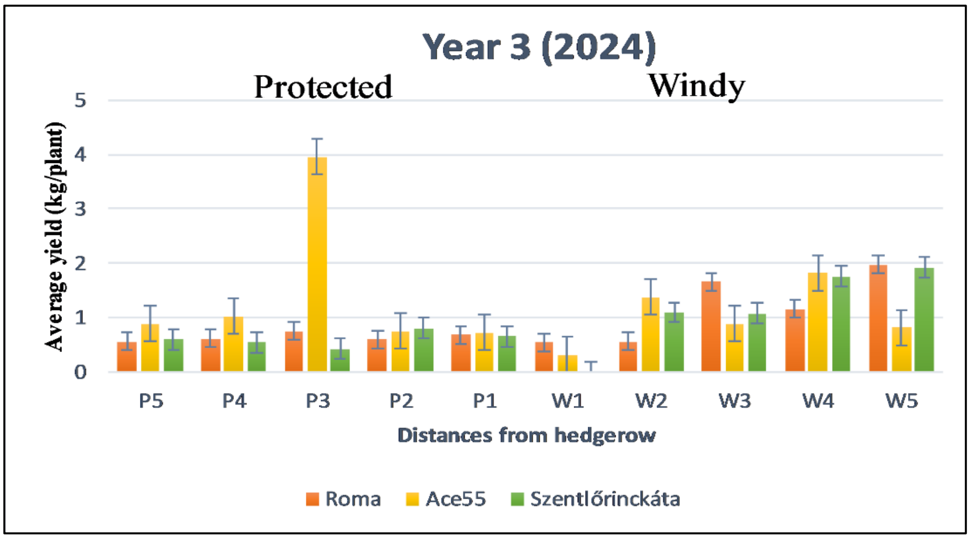


Figure 35. Tomato average yield results (mean ± SD) from the third year (2024). Interaction plots show the effects of distance from a hedgerow (W1–W5: Windy side; P1–P5: Protected side) in Soroksár, Hungary. Differing letters denote significant differences between values within side, harvest and variety ($p < 0.05$).

Ace55 continued to exhibit modest productivity, with minor differences across planting distances., The protected side, fruit weights differed from P3 showing the highest yield (4.83 kg). On the windy side, W2 recorded the maximum fruit weight (3.96 kg), while W3 (2.94 kg) and W4 (2.91 kg) showed intermediate performance. Szentlőrinckáta maintained consistent yields across both sides, with P2 (3.91 kg) performing best on the protected side, and W5 (3.84 kg) followed by W3 (3.61 kg) on the windy side. Szentlőrinckáta and Roma demonstrated higher yields in windy conditions, with Roma's fruit weight nearly tripled. Ace55 showed weak responsiveness, while Szentlőrinckáta maintained superior yields at W3 and W5. The results confirm that wind and light exposure significantly influence tomato fruit weight, and that varietal differences significantly determine yield potential under varying microclimatic condition (Appendix table 3).

4.4.2 Tomato fruit total yield per plot

The previously presented results are based on the average yield per plot, where fruiting plants were treated as repetitions. This allowed to prepare a statistical analysis for this dataset. However, this way of average yield calculation generates several issues, such as (1) hiding the extremely high or low yield values of individual plants, (2), hiding yield losses due to flower or fruit abortation in case of extreme climate conditions, and (3), being irrelevant from a practical point or view, where total yield is the main aspect for the consideration of agrotechnical technologies. Therefore, the average yield presentation was used for the scientific discussion, and parallel to this, a total yield per plot approach is also presented in this chapter to give a more practical picture about the impact of hedges on the yield of investigated tomato genotypes.

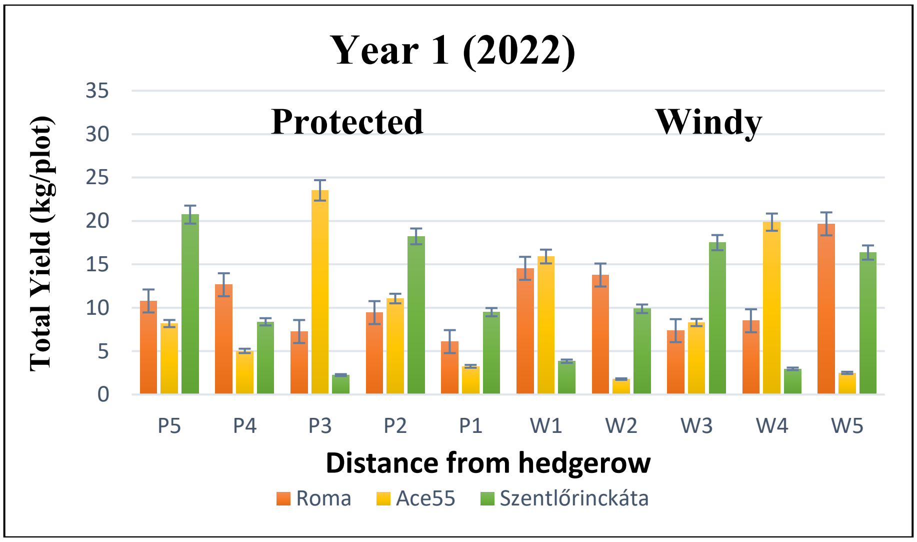


Figure 36. Tomato total fruit yield (kg/plot) results (mean ± SD) from the first year (2022), summarized by plots within varieties and distances. Interaction plots show the effects of distance from a hedgerow (W1–W5: Windy side; P1–P5: Protected side) in Soroksár, Hungary.

In the first year of the trial, Ace55 developed favourable yield results on the Protected side, especially at P3 distance. Szetlőrinckáta performed favourably on the protected side at P3 and P5 distances. On the Windy side, the results of Roma and Ace55 gave good results further from the hedge, at W4 and W5 distances (Figure 36). Generally, no significant differences were observed between the protected and windy sides. The yield development on the protected side was sometimes adversely affected by higher temperatures, especially in combination with infection. The high temperatures during the growing season caused sunburn damage to the plants, and heat stress caused the flowers and small fruits to abort, significantly reducing the harvestable yield.

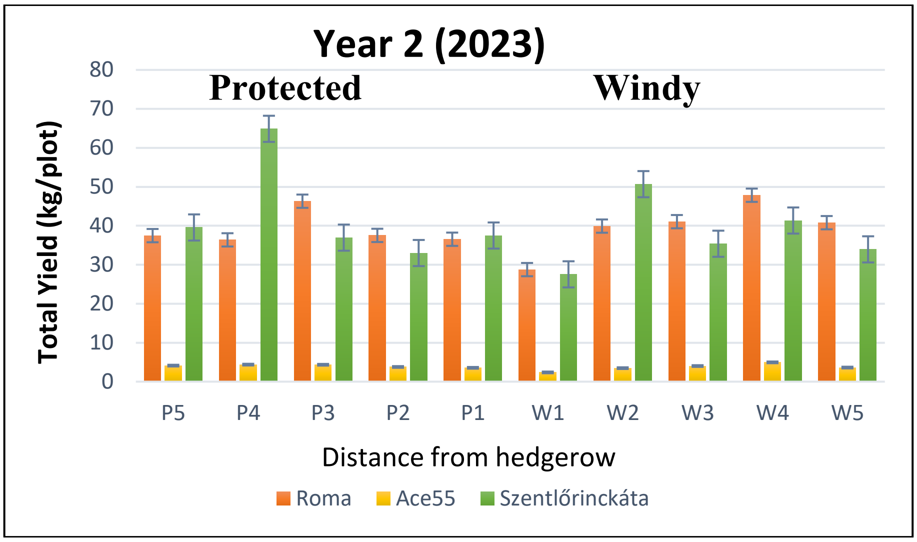


Figure 37. Tomato total fruit yield (kg/plot) results (mean ± SD) from the second year (2023), summarized by plots within varieties and distances. Interaction plots show the effects of distance from a hedgerow (W1–W5: Windy side; P1–P5: Protected side) in Soroksár, Hungary.

Examining the yield of 2023 expressed in kg per plot (Figure 37). We can conclude that the data series of the plot averages developed more favourably compared to 2022, giving a more balanced result for the yield average by analysing the yield data of three harvests. Among the varieties, the data of Ace55 stabilized at an unfavourably low level on both the protected and windy sides. Szetlőrinckáta performed better on the Protected side especially at P4 distance. On the Windy side, the results of Roma and Szentlőrinckata gave good results at distances W2 and W4 from the hedge. Overall, the yield data on the Protected side were not significantly higher. On the protected side, the development of the yield was sometimes adversely affected by higher temperatures, especially when combined with infection.

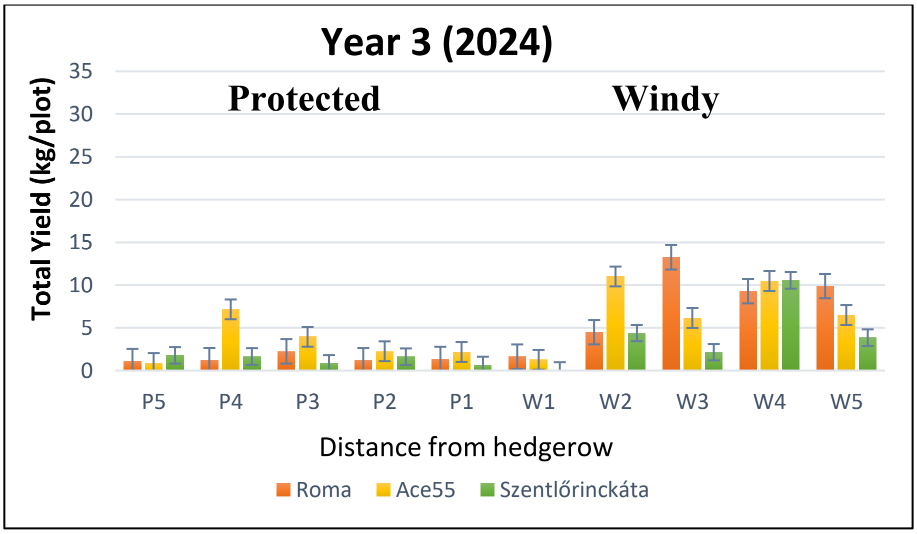


Figure 38. Tomato total fruit yield results (mean ± SD) from the third year (2024), summarized by plots within varieties and distances. Interaction plots show the effects of distance from a hedgerow (W1–W5: Windy side; P1–P5: Protected side) in Soroksár, Hungary.

Gradually lower yield was documented in the third year of the experiment, possibly due to heat extremities and irrigation issues (Figure 38). The total yield tended to be lower on the protected side than on the windy side for all genotypes, although the differences were not statistically significant. Both three genotypes yielded the highest at mid-distances, with Ace55 providing the highest values. On the Windy side, mid-distances were the most favourable as well. Roma favoured W3, while Ace55 performed the best on W2 and W4; The peak performance of Szentlőrinckáta at W4 was not as outstanding as for the others, which suggest its higher resilience towards changing environmental conditions. On the protected side, the yield was probably affected by higher temperatures, especially when combined with infection, heat stress may have cause flowers and fruits abortion.

4.4.3 Tomato fruit number across hedgerow sides and distances

Interestingly, the trend of tomato fruit numbers across the three year study revealed distinct varietal responses, hedgerow systems, and planting distance (Appendix table 4). In the first year (2022), fruit numbers varied significantly across both protected and windy sides, with statistical evidence supporting the influence of microclimatic conditions (Figure 39). Roma demonstrated moderate productivity on the protected side, with fruit numbers ranging from P5 (6.88) to a high at P4 (37.33). Windy side, yields surged dramatically, especially at W5 (111.00), indicating a strong positive response to increased light and airflow. Furthermore, windy positions such as W1 (43.43), W2 (44.00), and W4 (38.83) also achieved higher yields. Despite high variability ($p = 0.039$) confirmed significant heterogeneity across distances. ($p < 0.01$) indicated statistically significant differences in fruit numbers among positions, validating the side impact of the hedgerow.

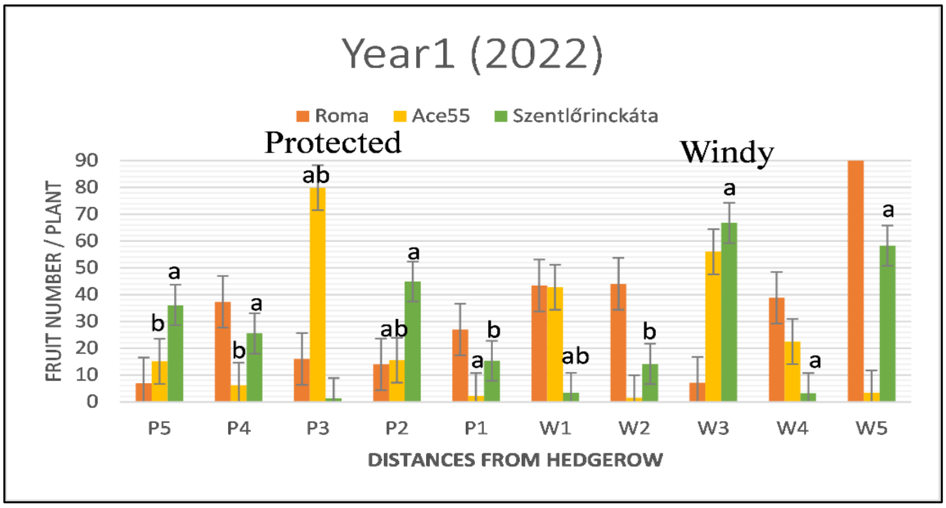


Figure 39. Tomato fruit number/plant results (mean ± SD) from the first year (2022). Interaction plots show the effects of distance from a hedgerow (W1–W5: Windy side; P1–P5: Protected side) in Soroksár, Hungary. Differing letters denote significant differences between values within side, harvest and variety ($p < 0.05$).

Ace55 demonstrated robust responsiveness on the protected side. Fruit numbers resulted at P3 (79.88), while lower yields were observed at P1 (2.25) and P4 (6.20), confirming strong significance ($p < 0.001$) across protected positions (Figure 39). On the windy side, performance was more variable: W3 (56.00) and W1 (42.75) had the highest fruit numbers, while W2 and W5 yielded less fruits. However, the overall model for windy side variation was less significant ($p = 0.075$), suggesting inconsistent responsiveness under wind conditions. Szentlőrinckáta exhibited a balanced and consistent yield pattern across both sides. On the protected side, fruit numbers ranged from P3 (1.33) to P2 (44.88), with P2 and P5 (36.13) performing best. However, windy side, fruit numbers were generally higher, with W3 (66.75) and W5 (58.25) emerging positions. Reduction at W1 and W4 were notably less productive ($p = 0.0053$), demonstrating unequal variance, and ($p < 0.001$) validated significant differences across planting distances, reinforcing the role of hedgerow microclimatic effects.

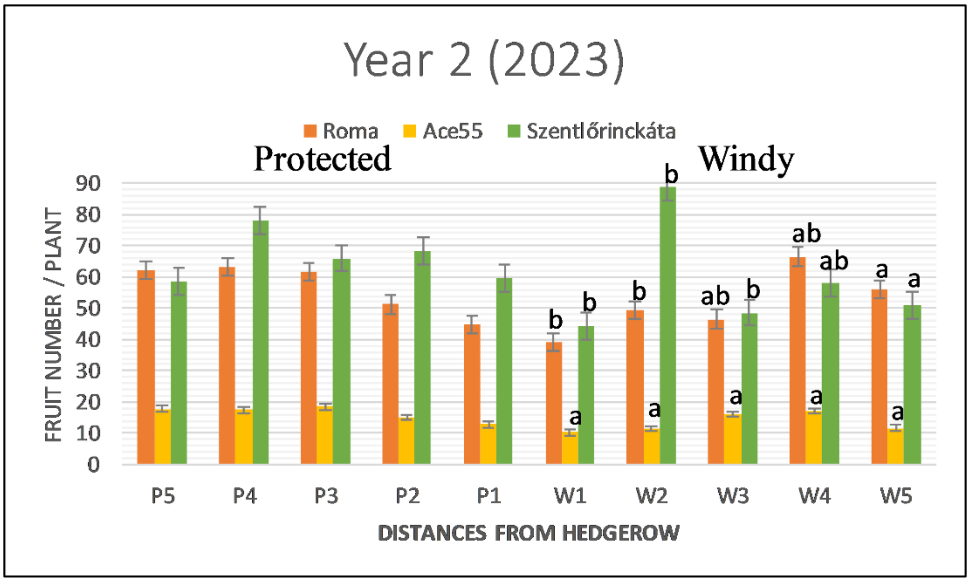


Figure 40. Tomato fruit number/plant results (mean ± SD) from the year (2023). Interaction plots show the effects of distance from a hedgerow (W1–W5: Windy side; P1–P5: Protected side) in Soroksár, Hungary. Differing letters denote significant differences between values within side, harvest and variety ($p < 0.05$).

In the second year (2023), fruit numbers remained high across all varieties, particularly for Szentlőrinckáta presents high yields across both sides. Protected side at P4 (78.13) and P2 (68.13), while windy side positions W2 (88.88) and W4 (58.00) also resulted strong results. ($p < 0.001$) confirmed significant variation, highlighting the variety's adaptability and yield stability on both sides of the hedgerow (Figure 40). Roma highlighting strong and consistent productivity across all positions, with fruit numbers ranging from P1 (44.88) to W4 (56.13). The protected side resulted at P4 (63.13) and P5 (62.13), while the windy side also performed well, especially at W3 (66.50). Ace55 recorded lower fruit numbers collectively, with minimal variation. Protected side yields ranged from P1 (12.88) to P3 (18.50), while the windy side indicated slightly better performance at W3 and W4. ($p = 0.031$) revealed heterogeneity, though in general responsiveness to hedgerow conditions.

By the third year, fruit numbers decreased as they had in the first years across all varieties and distances, with most values falling below 20 fruits. Roma presented slightly better performance on the windy side, especially at W3 (17.13) and W5 (12.40), while protected side yields remained low across all positions. Ace55 remained the least productive in terms of fruit number, with marginal change across both sides (Figure 41). Yields differed from P1 (1.00) to W3 (7.75), but no clear pattern emerged. Szentlőrinckáta maintained relatively higher yields compared to the other varieties. Protected side P4 (9.00) and P3 (9.00), while windy side positions W2 (7.83) and W5 (5.50) also performed moderately well. Demonstrating significant wider range, reinforcing the variety's resilience under declining conditions and environmental stress factors.

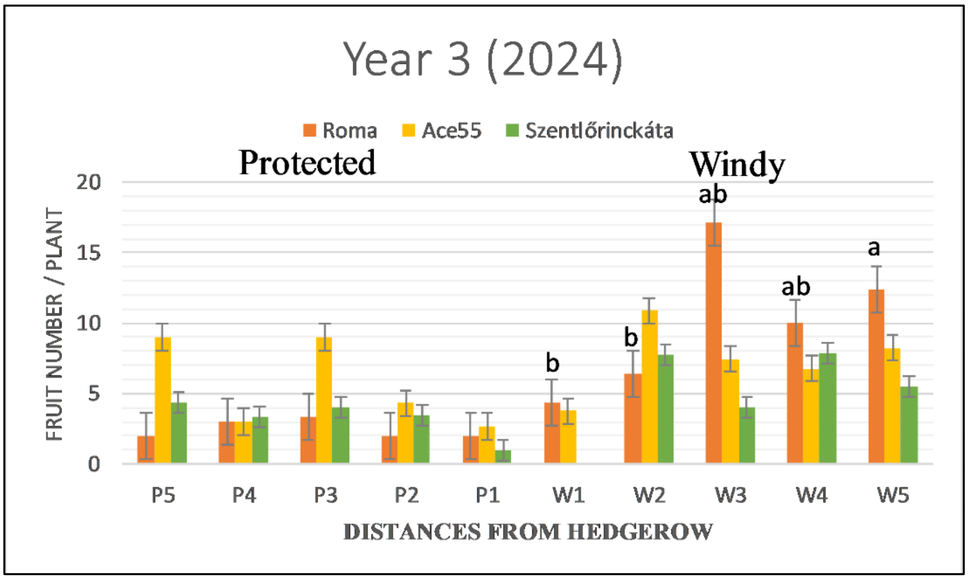


Figure 41. Tomato fruit number/plant results (mean ± SD) from the third year (2024). Interaction plots show the effects of distance from a hedgerow (W1–W5: Windy side; P1–P5: Protected side) in Soroksár, Hungary. Differing letters denote significant differences between values within side, harvest and variety ($p < 0.05$).

4.4.4 Pest and disease impact on tomato in a hedgerow system

In 2022, the first year of this experiment, we investigated how hedgerow systems influence pest and disease on tomato fruit yield. Three tomato genotypes, Szentlőrinckáta, Ace55, and Roma, were cultivated on both windy and protected sides of a hedgerow at five planting distances. Damage was assessed from key insect pests, including potato beetle (*Leptinotarsa decemlineata*) and cotton bollworm (*Helicoverpa armigera*), fungal infections by *Phytophthora infestans*, and wildlife such as rabbits (*Oryctolagus cuniculus*) and roe deer

(*Capreolus capreolus*) as shown in (Figure 42). Potato beetle damage was primarily genotype dependent, with Ace55 showing fewer damaged leaves across all treatments. Cotton bollworm damage was highest in Szentlőrinckáta, significantly influenced by side and distance. Fungal infections highlighted no significant variation among genotypes or sides factors. Wildlife damage increased with planting distance, with side patterns observed. Despite higher insect pressure on the protected side, it generally supported better fruit development, especially in Roma and Szentlőrinckáta.

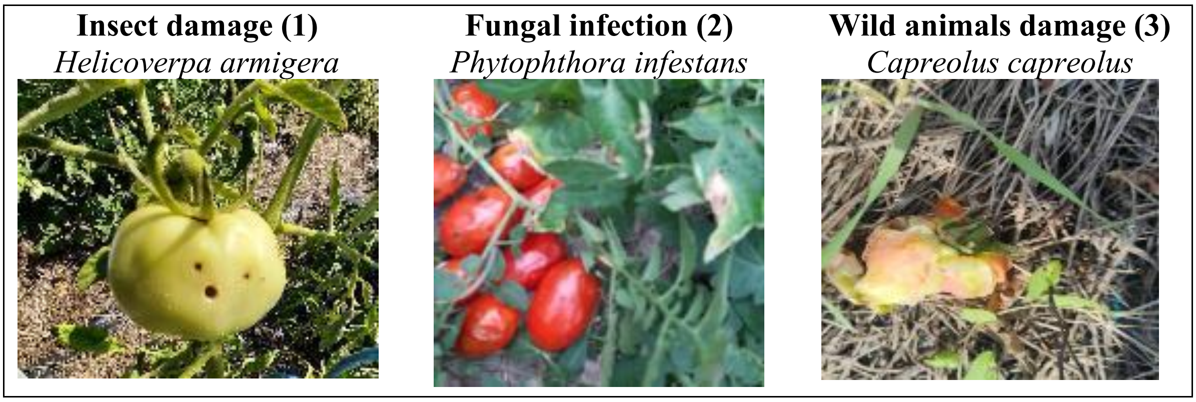
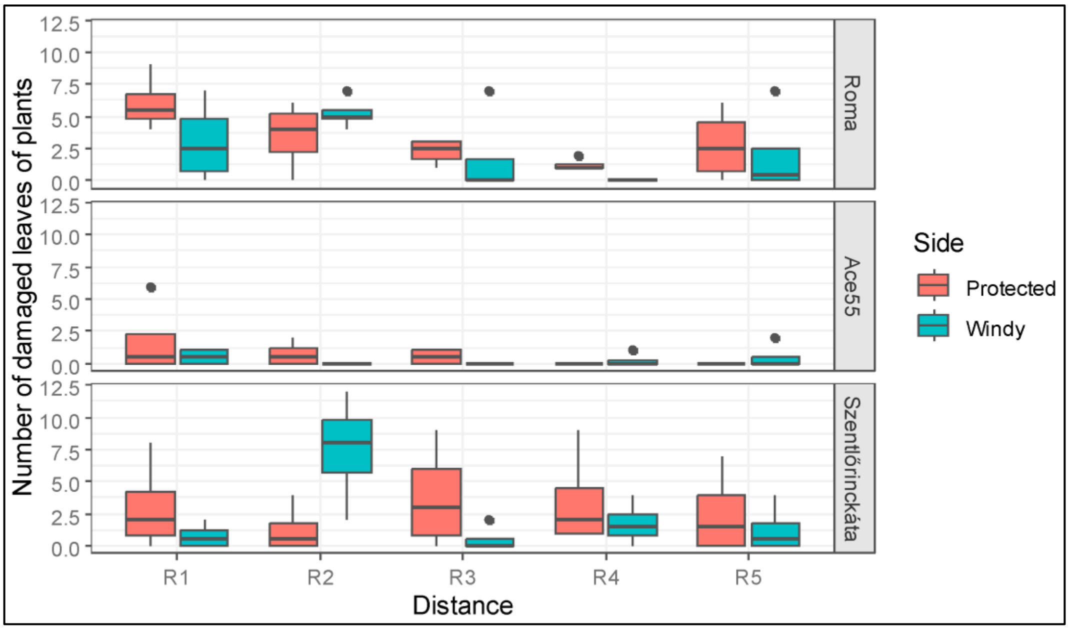


Figure 42. Symptoms of damage caused by pests (1), fungi (2), and wild animals (3) on tomato fruit (Mustafa, Adjei, et al., 2023).



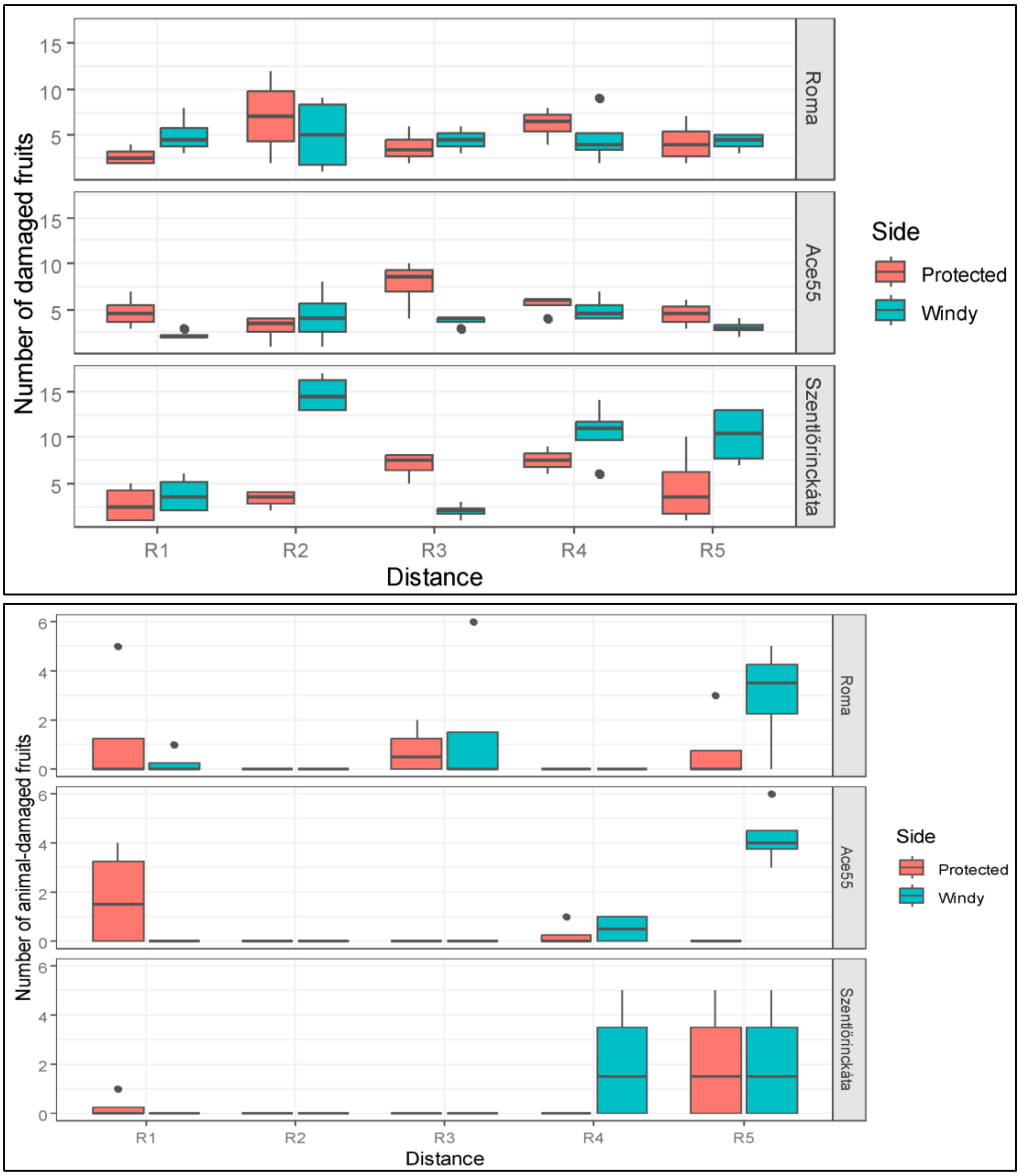


Figure 43: Combined damage and yield assessment across tomato varieties, sides, and planting distances: (1) shows leaf damage by potato beetle (0 - 45 leaves/plant); (2) presents fruit damage by cotton bollworm (0-38 fruits/plant); (3) illustrates wild animal damage (0-22 fruits/plant) using box-plot visualization(median range: 35-111 fruits/plant), with whiskers indicating damage and dots marking outliers.

However, the results revealed that tomato variety and location significantly influence the quantity of healthy green and red fruits (Figure 43). Ace55 produced fewer fruits than Roma and Szentlőrinckáta, with side and distance interactions affecting fruit weight. The protected side yielded the highest amount of healthy red fruit, while the windy side produced less damaged red fruit, which agrees with the results of (Nordey et al., 2017) on the protected cultivation of vegetable crops in sub-Saharan Africa. Despite insect damage, the protected side was more favourable for establishing healthy, marketable crops, suggesting further research for exploring strategies to reduce insect damage on organically managed tomato fields. These findings demonstrate the ecological value of hedgerow systems in regulating pest dynamics and enhancing tomato yield.

4.5 Tomato fruit quality traits: soluble solids, acidity, colour traits, and antioxidant profiles

The impact of hedgerow microclimate modulation influences tomato fruit quality, focusing on parameters valued by consumers such as sweetness acidity balance, nutritional composition, antioxidant capacity, and colour traits (TSS, TA, SAR, TPC, FRAP, Chroma (C*), and hue ($h°$)). The analysis was performed on different tomato genotypes cultivated in an organically managed open-field system, with comparisons between the Windy and Protected sides of the hedgerow, over two consecutive years (2023 - 2024).

4.5. 1 Tomato fruit puree colour-related results

According to the statistical analysis of the fruit puree colour related traits (Chroma, hue) (Table 7), all two- and three-way interactions were significant both in 2023 and in 2024 ($p < 0.05$, and $p<0.001$, respectively).

Table 8. Summary of wilk's lambda and F-test results for chroma and hue (2023 - 2024).

Treatment	Quality	Wilk's lambda	2023	2024
			<0.76 ***	<0.90 ***
		df1 of F	F(df1, 149)	F(df1, 133)
Variety	Chroma	2	31.66***	0.94 ns
	hue	2	16.97***	17.56***
Distance	Chroma	4	1.18 ns	5.26***
	hue	4	12.46 ***	3.05 *
Side	Chroma	1	4.81*	9.42**
	hue	1	41.74***	9.81**
2023: all two- and three-way interactions are significant (p<0.05)				
2024: all two- and three-way interactions are significant (p<0.001) Significance codes: *** p < 0.001, ** p < 0.01, * p < 0.05, + p < 0.10, ns = not significant				

4.5. 2. Chroma (C*) analysis

Chroma (C*) peaked at 39.39 ± 0.05 on the Protected side at P3, with distances (P2–P4) at Protected sides showing higher Chroma (C*) stability in the first harvest of the 2023 (Figure 44). The results show that distances closest to the hedge (P1-W1) consistently demonstrated a moderating effect on Chroma (C*). Notably, significant statistical effects were observed for side ($p < 0.01$ in 2024) and distance ($p < 0.001$), highlighting the influence of environmental exposure (Table 8). Based on CIELAB colour parameters (L*, a*, b*), Chroma (C*) values exhibited tomato genotype specific trends, environmental sensitivity, and inter-annual variability. Roma genotype exhibited high Chroma (C*) in the year of 2023, particularly at

Protected distances P2 (38.11 ± 0.7) and P3 (34.01 ± 2.55), On the Windy side, high values were also observed at W2 (38.18 ± 0.20) and at W4 (38.40 ± 0.08), but Chroma declined from 28.01 ± 0.08 to 24.69 ± 0.23.

Figure 44. Tomato fruit color traits (Chroma (C*)) across hedgerow distances reveal significant variation between protected and windy sides in Soroksár, Hungary (2023 – 2024). Differing letters denote significant differences between values within side, harvest and variety ($p < 0.05$).

Ace55 had high Chroma in the year of 2023 (Figure 44), especially at Protected distances P4 (38.79 ± 0.05) and P3 (36.92 ± 0.03), leading among all distances. Windy site distances W5 (35.12± 0.47), W3 (25.50 ± 0.48), and W4 (24.69 ± 0.23) also maintained high Chroma (C*) pigmentation, which remained relatively stable across harvests. Despite this, W5 consistently held its Chroma, suggesting better pigment retention under Windy exposure. Overall, protected plots reached higher peak values, but windy plots demonstrated greater consistency from first harvest to second harvest. Szentlőrinckáta showed more variable Chroma trends. Protected distances P3 (39.39 ± 0.05) and P4 (36.40 ± 0.06) led in overall performance, while P2 (27.04

± 0.03) improved in the second harvest (Figure 44). Windy distances W4 (39.44 ± 0.06), W2 (36.68 ± 0.14), and W5 (37.65 ± 0.14) recorded the highest values among windy sites. Conversely, W3 (30.41 ± 0.19) and P1 (24.07 ± 0.13) exhibited more fluctuation between harvests. These results underscore enhanced Chroma retention in specific Protected distances, while windy plots showed moderate but more stable expression (Appendix table 5).

4.5. 3 Hue (h°) analysis

Hue angle results in the 2023 showed that Protected rows at P2 (51.27 ± 0.10°), and P4 (49.37 ± 3.82°) consistently reached optimal hue (45 – 53°) with minimal variation, indicating uniform ripening. In the 2024, hue values were gradually lower, particularly at W4 (from 46.74° to 30.39), and at P1 and W1 during the second harvest (Figure 45). Mid distances, especially P2, P3, W2, and W3, consistently outperformed others across years, confirming that intermediate distances significantly stabilised fruit coloration under variable microclimatic impact. Hue, calculated from L*, a*, and b* values, varied across the three tomato genotypes, seasons, and exposures (Figure 45). In Roma, first-year Protected plots showed optimal hue value at distances P2 (51.27 ± 0.10°) and P4 (49.37 ± 3.82°). A notable reduction in second harvests was observed, particularly at site P1 (39.95 ± 0.50°). Windy side performance was less consistent; at W1 it improved (44.35 ± 0.02° to 45.06 ± 2.47°), Table 8. while in W3 it declined. However, in the 2024, P5 peaked (48.17 ± 0.22). W5 increased (35.97 to 39.77), but W2 declined **(**35.35 ± 0.15° to 30.44 ± 0.10°).

Ace55 showed higher h**°**. In the year of 2023 (Figure 45), on Protected sites recorded at distances P2 (51.27 ± 0.10°) and P3 (49.67 ± 3.86°), there is no significant difference between the first and second harvest. On the Windy side, W1 increased sharply (44.35 to 52.33), while distances W4 (43.70 ± 1.29° to 30.39 ± 0.31°) and W5 (42.33 ± 0.27° to 32.05 ± 0.13°) showed lower values in the second harvests. However, in the 2024, higher values were measured, peaking at P3 (53.06 ± 0.30). In contrast, Szentlőrinckáta was balanced with the year of 2023 values on the Protected side distances (P2: 51.27 ± 0.10°, P3: 49.67 ± 3.86°), showing slight reductions in the second harvest (Figure 45). The Windy side demonstrated decreasing trends. However, second harvests underwent a reduction across positions, indicating reduced stability under hedgerow systems (Appendix table 6).

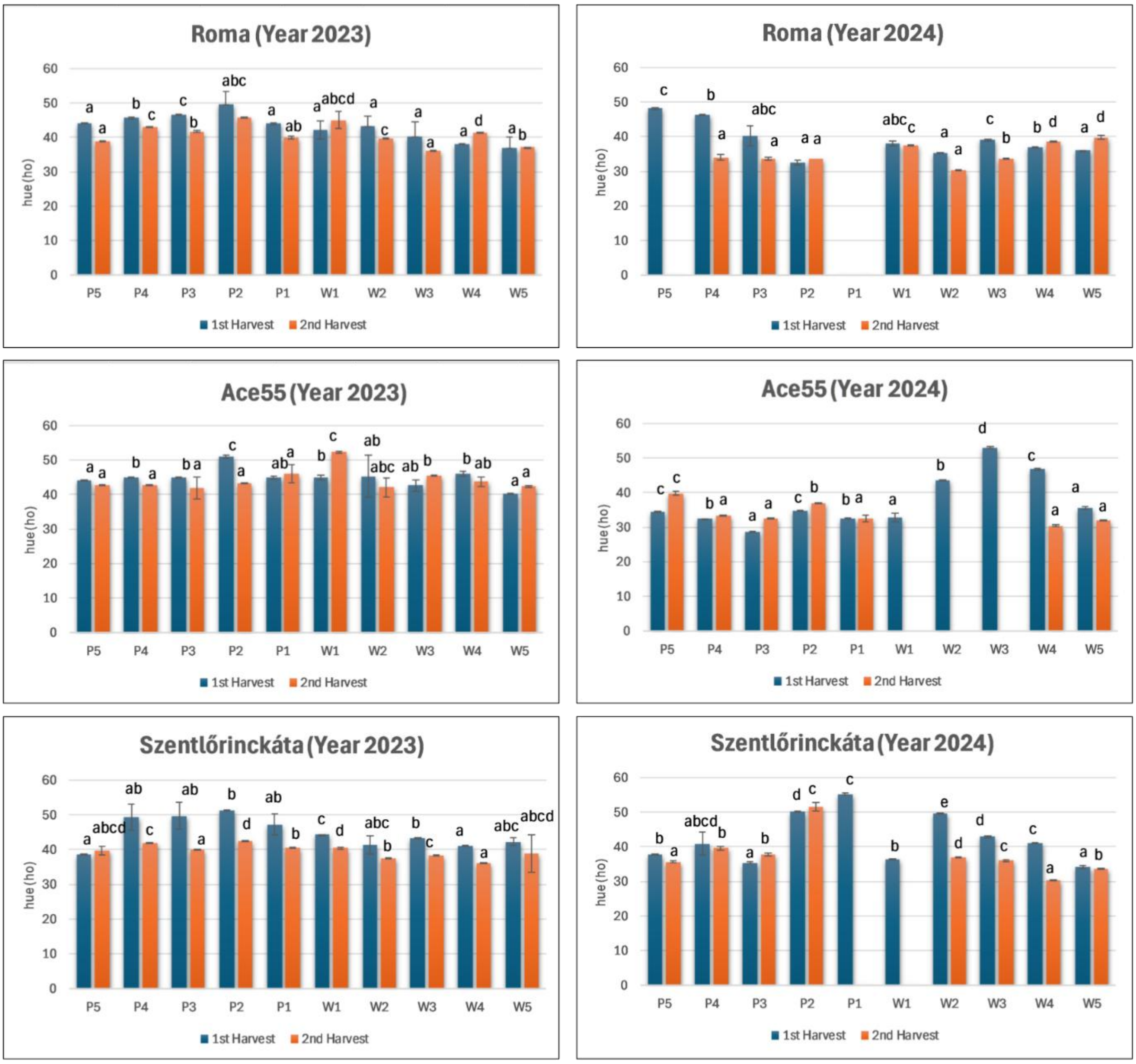


Figure 45. Tomato fruit Hue (h°) across hedgerow distances reveal significant variation between protected and windy sides in Soroksár, Hungary (2023 – 2024). Differing letters denote significant differences between values within side, harvest and variety ($p < 0.05$).

4.6 Tomato nutritional quality related traits

According to the results of the statistical analysis of nutritional quality related traits, all two- and three-way interactions were significant in both years (Table 9).

Table 9. Multivariate test results for fruit quality traits (TPC, FRAP, TSS, TA, and SA Ratio) in 2023 and 2024.

Treatments	Quality Traits	Wilk's lambda	2023	2024
			<0.50 ***	<0.77 ***
		df1 of F	F(df1, 149)	F(df1, 126)
Variety	TPC	2	9.18 ***	5.17 **
	FRAP	2	13.55 ***	3.88 *
	TSS	2	248.19 ***	4.37 *
	TA	2	0.098 ns	2.57 +
	SAR	2	22.66 ***	3.96 *

Distance	TPC	4	5.68 ***	7.33 ***
	FRAP	4	23.44 ***	5.52 ***
	TSS	4	6.06 ***	6.07 ***
	TA	4	3.47 *	2.1 +
	SAR	4	0.856 ns	2.21 +
Side	TPC	1	27.74 ***	20.9 ***
	FRAP	1	141.09 ***	16.54 ***
	TSS	1	0.33 ns	4.05 *
	TA	1	0.03 ns	10.01 **
	SAR	1	0.06 ns	5.95 *
2023: all two- and three-way interactions are significant ($p<0.05$)				
2024: all two- and three-way interactions are significant ($p<0.001$) Significance codes: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, + $p < 0.10$, ns = not significant				

4.6. 1 Total soluble solid (TSS, °Brix)

TSS accumulation increased significantly across mid distances, with high significance in the year of 2023 ($p < 0.001$) (Table 9), with 6.80 ± 0.10 °Bx at P3, and 6.67 ± 0.15 °Bx at W5. Windy sides outperformed in the 2024, particularly the first harvest at W1 (7.00 ± 0.00 °Bx) and W5 (6.67 ± 0.15 °Bx, $p < 0.05$). TSS levels were moderate among genotypes. Roma, Ace55, and Szentlőrinckáta genotypes showed stable TSS levels (Figure 46), with limited variability influenced by microclimatic exposure. Roma recorded its highest TSS values on the Protected side during the year of 2023 at distances P5 (5.17 ± 0.06 °Bx), and P3 (4.33 ± 0.06 °Bx), with minimal intra-distance variation (± 0.06 °Bx). The Windy side displayed similarly stable values across all distances, ranging from 4.37 to 4.93 °Bx, with standard deviations between ± 0.12 °Bx. Seasonal differences were minor, with slight increases at P1 (4.67 ± 0.06 °Bx) and modest decreases at distance P3 (4.23 ± 0.06 °Bx), during the second harvest. In the year of 2024 (Figure 46), TSS values increased across exposures, reaching up to (6.80 ± 0.10 °Bx) at P3 and (5.83 ± 0.06 °Bx) at P2. Notably, W4 showed an increase from (5.50 to 6.50 °Bx) in the second harvest, which reflects elevated sugar levels.

Regarding genotypes, Ace55 exhibited the highest TSS values relative to Roma and Szentlőrinckáta (Figure 46). In the year of 2023, protected side peaks were observed at distances P3 (5.60 °Bx) and P4 (5.67 ± 0.06 °Bx), with variability across positions ranging from ± 0.00 to ± 0.12. Windy positions showed higher values, with maximum TSS at distances W2 (6.70 ± 0.10 °Bx), and W5 (6.67 ± 0.15 °Bx), while greater fluctuations were seen at W1 (7.00 ± 0.00 °Bx) and W3 (6.43 ± 0.06 °Bx). Second harvests revealed significant increases at multiple points, including a marked rise at P2 from 5.23 to 5.53 °Bx TSS. In contrast, second-year values decreased under both exposure conditions (Figure 46), with Protected side peaks at P3 (5.63 ± 0.21 °Bx), and P5 (5.73 ± 0.21 °Bx). However, late-season sugar accumulation was still evident at P2, where values increased from 5.23 to 5.90 °Bx. On the Windy side, W2 (6.70 ± 0.10 °Bx), and W3 (6.43 ± 0.06 °Bx) exhibited the highest TSS values, with mid distances W3- and terminal distances W5 consistently outperforming others, particularly during second harvests.

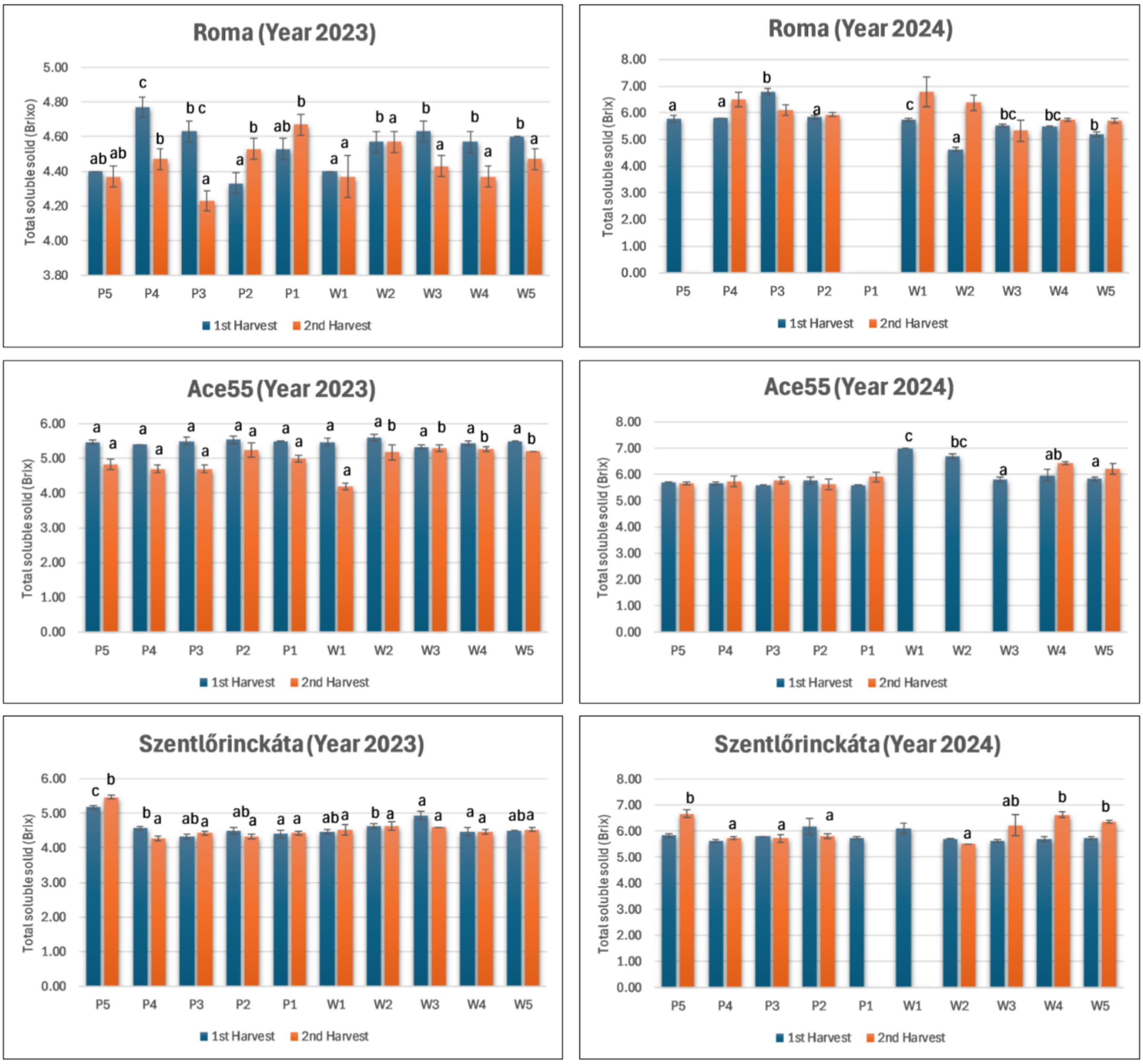


Figure 46. Total soluble solids (TSS, °Brix) across hedgerow distances reveal significant variation between protected and windy sides in Soroksár, Hungary (2023 – 2024). Differing letters denote significant differences between values within side, harvest and variety ($p < 0.05$).

Szentlőrinckáta genotype displayed moderate but consistent TSS values throughout both years. In the year of 2023, protected side values peaked at P5 (5.17 ± 0.06 °Bx) and P3 (4.33 ± 0.06 °Bx) (Figure 46). The Windy side showed a similar pattern, with values ranging from 4.47 to 4.93 °Bx. Second harvest variations were minimal, averaging ± 2.1%. Second-year data showed general enhancement in TSS (Figure 46), with the highest Protected side values at distances P2 (6.17 ± 0.32 °Bx), and P5 (5.83 ± 0.06 °Bx). On the Windy side, distances W4 (6.37 ± 0.06 °Bx), and W5 (6.37 ± 0.06 °Bx) recorded the highest values, while W3 increased from 5.63 to 6.23 °Bx in the second harvest, indicating steady sugar accumulation influenced by microclimatic positioning (Appendix table 7).

4.6.2 Titratable acidity (TA)

Titratable acidity in the year of 2023 remained moderate and stable across both sides, with peak values at W5 (0.60 ± 0.03%) and P5 (0.54 ± 0.06%) as illustrated in (Figure 47). TA values increased notably in the year of 2024 under Windy side conditions, peaking at W3 (0.94 ± 0.04%) and W2 (0.75 ± 0.21%), surpassing Protected sides. Mid distances on Protected sides (P2 – P4) offered stability, while second harvests showed pronounced decreases. TA levels varied significantly by genotype, year, harvest timing, and position relative to hedge exposure, with early harvests and Protected distances characterized by elevated acidity levels (Figure 47). In the year of 2024, marginally significant or significant effects appeared: variety ($F = 2.57$ +), distance ($F = 2.10$ +), side ($F = 10.01$ **), as shown in Table 9. Roma displayed distinct spatial and temporal acidity patterns. However, protected distances P5 (0.54 ± 0.06%), and P3 (0.49 ± 0.07%) had the highest TA in the year of 2023. Windy-side values ranged between 0.40 – 0.62%. Harvest differences were plot-specific, with TA declining at distances P3 (0.41 ± 0.13%), but rising at W1 (0.68 ± 0.04%). Furthermore, acidity levels progressively increased with increasing distance. P2 (0.70 ± 0.05%) and W3 (0.71 ± 0.05%) led, the latter maintaining stability across harvests. Windy sides like W3 resulted (0.94 ± 0.04%), while the highest acidity clustered at mid distances (P2 – P4), especially under windy conditions. First harvests resulted in significantly greater acidity ($p < 0.05$), reinforcing their value for optimal organic acid retention (Figure 47).

Ace55 maintained stable TA values in the year of 2023 (Figure 47), peaking at Protected distances P5 (0.54 ± 0.06%) and P3 (0.49 ± 0.07%). A strong decline at P4 (0.48 ± 0.06%) between harvests highlighted the advantage of early harvest in preserving higher acidity levels. Windy plots showed significantly higher variance, with distance W5 (0.52 ± 0.03%). Furthermore, TA increased at Protected sites, with P3 reaching 0.70 ± 0.04%, though variability rose on P4 (SD ± 0.13) in the 2024. Windy sides led to erratic variability, with a pronounced TA value at W3 (0.94 ± 0.04%). Across both years, mid-distance (P2, P3, and P4) Protected plots offered the most consistent TA, while Windy plots showed isolated peaks but higher instability.

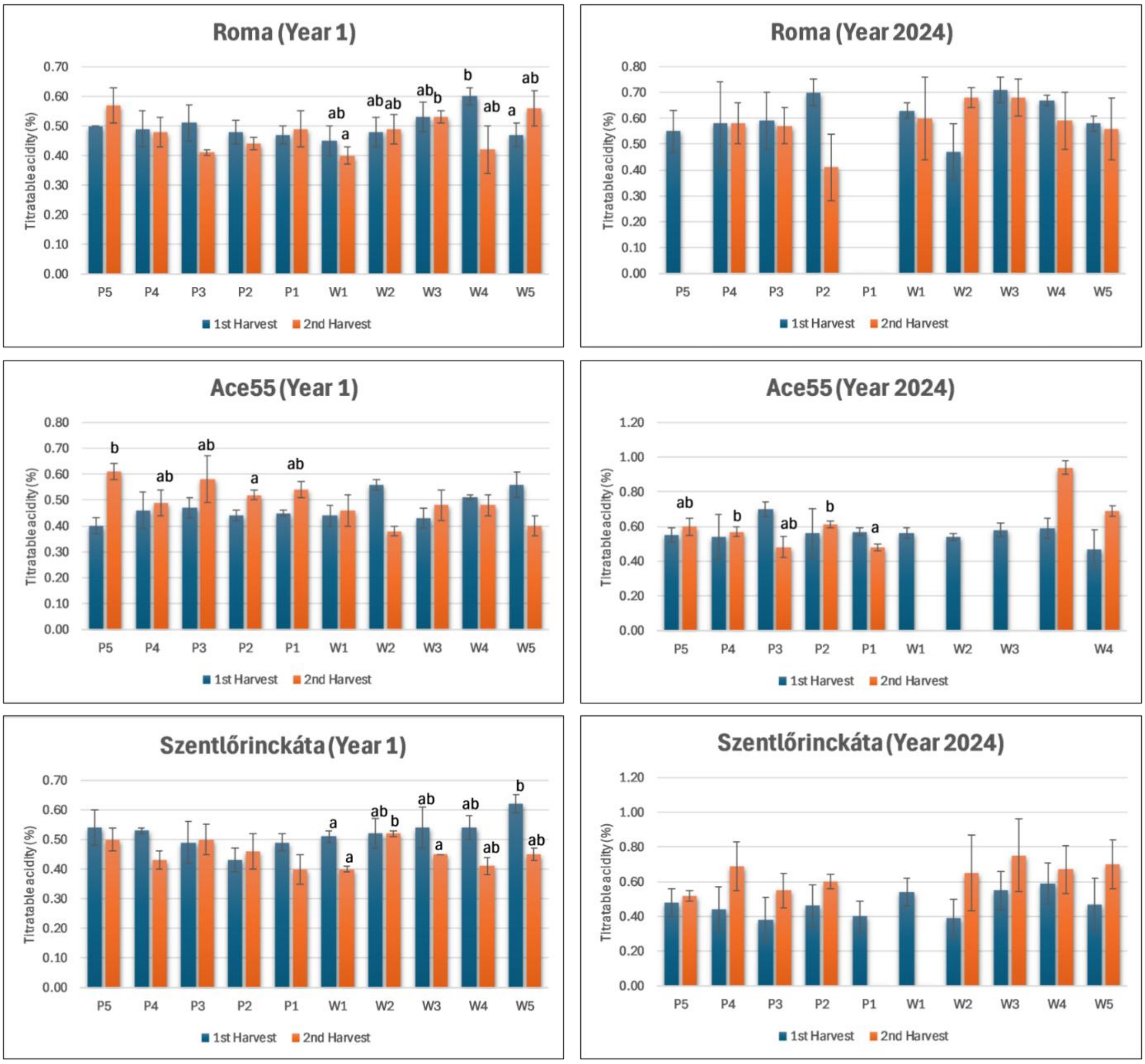


Figure 47. Titratable acidity (TA**)** across hedgerow distances reveals significant variation between protected and windy sides in Soroksár, Hungary (2023 – 2024). Differing letters denote significant differences between values within side, harvest and variety ($p < 0.05$).

Szentlőrinckáta showed moderate TA with heightened sensitivity to spatial and seasonal factors. In the year of 2023 (Figure 47), Protected at distances P5 (0.54 ± 0.06%) and P3 (0.49 ± 0.07%) led. A second harvest drop at P1 (0.40 ± 0.05%) was experienced. Windy distance W5 excelled early (0.62 ± 0.03%) but declined steeply, while W2 remained stable (Table 9). However, TA became more volatile in the year of 2024. Among Protected sides, P3 recorded the highest value (0.60 ± 0.04%), but with elevated variance compared to the year of 2023. W2 peaked at 0.75 ± 0.21%, yet W1 and W5 recorded no yield. These results suggest that early harvests and mid-terminal Protected plots distances (P3–P5) offer greater TA stability, while wind exposure can enhance or destabilize acid retention depending on maturity stage (Appendix table 8).

4.6.3 Sugar acid ratio (SAR)

Mid-distance Protected sides (P2 – P4) demonstrated higher SAR values across both years, for Szentlőrinckáta at P3 with 16.35 in the first harvest of the year of 2024. In contrast, Windy sides exhibited lower SAR and greater variability across both harvests, suggesting that Protected sides were instrumental in reducing fluctuations and enhancing fruit quality. SAR values revealed marked spatial, seasonal, and tomato genotypic variability. Second harvests in the year of 2023 generally produced a more favourable ratio (Figure 48), and SAR values were generally elevated, exceeding the ideal range for balanced tomato flavour. Roma showed strong second-harvest 2023 gains, with Protected distances P2 (10.28 ± 0.65), followed by increases at P1 (9.62 ± 1.15) and P3 (10.38 ± 0.38). Windy plots exhibited higher SAR due to lower acidity, with, for instance, Roma increasing from 8.11 ± 0.94 at W5 in the first harvest, 2023, to 10.53 ± 2.43 in the second harvest, 2024. However, SAR rose significantly as sugars increased and acids declined. For Roma, distances P3 and P4 led the Protected side, while P2 increased from 8.38 ± 0.69 in the 2024 to 15.33 ± 4.10 for the second harvest. Windy distances W3 and W5 indicate a balanced sweetness and acidity in these cultivars (Stevens et al., 1979). Side became significant in the 2024(*F = 5.95 *), while distance remained mostly insignificant (Table 9). Ace55 exhibited consistently high SAR across both years. In the year of 2023, distances P5 (13.73 ± 0.79) and P3 (11.83 ± 1.02) led the Protected side, while Windy W4 (10.59 ± 0.36) performed best due to TA reduction. W5 also improved its 2023 value (9.81 ± 0.82) to 13.04 ± 1.41 in the second harvest.

Furthermore, SAR rose further, with P3 (12.18 ± 1.64) and P4 (9.98 ± 0.44) indicating strong performance. Windy W4 dropped to 6.84 ± 0.34, being among the lowest overall, while W1 and W5 experienced stress-related failures, yielding no fruits in the 2024. Szentlőrinckáta displayed the highest SAR variability. In the year of 2023, protected distances P3 (16.35 ± 5.41) and P5 (12.28 ± 2.04) performed well, while P2 showed second-harvest improvement (Figure 48). Windy W5 initially reached 13.29 ± 4.93 in the 2024first harvest but declined sharply; W2 and W3 remained moderate, 15.52 ± 4.10 and 10.49 ± 2.49, respectively. Furthermore, SAR values showed distinct variation in the 2024, at distance P4 (8.51 ± 1.60) and P3 (10.63 ± 1.54) on the Protected side. W3 recorded the highest SAR across all distances, reaching 13.04 ±1.41, indicating a stronger perceived sweetness and flavour intensity (Appendix table 9).

Figure 48. Sugar acid ratio (SAR) Analysis across hedgerow distances reveal significant variation between protected and windy sides in Soroksár, Hungary (2023 – 2024). Differing letters denote significant differences between values within side, harvest and variety ($p < 0.05$).

4.6.4 Ferric reducing antioxidant power (FRAP)

Hedgerow enhanced FRAP antioxidant levels; Windy sides exhibited elevated values on W1 (23.67 ± 1.73 mg AAE 100 g^{-1}) and P1 (21.12 ± 0.72 mg AAE 100 g^{-1}) in the year of 2024, though with greater variability. Notably, FRAP showed a significant effect in the year of 2023 ($p < 0.001$), as shown in Table 9. Distance played a key role; hedgerows peaked in the 2023 at W1 (19.89 ± 2.39), while mid distances dominated in the 2024, at P3 (15.31 ± 1.26 mg AAE 100 g^{-1}), and at W3 (20.63 ± 0.66 mg AAE 100 g^{-1}). In Roma samples, FRAP values were moderate and stable on the Protected side, and at distances with the highest concentrations occurring at distances P1 (12.94 ± 0.09 mg AAE 100 g^{-1}), and P2 (15.43 ± 0.20 mg AAE 100 g^{-1}), as shown (Figure 49). However, at distance P4, FRAP values decreased to 6.81 ± 1.15, followed by a slight increase in subsequent measurements. In the second harvest, FRAP at P1 was reduced from 12.94 to 6.11 mg AAE 100 g^{-1}, this could be interpreted as an effect of environmental exposure and positional stress. On the Windy side, FRAP values were generally higher, yet more variable, with W5 (16.28 ± 0.17 mg AAE 100 g^{-1}) and W1 (19.64 ± 0.50 mg AAE 100 g^{-1}) marking the highest positions. However, distances W4 (10.34 ± 0.46 mg AAE 100 g^{-1}) showed the lowest values. Antioxidant levels tended to decrease in the second harvest, highlighting seasonal effects. Interestingly, Roma showed improved FRAP values in the second ye (Figure 49), especially on the Protected side, with distance P3 reaching 15.31 ± 1.26 mg AAE 100 g^{-1}, presenting a substantial increase compared to the 2023 r. However, second harvests showed significant FRAP decreases at distance P5 (5.91 ± 0.81 mg AAE 100 g^{-1}).

In Ace55, in the year of 2023 results on the Protected side showed moderate FRAP values, with peaks at distances P4 (10.65 ± 0.67 mg AAE 100 g^{-1}) and P3 (14.49 ± 0.21 mg AAE 100 g^{-1}), as shown in (Figure 49). Notably, second harvest values improve significantly at all distances, as observed at distance P1 (14.26 ± 1.44 mg AAE 100 g^{-1}), pointing to a deferred antioxidant reaction compared to the first harvest. The Windy side presented more variation, with the highest values at distance W3 (120.63 ± 0.66), and distance W5 (13.73 ± 2.10 mg AAE 100 g^{-1}), and the lowest at W4 (3.70 ± 0.60), and W2 (3.10 ± 0.68**).** In the second harvest, W3 showed higher values (14.62 to 20.63 mg AAE 100 g^{-1}), suggesting environmental influence induced stimulation during late phenological stages. Furthermore, FRAP values for Ace55 decrease overall in the 2024, as illustrated in (Figure 49). The Protected side showed modest activity, with the highest values at P5 (10.45 ± 1.17 mg AAE 100 g^{-1}) and P3 (3.61 ± 0.52 mg AAE 100 g^{-1}), and the lowest at P2 (3.53 ± 0.41 mg AAE 100 g^{-1}). Despite the overall drop, the second harvests recorded strong relative environmental stress impacts. The Windy side remained superior in FRAP activity, with W3 (8.61 ± 0.70 mg AAE 100 g^{-1}), and W5 (8.76 ± 1.25 mg AAE 100 g^{-1}) being statistically significant ($p < 0.05$). Second harvest increases were substantial, with W4 increasing from 3.43 to 7.68 mg AAE 100 g^{-1} (+124%), on (Appendix table 10).

For Szentlőrinckáta, the year of 2023 showed steady FRAP levels on the Protected side (Figure 49), at distances P3 (14.49 ± 0.21 mg AAE 100 g^{-1}), and P1 (12.44 ± 0.72 mg AAE 100 g^{-1}). Second harvest values showed a clear improvement, particularly at P1 (12.44 to 21.12 mg AAE 100 g^{-1}), indicating enhanced antioxidant biosynthesis in the closest distance. The Windy side recorded higher, and more variable FRAP levels, especially at distances W1 (23.67 ± 1.73 mg AAE 100 g^{-1}) and W5 (13.67 ± 0.18 mg AAE 100 g^{-1}), with the lowest at W4 (10.34 ± 0.46 mg AAE 100 g^{-1}). Second harvests showed reverse trends. FRAP values declined significantly across both exposures, showing the highest levels at distances P1 (13.48 ± 1.99 mg AAE 100 g^{-1}) and P5 (8.03 ± 0.40 mg AAE 100 g^{-1}) in the 2024results (Figure 49). However, second harvests demonstrated reductions, such as at P5 (8.03 to 1.13 mg AAE 100 g^{-1}), reflecting stress-induced physiological limitations or reduced biosynthesis under stress conditions. Windy side results mirrored this downturn, with W5 (13.77 ± 1.81 mg AAE 100 g^{-1}) and W4 (8.21 ± 0.45 mg AAE 100 g^{-1}) demonstrated optimal results (Appendix table 10).

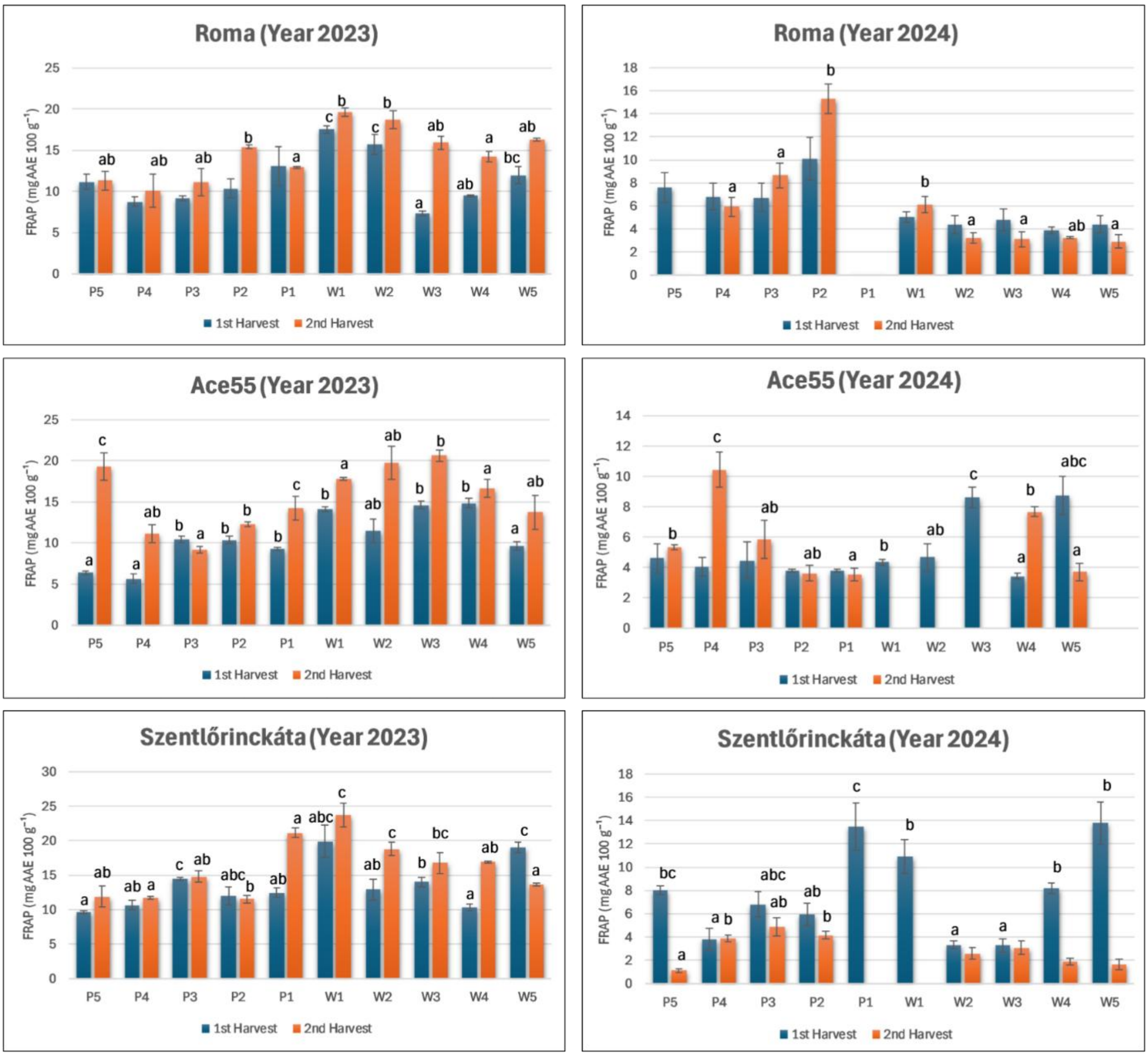


Figure 49. FRAP Analysis across hedgerow distances reveal significant variation between protected and windy sides in Soroksár, Hungary (2023 – 2024). Differing letters denote significant differences between values within side, harvest and variety ($p < 0.05$).

4.6.5 Total phenolic content (TPC)

Windy plots consistently exhibited elevated TPC (up to 145.33 ± 9.57 mg GAE 100 g^{-1}) than Protected sides. In the year of 2023, edge distances (P1, P5, W1, W5) had peak TPC, while in the 2024, mid-distances (P2, P3, W2, W4) dominated. Second-year TPC levels rose significantly (up to 244.17 ± 18 mg GAE 100 g$^{-1)}$, especially at W4 and W1, highlighting the hedgerow's impact on phenolic biosynthesis. TPC levels were moderately different distances across genotypes. Roma and Szentlőrinckáta genotypes showed moderate TPC levels (Figure 50). Side showed robust significance (*F = 27.74 *** and *F = 20.9 ***), with higher values on the Windy side (Table 9), varying influences from microclimatic exposure. However, Roma had significant TPC on the Windy side, with a maximum value at W5 (144.0 ± 23.3 mg GAE 100 g^{-1}), compared to more stable, but slightly lower values on the Protected side at distance P1 (135.33 ± 12.10). Ace55 followed a similar relationship, peaking at W5 (145.33 ± 9.57 mg GAE/100 g^{-1}), with W4 exhibiting the lowest TPC (79.67 ± 17.13 mg GAE/100 g^{-1}), . Szentlőrinckáta genotype exhibited the highest TPC values and the least variability, peaking at P1 (158.17 ± 9.45 mg GAE 100 g^{-1}). TPC was significantly dropped in the second harvest, demonstrating a reduction in phenolic content. In Roma, TPC showed lower values at W1 (first harvest: 86.5 ± 4.36, second harvest: ~65.3 ± 3.2 mg GAE 100 g^{-1}, $p < 0.05$), while Ace55 and Szentlőrinckáta exhibited declines of 15 – 22% and 8 – 35%, respectively, in the year of 2023 result.

Furthermore, 2024analysis of TPC showed significantly higher values across all genotypes. Ace55 exhibited higher values in the Protected side, reaching 188.33 ± 6.01 mg GAE 100 g^{-1} at P2, a threefold of values from the previous year's maximum. Szentlőrinckáta also achieved elevated values, especially at distances P2 (192.5 ± 11.46 mg GAE 100 g^{-1}) and W3 (151.67 ± 18.82 mg GAE 100 g^{-1}), with significant variation from the 2023. Roma exhibited modestly at P3 (171.00 ± 21.78 mg GAE 100 g^{-1}), but its absolute values remained comparatively lower. In the second harvest of the 2024 (Figure 50), a consistent 25 – 45% decline in TPC was observed across most genotypes and treatments. However, an exception was noted in Szentlőrinckáta at W3, where a 9.4% higher value in TPC was observed (appendix table 11).

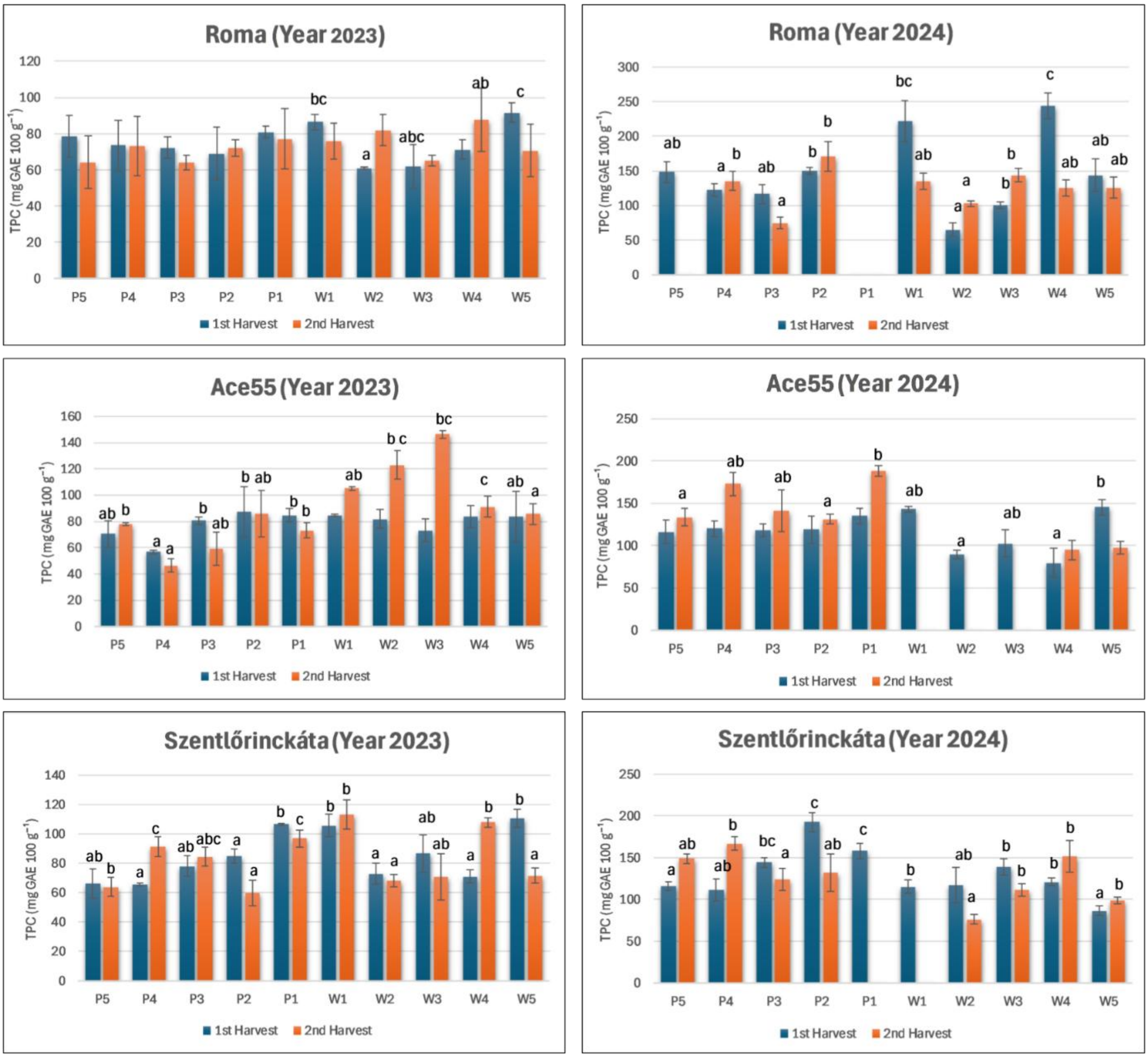


Figure 50. TPC, Analysis across hedgerow distances reveal significant variation between protected and windy sides in Soroksár, Hungary (2023 – 2024). Differing letters denote significant differences between values within side, harvest and variety ($p < 0.05$).

5. DISCUSSIONS

This three-year analysis highlights the microclimatic impact of hedgerow systems at different distances. Temperatures (°C) and relative humidity (RH) measured at varying distances from the hedge spatial patterns (Borec et al., 2023). The Protected side (P1–P5) showed a higher temperature from hedgerow conditions than the Windy side (W1–W5), with peak differences of +3.54°C (Protected) and +2.49°C (Windy). At (P5) 15 meters from the hedge, the Protected side experienced the hedge effect, with an air temperature increase of +1.87°C. Interannual comparisons 2022 as the warmest year, while May was the coldest month and July the hottest across all seasons. (P4) and (W5) exhibited the widest thermal ranges, confirming hedge proximity as a key factor driving microclimatic variability (Vanneste et al., 2020). Using hedgerow interior RH as a reference (Thomsit-Ireland et al., 2020), the Windy side showed higher moisture retention (+5.97% in 2023, +7.44%) in 2024 compared to the Protected side (+3.74% in 2023, +6.26%) in 2024 (Ravi et al., 2004). Relative humidity (RH) was lowest in May and in September, with maximum values at W5 and P2 in 2024. These patterns the hedgerow's role in regulating ambient moisture, supporting climate-adaptive field design. Hedgerows significantly stabilize microclimates (Thomsit et al., 2020; Vanneste et al., 2020), with the Protected side showing higher average temperatures (°C) and reduced fluctuations, especially compared to the Windy side (Gustavsson, 1995; Stoutjesdijk, 1974).

Soil parameters under hedgerow conditions revealed clear variations among parcels within each year. Organic matter stability and quality differed markedly across parcels, with the highest values recorded at the windy control (WC), reaching 0.64 and 2.57, respectively in 2023 (An et al., 2023; Körschens, 2021), while protected (P) and windy (W) parcels exhibited lower values. Indicating improved organic matter decomposition under hedgerow conditions (Bhogal et al., 2018; Xu et al., 2021). Soil biological activity also responded to hedgerow proximity, as phosphatase activity reached 14.61 µg/g at protected parcels in 2022, and dehydrogenase activity peaked at 1.17 µg/g at P and 1.14 µg/g at WC in 2023 (Boteva et al., 2016; García-Gil et al., 2013; Pérez-de-Mora et al., 2008). Potassium reached a maximum of 675.60 mg/kg at WC in 2024, while phosphorus peaked at 524.96 mg/kg at WC in 2024, indicating enhanced nutrient retention at greater distances from the hedgerow (Schlindwein et al., 2013; Setu, 2022). Soil moisture content showed spatial variation among parcels, with significant differences between protected and windy parcels detected only in the final year (2024) (Lashkarizadeh et al., 2016; Setiawan J. A., 2016). Glycosidase activity was highest at protected parcels, reaching 43.31 µmol/g/h in 2023, reflecting enzymatic sensitivity to hedgerow conditions (Reszka et al., 2020). The results indicate that parcel position and distance from the hedgerow influenced soil processes, confirming the role of hedgerows in moderating wind effects and supporting soil sustainability under field conditions (Enescu et al., 2025).

Hedgerow technology influences the physiological and nutritional attributes of three tomato genotypes, Roma, Ace55, and Szentlőrinckáta, under open-field conditions on Protected sides distances (P1, P3, P5) and windy sides (W1, W3, W5) of the hedgerow. Nutritional metrics, including nitrogen (N), phosphorus (P), potassium (K), chlorophyll A and B, and carotene, were analysed based on distance and sides from hedgerow trees. The study revealed that nutrient accumulation and pigment levels varied significantly across genotypes, sides, and distances (C. A. da Silva et al., 2025). The Roma genotype consistently showed higher values, with nitrogen reaching 59.51 mg/100 g on the windy side and potassium up to 26.33 mg/100 g, particularly at outer distances. Roma also exhibited higher pigment concentrations, with chlorophyll A peaking at 2106.98 mg/100 g and chlorophyll B at 1170.32 mg/100 g on the windy side. Carotene levels were likewise highest in Roma, reaching 485.62 mg/100 g at W3 and 481.29 mg/100 g at P3 (Ehilé et al., 2018). In contrast, Szentlőrinckáta generally recorded lower chlorophyll concentrations, particularly for chlorophyll A (1077.03 mg/100 g) and chlorophyll B (543.42 mg/100 g). Phosphorus content peaked in Szentlőrinckáta at P5 (5.48 mg/100 g), while the lowest phosphorus value was observed in Ace55 at P5 (2.07 mg/100 g). Significant differences were detected among genotypes and distances ($p < 0.05$), with notable interactions between Ace55 and Szentlőrinckáta in nitrogen content. While protected-side distances favoured higher phosphorus and carotene accumulation, windy-side distances generally promoted greater chlorophyll A and B concentrations. These results support the hypothesis that hedgerow systems can enhance tomato productivity and biomass and nutrient efficiency under protected sides and organic farming conditions, echoing the conclusions of (Caulfield et al., 2020; Vicente et al., 2015).

Tomato yield was significantly influenced by hedgerow (windy vs. protected sides), planting distance, and varietal response. The hedgerow system functioned as a microclimatic regulator, modulating exposure to wind, light, and temperature, which in turn affected fruit development (Saidi et al., 2013). Roma and Szentlőrinckáta consistently responded positively to the windy side, particularly at outer distances (W3–W5), while Ace55 reflected a marked preference for protected intermediate distances. In the first-year experiment, Roma resulted its highest fruit number at W5, with 111 fruits and a corresponding fruit weight of 2.81 kg. Szentlőrinckáta also performed strongly on the windy side, resulted 66.75 fruits at W3 and 2.19 kg at the same distance. On the protected side, it achieved 2.59 kg at P5, indicating adaptability across both conditions. Ace55 demonstrated its best performance at P3, with 79.88 fruits and 2.94 kg, confirming its sensitivity to wind exposure and preference for buffered conditions (Adams et al., 2001; Roy & Boulard, 2005). Second year experiments, . Roma achieved 63.13 fruits at P4 and achieved its highest fruit weight at W4 (5.98 kg) and W3 (5.13 kg). Szentlőrinckáta achieved its best yield at W2 with 8.11 kg, followed by W3 (6.34 kg) and P4 (78.13 fruits). Ace55 remained low yielding, with its best fruit number at P3 (18.50 fruits) and highest fruit weight at W4 (0.62 kg). 2023 was the most productive year collectively, likely due to favorable growing conditions and optimal microclimatic balance (Šalagovič et al., 2024a). However, generally yield declined substantially across all varieties, likely due to seasonal heat stress and cumulative environmental pressure in the third year of the experiment (Mohammed et al., 2025). Roma still performed best at W3 (17.13 fruits, 1.66 kg) and W5 (12.40 fruits, 1.98 kg), while Szentlőrinckáta maintained balanced yields at W2 (7.83 kg) and W4 (58.00 fruits). Ace55 demonstrated a single standout value at P3 with 3.96 kg, reaffirming its preference for protected intermediate spacing. Fruit numbers dropped across all varieties, with Roma ranging from 2 to 17 fruits, Szentlőrinckáta between 4 and 16 fruits, and Ace55 showing limited variability. These results confirm that hedgerow systems exert a measurable impact on tomato yield components (Gómez-Del-Campo et al., 2009). Windy side exposure enhanced productivity for wind tolerant varieties like Roma and Szentlőrinckáta, while protected side conditions favoured Ace55. The consistent varietal patterns across years underscore the importance of aligning planting layout with cultivar responses to hedgerow microclimatic gradients (Harterreiten-Souza et al., 2014b). Pest and disease pressure was higher on the protected side due to reduced air circulation, contributing to lower tomato yield (Mustafa, Adjei, et al., 2023). Yet, its close association with the hedgerow supported beneficial insects and soil activity, enhancing ecological balance and long-term crop resilience (Long et al., 2017).

The comparative performance of the three tomato genotypes, Roma, Ace55, and Szentlőrinckáta, under ten distinct microclimatic exposures, Windy and Protected sides, hedgerow distances, and two harvest timings, reveals critical genotype × environment and time interactions influencing fruit quality traits (Chroma (C*), hue (h°), TSS, TA, SAR, FRAP, TPC) indices across two consecutive growing years. The CIELAB colour space parameters (L*, a*, b*) are critical indicators of tomato fruit quality, particularly in terms of consumer preference and ripeness. Chroma (C*) and hue angle are closely related to pigment accumulation, with Chroma generally increasing during ripening and the hue angle approaching 40° in fully mature fruits, as reported by a previous study (Radzevičius et al., 2009). These parameters are also influenced by genotype. In the present study, Roma showed a Chroma value of 39.71 at W3 in the year of 2023, while in the 2024, higher Chroma was observed on the Protected side at P2 (38.11 ± 0.7). Ace55 displayed similarly elevated Chroma values, demonstrated at P4 (36.93 ± 0.03) and W5 (35.12 ± 0.47). Szentlőrinckáta exhibited the highest Chroma (39.44 at W4), indicating potential instability in pigment development under certain environmental conditions (Ilahy et al., 2018). Hue angle stability was most consistently maintained in Roma in the year of 2023 at P2 (51.27 ± 0.10°) and Ace55 on the Protected side at P3 with (53.06 ± 0.30°), particularly during the first harvest. Hue and Chroma values reflect a highly saturated fruit colour, with a strong association between these parameters. No significant differences were detected among distances or sides, suggesting that the presence of a hedge did not markedly affect fruit coloration. However, genotypic variation contributed substantially to colour differences among cultivars, as reported by the study findings (Brandt et al., 2006; Shi et al., 1999).

Total soluble solids (TSS) are influenced by genotype, environment, with significant heritability estimates reported for total titratable acid (Panthee et al., 2012), followed by a more consistent genotype specific pattern. Ace55 outperformed Roma and Szentlőrinckáta genotypes in absolute TSS values (Helyes et al., 2006; Jayasinghe & Kumar, 2021), particularly under Windy conditions in the year of 2023 , Roma demonstrated comparatively low TSS on the Windy side, at distances W2 (6.70 ± 0.10 °Bx) and W5 (6.67 ± 0.15 °Bx), while W1 (7.00 ± 0.00 °Bx) recorded the highest values during the second harvest, indicating localized improvements despite the overall trend. The 2024yielded reduced TSS levels across all genotypes, though second harvests frequently demonstrated late-stage gains, such as P2 (45.23 to 5.90 °Bx) and P5 reaching (5.73 ± 0.21 °Bx) for Ace55. Roma and Szentlőrinckáta presented a more restrained accumulation of TSS, with Protected-side rows, especially on P2–W3, performing the best. However, our result agrees with the study that explores the impact of variety on the quality of tomatoes stored under ambient conditions (Tigist et al., 2013). Titratable acidity (TA) patterns highlighted Roma's strength in acid retention (Rana et al., 2014a), on the Protected side on P3 (0.59 ± 0.11%) in the 2024. TA values increased at W3 (0.71 ± 0.05%) and W1 (0.68 ± 0.04%), indicating strong environmental factor acid retention. Ace55's TA dropped significantly in the second harvests, consistent with sugar dominant maturation, with Protected side values peaking at P3 (0.61 ± 0.02%) and getting lower at P4 (0.48 ± 0.06%). Windy plots showed more volatility, with W5 (0.52 ± 0.03%) reducing acid rapidly, while Szentlőrinckáta showed moderate TA at P3 (0.60 ± 0.04%), especially under 2024conditions. TA at W3 (0.67 ± 0.14%) was erratic, and W1 and W5 recorded no yield.

These results support research findings that Protected conditions resulted in more acidic fruits with greater titratable acidity compared to those produced in open fields (Ilić et al., 2012).

According to recent research investigations, tomatoes generally show superior quality traits, higher TSS, and ascorbic acid supported when grown under field conditions compared to protected environments (Brunele Caliman et al., 2010; Rana et al., 2014b). The sugar acid ratio (SAR), a critical quality index, aligned predictably with genotypic strengths. In 2024, Roma exhibited a balanced profile under protected conditions, with P3 (10.38 ± 0.38) and W1 (12.12) showing the highest values. Ace55 again benefited from second harvest timing, with consistent sugar acid ratio improvements between harvests. Szentlőrinckáta showed high potential but high variability, with extremes ranging from 13.05 ± 3.52 to 15.52 ± 4.10 as a result of finding that high sugar and acid content in tomato cultivars can result in favourable taste (Davies & Hobson, 1981). Roma exhibited higher FRAP under Windy conditions in both years, with distances W4 and W5 being the most active positions in the 2024 (24.17 ± 18.06 mg AAE 100 g^{-1} at W4). The Protected side demonstrated lower but more stable FRAP levels. FRAP values increased 2.1 – 2.8-fold, with optimal accumulation shifting from hedge distances (W1, P1) in the 2023 to mid-distances (P3, W3) in the 2024. Consistent with these findings, other studies have reported significant increases in FRAP under open-field conditions. However, the effect of the side was not statistically significant, suggesting that specific environmental factors may not exert a major influence on FRAP levels when comparing open-field and polytunnel-grown tomatoes (Csambalik et al., 2016; Periago et al., 2002b).

Research indicates that environmental stress, like high temperature and solar radiation, can enhance phytonutrient content and antioxidant capacity in tomatoes, especially in low-tech greenhouses (Rosales et al., 2011). Ace55 displayed a distinct pattern. Unlike Roma, this genotype consistently showed higher FRAP in the second harvests, demonstrating late-season enhancement observed in both years. However, this genotype exhibited larger relative gains between harvests in 2024. P4 moved up from 4.04 to 10.45 mg AAE 100 g^{-1}. Wind exposure enhanced FRAP activity, particularly at mid distances. This reversed trend, promoting antioxidant accumulation in the late season, was unique among genotypes and Ace55's adaptive metabolic plasticity. However, environmental factors may influence antioxidant activity variations among tomato varieties, as attributed to the varietal factor (Mostapha et al., 2014; Perea-Domínguez et al., 2018). Szentlőrinckáta exhibited strong inter-annual variation. While the 2023 revealed a positive environmental conditions effect with FRAP increases, the 2024 recorded lower values as steep as in the second harvests at W5 (13.77 to 1.66 mg AAE 100 g^{-1}). These findings reflect on the study of climate on the yield, quality, and climate suitability, a high environmental sensitivity, and suggest potential genotype × environment interactions that impair antioxidant resilience under fluctuating stress conditions (Jayasinghe & Kumar, 2021).

Tomato antioxidants exhibit significant variability across cultivars, with environmental factors and agricultural techniques significantly influencing antioxidant levels, with temperature playing a crucial role in lycopene biosynthesis (Dumas et al., 2003b). However, the correlation between TPC and antioxidant activity is not always robust, indicating the necessity for multiple assays to accurately evaluate antioxidant properties (Čeryová, 2022; Csambalik et al., 2016). Previous results showed that cultivar and climatic conditions significantly influenced tomato TPC (Kacjan Maršić et al., 2011). Roma tomatoes showed significantly elevated TPC values on the Windy side in the year of 2023, recorded at W5 (144.00 ± 23.30 mg GAE 100 $g^{-1)}$, while the Protected side remained more stable but lower at P1 (135.33 ± 12.10). Ace55 followed a similar pattern, with the highest values at W5 (145.33 ± 9.57 mg GAE 100 g^{-1}), though W4 (79.67 ± 17.13 mg GAE 100 g^{-1}**)** consistently represented lower TPC across genotypes. Szentlőrinckáta displayed both the highest absolute TPC values and the least variability, reaching at P1 (158.17 ± 9.45 mg GAE 100 g^{-1}), and significantly different TPC values between positions ($p < 0.05$). Notably, 2024results marked a significant result, particularly for Ace55, which recorded an exceptional value at P2 (188.33 ± 6.01 mg GAE 100 g^{-1}), nearly tripling its previous maximum. Szentlőrinckáta also attained elevated TPC in the 2024, especially at P2 (192.50 ± 11.46 mg GAE 100 g^{-1}) and at W3 (151.67 ± 18.82 mg GAE 100 g^{-1}). However, a consistent trend was observed across all genotypes: TPC values resulted a reduction during the in the second harvest, highlighting the temporal sensitivity of phenolic compound biosynthesis. This observation aligns with findings of (Čeryová, 2022), who reported weak correlations between antioxidant activity and polyphenol content across seven tomato cultivars, suggesting a strong influence of genotype and environmental stress on phenolic expression (Balogh et al., 2010). While physiological stress markers were not directly measured, our FRAP and TPC results suggest possible activation of antioxidant pathways, aligning with responses to microclimatic stress reported in similar studies (Gil-Ortiz et al., 2023; Machado et al., 2023). Genotype microclimate interactions significantly influence tomato quality traits (Parisi et al., 2021 ; Šalagovič et al., 2024b). Ace55 responded dynamically to wind exposure, enhancing antioxidant and sugar levels late in the season. Roma remained compositionally stable but showed susceptibility to pigment loss. Szentlőrinckáta exhibited strong spatial adaptability with consistent phenolic accumulation, particularly at P5 and W5 distances (Burato et al., 2025).

6. CONCLUSIONS and RECOMMENDATIONS

Agroforestry, such as hedgerows, offers a potential solution, as trees create unique microclimates altering temperature, humidity, and wind speed that influence crop resilience. This study assessed the microclimatic influence of hedgerow systems on Roma, ACE55, and Szentlőrinckáta tomato genotypes across varying distances. The Protected side P1–P5 exhibited stronger thermal buffering, with temperature (°C) deviations peaking at +3.54°C, especially at P5, while the Windy side W1–W5 showed greater humidity retention +7.44% in 2024. 2022 marked the warmest year, while thermal extremes consistently occurred in May (coldest) and July (hottest), with P4 and W5 showing the widest temperature ranges. Relative humidity (RH) resulted in September and was lowest in May, with W5 and P2 registering maximum RH values, highlighting hedgerows' role in ambient moisture regulation. Overall, hedge proximity emerged as a critical driver of microclimatic stability, improving growing conditions and supporting climate-resilient tomato cultivation.

The hedgerow system demonstrated a significant and consistent positive impact on soil health across physical, chemical, and biological parameters. Protected and controlled plots (P, PC) showed superior performance in moisture retention, nutrient enrichment, and microbial activity compared to windy and uncovered sides. The increase in organic matter quality, and enzymatic functions such as phosphatase and glycosidase confirms the hedgerow's role in fostering a biologically active and resilient soil environment. These findings underscore the value of hedgerows not only as windbreaks but as essential components of sustainable land management strategies, capable of mitigating climate-induced stress and enhancing long-term soil fertility and ecosystem stability.

The nutritional quality parameters of tomato genotypes were evaluated in a hedgerow system. Roma exhibited the highest nitrogen, potassium, chlorophyll A and B, and carotene contents across most sample treatments, particularly on the windy side (W1–W5). In contrast, Szentlőrinckáta consistently showed lower chlorophyll levels and weaker nutrient accumulation. Significant differences were observed among varieties and hedgerow distances, notably for nitrogen, phosphorus, and potassium, with genotype × distance interactions, especially between Ace55 and Szentlőrinckáta. While the windy side enhanced photosynthetic traits, protected-side distances (P1–P5) supported higher phosphorus and carotene accumulation. These results highlight the potential of hedgerow agroforestry systems to improve nutrient efficiency and physiological quality of tomato plants under organic field conditions.

This study demonstrates that hedgerow conditions, specifically the contrast between windy and protected sides, significantly affect tomato yield in open field conditions. Roma and Szentlőrinckáta consistently benefited from the windy side, particularly at W3–W5, while Ace55 presented optimal performance under protected conditions at P3. Tomato total fruit yield per plot was generally higher on the protected side, especially at mid-distances (P3–P4) in 2022 and 2023. However, in 2024, heat stress and infection significantly reduced plot level yield on the protected side, highlighting its vulnerability under extreme conditions. Although the protected side offers environmental safeguard and higher humidity, it also creates a microclimate that favours pest and disease buildup due to reduced air circulation. This contributed to lower yields in some genotypes. However, its relative distance to the hedge supports biodiversity enhancing beneficial insects, natural predators, and soil microorganisms which may improve ecological balance and long-term crop resilience. These findings highlight the role of hedgerow systems as agroecological tools for managing pest pressure and enhancing yield stability under variable field conditions.

Hedgerow Microclimates influenced tomato antioxidant and phenolic traits. The study confirms the finding that wind exposure enhances antioxidant metrics but increases variability and pigment instability. The Protected side and distances provide better consistency in TSS, acidity, and hue. Spatial position also plays a role, with midfield distances (P3–P4, W3–W4) repeatedly resulting in the highest quality outcomes across metrics. The observed genotypes with hedgerow environment and time interactions provide critical guidance for precision agriculture. For practical applications, Ace55 is ideal for systems targeting extended harvests and high sugars, Roma suits to early harvests expressing acid-rich profiles, and Szentlőrinckáta requires Protected sides of hedgerows with carefully timed harvests to capitalize on its phenolic and fruit quality potential. Tomato plants respond differently to the varying microclimates created by hedgerows for relief of abiotic stress factors, with these responses closely tied to their genetic traits. Selecting the most suitable variety is essential for successful cultivation in vegetable agroforestry systems, especially when aiming to optimise fruit quality.

7. NEW SCIENTIFIC RESULTS

From My Dissertation, I Have Found Out:

1. My research proves that planting distance from hedgerow (Width:5 m, Height: 5m, angle with the prevailing wind direction) significantly influenced tomato yield quantity over three years (2022, 2023, and 2024), with total yield per plot ranging up to 130% higher. Mid-distance protected plots (9 -12 m; P3- P4) produced the highest yields in 2023, with values of about 45 to 65 kg/plot.

2. My research demonstrated that the main result is that the supportive role of hedge depends on genotype. Szentlőrinckáta exhibited superior fruit weight under windy conditions, particularly in 2023 (4.4 - 6.3 kg/plant at W2-W5). Roma showed consistently high fruit weight across several windy distances, especially in 2023 (5.0 - 6.0 kg/plant) and 2024 at W3 -W5 (1.2 - 2.0 kg/plant). In contrast, Ace55 performed best in protected microclimates, at mid-protected distances (P3) in 2024 (4.0 kg/plant).

3. In my research, it was proven that planting at mid-distance protected sides of the hedgerow (9-12 m; P3-P4) enhanced sugar accumulation and flavour balance in tomato fruits, with genotype-specific enhancements observed in Ace55, Roma, and Szentlőrinckáta.

4. The findings indicate that windy side distances of the hedgerow (9 -15 m; W3-W5) was more stressful environment for the plant, generally enhanced antioxidant capacity across all genotypes, increasing FRAP (14 -23 mg AAE 100 g^{-1} in 2023; 8 -14 mg AAE 100 g^{-1} in 2024) and TPC (85 - 145 mg GAE 100 g^{-1} in 2023; 120 - 245 mg GAE 100 g^{-1} in 2024), despite greater variability observed in Roma.

5. My research proves that each genotype exhibits distinct fruit quality responses to microclimate interactions: Ace55 responded dynamically under wind exposure in terms of antioxidant and sugar accumulation, Roma remained compositionally stable but pigment-sensitive, while Szentlőrinckáta consistently accumulated phenolics at distal positions.

6. My research presents novel evidence that protected hedgerow microclimates enhancing tomato resilience by, improving relative humidity enriching soil, and boosting yield and quality. Strategic positioning at mid-distance protected plots of the hedgerow (9-12 m; P3-P4) supports climate-adaptive tomato cultivation under site-specific conditions.

8. SUMMARY

Hedgerow systems play a vital role in agroecosystems by mitigating environmental stressors and delivering essential ecosystem services that support crop development. Their influence on microclimatic conditions such as temperature (°C), relative humidity (RH), and wind exposure can significantly affect soil health and crop performance. This three year study investigates the impact of hedgerow-induced microclimates on the growth and productivity of three tomato genotypes: Szentlőrinckáta, Ace55, and Roma. The research focuses on evaluating changes in soil physical, chemical, and biological properties, alongside crop phenology, physiology, yield components, biochemical traits, and fruit quality. A key objective is to determine whether hedgerow integration enhances tomato productivity, improves nutrient use efficiency, and strengthens environmental services through increased system complementarity. Tomato plants were cultivated in a randomized block design on both the protected and windy sides of a hedgerow, with five sampling distances from the hedgerow on each side. The experiment was conducted over three consecutive growing seasons (2022–2024) at the Soroksár Experimental Field of the Hungarian University of Agriculture and Life Sciences. This multi-year study aims to provide insights into the ecological and agronomic benefits of hedgerow systems in sustainable horticultural production.

The hedgerow system demonstrated a strong influence on temperature and relative humidity across sides and distances. The protected side (P1–P5) showed greater thermal deviation, resulting in +3.54°C, compared to +2.49°C on the Windy side (W1–W5). The most pronounced hedge effect occurred at 15 metres (P5), with a +1.87°C temperature increase. Interannual data identified 2022 as the warmest year, with July consistently the hottest month. Relative humidity was highest in September and lowest in May, with the windy side retaining more moisture (+7.44% in 2024) than the protected side (+6.26%). P4 and W5 exhibited the widest thermal ranges, confirming hedge sides as a key driver of microclimatic variability. These findings underscore the hedgerow's systems in stabilizing field conditions and enhancing climate resilience in open field agriculture. In terms of soil health, clear variations were observed among parcels rather than a uniform improvement on protected sides. Soil moisture showed spatial variation, with significant differences between protected and windy parcels detected only in 2024, rather than a steady increase from 2022 to 2024. Soil pH remained alkaline and stable, without a consistent drop to 7.50. Organic matter stability (0.64) and organic matter quality (2.57) reached their highest values at the windy control (WC) in 2023, not on protected sides. Phosphorus peaked at 524.96 mg/kg and potassium at 675.60 mg/kg, both at WC in 2024, rather than reaching 750–800 mg/kg. Phosphatase activity reached 14.61 µg/g at protected parcels in 2022, while dehydrogenase activity peaked at 1.17 µg/g at protected parcels and 1.14 µg/g at WC in 2023, not higher values. Glycosidase activity was highest at protected parcels, reaching 43.31 µmol/g/h in 2023, confirming enzymatic sensitivity to hedgerow conditions rather than exceeding 50 µmol/g/h.

Hedgerow microclimates significantly influenced the physiological and nutritional traits of the three tomato genotypes. Roma showed superior nutrient and pigment accumulation, with nitrogen reaching 59.51 mg/100 g, potassium 26.33 mg/100 g, and carotene peaking at 485.62 mg/100 g, mainly on the windy side. Szentlőrinckáta exhibited the lowest chlorophyll levels but the highest phosphorus content at P5 (5.48 mg/100 g). Significant differences were observed among genotypes and distances ($p < 0.05$). Windy-side exposure generally enhanced chlorophyll A and B content**.** These results confirm that hedgerow systems can boost tomato productivity and nutrient efficiency.

Across the three year investigation, tomato yield was shaped by the interaction between hedgerow orientation, planting distance, and varietal adaptability. Roma consistently favored the windy side, with its highest fruit number (111 fruits) and fruit weight (5.98 kg) reached at W5 and W4, respectively. Szentlőrinckáta demonstrated strong performance across both sides, peaking at W2 with 8.11 kg and maintaining high fruit numbers at W3 and W5. Ace55 performed best at protected side intermediate distances, approaching 79.88 fruits and 3.96 kg at P3. The hedgerow system proved to be effective in modulating microclimatic stress, with varietal responses guiding optimal planting strategies for sustainable tomato production. However, Tomato total yield per plot was generally higher on the protected side, especially in the first two years. Mid-distance plots (P3–P4) favored yield development, though heat stress and infection increasingly suppressed performance.

Tomato quality parameters, CIELAB color parameters revealed strong genotype-driven variation in tomato fruit color. Roma and Ace55 maintained high Chroma values Roma peaking at W3 (39.71) in the year of 2023, and Ace55 showing elevated values at P4 (36.93 ± 0.03) and W5 (35.12 ± 0.47). Szentlőrinckáta recorded the highest Chroma at W4 (39.44) in the 2024, indicating pigment instability under wind exposure. No significant differences were found across hedge distances or sides, confirming that fruit coloration was primarily influenced by genotype rather than hedgerow condition.

Genotype played a dominant role in determining Total Soluble Solids (TSS), Titratable Acidity (TA), and Sugar-Acid Ratio (SAR). Ace55 consistently showed superior TSS, with a 159% increase at P4 in the second-year harvest. Roma excelled in acid retention, notably at W3

(0.94 ± 0.04%) in the 2024 and at P3 (0.49 ± 0.07%) in the 2023. Szentlőrinckáta displayed high but erratic TA values, with W2 peaking at 0.75 ± 0.21%. SAR trends confirmed genotype-specific flavor profiles: Roma reached 10.38 ± 0.38 at P3 in the year of 2023 and 15.33 ± 4.10 at P2 in the second-year second harvest; Szentlőrinckáta peaked at P3 (16.35 ± 5.41); Ace55 showed strong SAR at P5 (13.73 ± 0.79) and W5 (13.04 ± 1.41). Protected conditions generally enhanced acidity and flavor stability, while Windy sides showed greater variability. Significant differences ($p < 0.05$) were observed across distances and harvests.

FRAP and TPC analyses revealed genotype-specific antioxidant responses. Ace55 showed peak FRAP at W3 (120.63 ± 0.66 mg AAE 100 g^{-1}) in the first harvest and a 124% increase at W4 during the second harvest. Szentlőrinckáta recorded the highest TPC at P2 (192.5 ± 11.46 mg GAE 100 g^{-1}) in the first harvest of the 2024, with a unique 9.4% increase at W3 in the second harvest. Roma exhibited moderate FRAP and TPC values, with post-harvest declines. All genotypes showed reduced TPC in second harvests, except for Szentlőrinckáta at W3. These results confirm that antioxidant resilience and phenolic biosynthesis in tomatoes are highly sensitive to genotype × environment interactions, with FRAP and TPC levels fluctuating under climatic stress and harvest timing.

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10. REFERENCES

1. Acharya, T., Bena, D. W., Sauerhaft Senior Manager, B. C., Stewardship, E., Beverages America, P., & Derek Yach, P. (2010). The role of the food industry in strengthening links between agriculture, nutrition and environmental sustainability. *Wiley Online Library*, *1*(3), 327–329. https://doi.org/10.1111/j.1758-5899.2010.00051.x
2. Adams, S. R., Cockshull, K. E., & Cave, C. R. J. (2001). Effect of Temperature on the Growth and Development of Tomato Fruits. *Annals of Botany*, *88*(5), 869–877. https://doi.org/10.1006/ANBO.2001.1524
3. Adhikari, D., Kobashi, Y., Kai, T., Kawagoe, T., Kubota, K., Araki, K. S., & Kubo, M. (2018). Suitable Soil Conditions for Tomato Cultivation under an Organic Farming System. *Journal of Agricultural Chemistry and Environment*, *07*(03), 117–132. https://doi.org/10.4236/jacen.2018.73011
4. Agarwal, S., & Rao, A. V. (2000). Tomato lycopene and its role in human health and chronic diseases. *CMAJ : Canadian Medical Association Journal = Journal de l'Association Medicale Canadienne*.
5. Alaguero-cordovilla, A., Javier, F., Tormos-molt, S., & Manuel, P. (2018). *Morphological Characterization of Root System Architecture in Diverse Tomato Genotypes during Early Growth*. https://doi.org/10.3390/ijms19123888
6. Alam, M., Islam, N., Ahmad, S., Hossen, M., & Islam, M. (2016). Effect of different staking methods and stem pruning on yield and quality of summer tomato. *Bangladesh Journal of Agricultural Research*, *41*(3), 419–432. https://doi.org/10.3329/bjar.v41i3.29714
7. Alamo, J. M., Maquieira, A., Puchades, R., & Sagrado, S. (1993). Determination of titratable acidity and ascorbic acid in fruit juices in continuous-flow systems. *Fresenius' Journal of Analytical Chemistry*, *347*(6–7), 293–298. https://doi.org/10.1007/BF00323975/METRICS
8. Alef, K., & Nannipieri, P. (Eds.). (1995). *Methods in applied soil microbiology and biochemistry* (xix + 576 pp.). Academic Press. ISBN 978-0-12-513840-6.
9. Ali, M. Y., Sina, A. A. I., Khandker, S. S., Neesa, L., Tanvir, E. M., Kabir, A., Khalil, M. I., & Gan, S. H. (2021). Nutritional composition and bioactive compounds in tomatoes and their impact on human health and disease: A review. *Foods*, *10*(1). https://doi.org/10.3390/foods10010045
10. Altuntas, O., & Ozkurt, H. (2019). The assessment of tomato fruit quality parameters under different sound waves. *Journal of Food Science and Technology*, *56*(4), 2186–2194. https://doi.org/10.1007/s13197-019-03701-0
11. An, Z., Pokharel, P., Plante, A. F., Bork, E. W., Carlyle, C. N., Williams, E. K., & Chang, S. X. (2023). Soil organic matter stability in forest and cropland components of two agroforestry systems in western Canada. *Geoderma*, *433*(November 2022), 116463. https://doi.org/10.1016/j.geoderma.2023.116463
12. Angelova, L., Genova, N., Pencheva, G., Statkova, Y., Yotova, V., & Surleva, A. (2022). Contribution to the Molybdenum Blue Reaction and its Application in Soil Analysis. *Methods and Objects of Chemical Analysis*, *17*(2), 59–69. https://doi.org/10.17721/moca.2022.59-69
13. AOAC. (1995). Official methods of analysis, 14th edition. In *Journal of Chromatography A* (Vol. 351, Issue 3). https://doi.org/10.1016/s0021-9673(01)83549-4
14. Ara, N., Bashar, M., Begum, S., & Kakon, S. (2007). *Effect of spacing and stem pruning on the growth and yield of tomato. Int. J. Sustain. Crop Prod*. 2(3):35-39.

15. Ara, N., Bashar, M., Begum, S., Of, S. K.-I. J., & 2007, U. (2007). Effect of spacing and stem pruning on the growth and yield of tomato. *Academia.Edu*. https://www.academia.edu/download/32986080/8.35-39.pdf
16. Arah, I. K., Amaglo, H., Kumah, E. K., & Ofori, H. (2015). Preharvest and postharvest factors affecting the quality and shelf life of harvested tomatoes: A mini review. *International Journal of Agronomy*, *2015*. https://doi.org/10.1155/2015/478041
17. Arah, I. K., Kumah, E. K., Anku, E. K., & Amaglo, H. (2015). An Overview of Post-Harvest Losses in Tomato Production in Africa: Causes and Possible Prevention Strategies. *Journal of Biology, Agriculture and Healthcare*, *5*(16), 78–89.
18. Argyropoulos, C., Tsiafouli, M. A., Sgardelis, S. P., & Pantis, J. D. (2013). Organic farming without organic products. *Land Use Policy*, *32*, 324–328. https://doi.org/10.1016/j.landusepol.2012.11.008
19. Baglieri, A., Cadili, V., Mozzetti Monterumici, C., Gennari, M., Tabasso, S., Montoneri, E., Nardi, S., & Negre, M. (2014). Fertilization of bean plants with tomato plants hydrolysates. Effect on biomass production, chlorophyll content and N assimilation. *Scientia Horticulturae*, *176*, 194–199. https://doi.org/10.1016/j.scienta.2014.07.002
20. Bakucs, Z., Fertő, I., & Vígh, E. (2020). Crop Productivity and Climatic Conditions: Evidence from Hungary. *Agriculture*, *10*(9), 1–12. https://doi.org/10.3390/AGRICULTURE10090421
21. Balogh, E., Hegedus, A., & Stefanovits-Bányai, É. (2010). Application of and correlation among antioxidant and antiradical assays for characterizing antioxidant capacity of berries. *Scientia Horticulturae*, *125*(3), 332–336. https://doi.org/10.1016/J.SCIENTA.2010.04.015
22. Baresel, J. P., Zimmermann, G., & Reents, H. J. (2008). Effects of genotype and environment on N uptake and N partition in organically grown winter wheat (Triticum aestivum L.) in Germany. *Euphytica*, *163*(3), 347–354. https://doi.org/10.1007/s10681-008-9718-1
23. Bedoussac, L., Journet, E.-P., Hauggaard-Nielsen, H., Naudin, C., G. Corre Hellou, G., Jensen, E. S., & Justes, E. (2018). *Grain legume–cereal intercropping systems*. 243–256. https://doi.org/10.19103/AS.2017.0023.14
24. Benzie, I. F. F., & Strain, J. J. (1996). The Ferric Reducing Ability of Plasma (FRAP) as a Measure of "Antioxidant Power": The FRAP Assay. *Analytical Biochemistry*, *239*(1), 70–76. https://doi.org/10.1006/ABIO.1996.0292
25. Bergougnoux, V. (2014). The history of tomato: From domestication to biopharming. *Biotechnology Advances*, *32*(1), 170–189. https://doi.org/10.1016/j.biotechadv.2013.11.003
26. Bhogal, A., Nicholson, F. A., Rollett, A., Taylor, M., Litterick, A., Whittingham, M. J., & Williams, J. R. (2018). Improvements in the Quality of Agricultural Soils Following Organic Material Additions Depend on Both the Quantity and Quality of the Materials Applied. *Frontiers in Sustainable Food Systems*, *2*(9), 337983. https://doi.org/10.3389/FSUFS.2018.00009/BIBTEX
27. Blanca, J., Montero-Pau, J., Sauvage, C., Bauchet, G., Illa, E., Díez, M. J., Francis, D., Causse, M., van der Knaap, E., & Cañizares, J. (2015). Genomic variation in tomato, from wild ancestors to contemporary breeding accessions. *BMC Genomics*, *16*(1), 1–19. https://doi.org/10.1186/s12864-015-1444-1
28. Bobo-García, G., Davidov-Pardo, G., Arroqui, C., Vírseda, P., Marín-Arroyo, M. R., & Navarro, M. (2015). Intra-laboratory validation of microplate methods for total phenolic content and antioxidant activity on polyphenolic extracts, and comparison

with conventional spectrophotometric methods. *The Journal of the Science of Food and Agriculture*, *95*(1), 204–209. https://doi.org/10.1002/JSFA.6706
29. Borec, A., Lešnik, T., Kraner Šumenjak, T., & Muršec, M. (2023). The Effects of Hedgerows Shading on Soil Temperature and Gravimetric Soil Water Content. *Agricultura Scientia*, *20*(2), 1–9. https://doi.org/10.18690/agricsci.20.2.1
30. Borguini, R. G., & da Silva Torres, E. A. F. (2009). Tomatoes and Tomato Products as Dietary Sources of Antioxidants. *Food Reviews International*, *25*(4), 313–325. https://doi.org/10.1080/87559120903155859
31. Bošković, J., Prijić, Ž., Agriculture, A. I.-E. of, & 2010, U. (2010). Economic and ecological impact of shelterbelts. *Economics of Agriculture, 27*(V), 51–57.
32. Bosland, P., Votava, E., & Heuvelink, T. E. (2005). *Crop Production Science in Horticulture 13, Tomatoes*. https://www.cabidigitallibrary.org/doi/pdf/10.1079/9780851993966.0000
33. Boteva, S., Radeva, G., Traykov, I., & Kenarova, A. (2016). Effects of long-term radionuclide and heavy metal contamination on the activity of microbial communities, inhabiting uranium mining impacted soils. *Environmental Science and Pollution Research International*, *23*(6), 5644–5653. https://doi.org/10.1007/S11356-015-5788-5
34. Boziné-Pullai, K., Csambalik, L., Drexler, D., Reiter, D., Tóth, F., Bogdányi, F. T., & Ladányi, M. (2021). Tomato landraces are competitive with commercial varieties in terms of tolerance to plant pathogens-a case study of hungarian gene bank accessions on organic farms. *Diversity*, *13*(5). https://doi.org/10.3390/d13050195
35. Brandle, J. R., Hodges, L., & Zhou, X. H. (2004a). *Windbreaks in North American agricultural systems*. *Burke 1998*, 65–78. https://doi.org/10.1007/978-94-017-2424-1_5
36. Brandle, J. R., Hodges, L., & Zhou, X. H. (2004b). *Windbreaks in North American agricultural systems*. 65–78. https://doi.org/10.1007/978-94-017-2424-1_5
37. Brandle, J. R., Takle, E., & Zhou, X. (2022). Windbreak Practices. *North American Agroforestry: Third Edition*, 89–126. https://doi.org/10.1002/9780891183785.CH5
38. Brandt, S., Pék, Z., Barna, É., Lugasi, A., & Helyes, L. (2006). Lycopene content and colour of ripening tomatoes as affected by environmental conditions. *Journal of the Science of Food and Agriculture*, *86*(4), 568–572. https://doi.org/10.1002/JSFA.2390;SUBPAGE:STRING:FULL
39. Brunele Caliman, F. R., Henriques da Silva, D. J., Stringheta, P. C., Rezende Fontes, P. C., Rodrigues Moreira, G., & Chartuni Mantovani, E. (2010). Quality of tomatoes grown under a protected environment and field conditions. *Idesia (Arica)*, *28*(2). https://doi.org/10.4067/S0718-34292010000200009
40. Bryant, C., Fuenzalida, T. I., Brothers, N., Mencuccini, M., Sack, L., Binks, O., & Ball, M. C. (2021). Shifting access to pools of shoot water sustains gas exchange and increases stem hydraulic safety during seasonal atmospheric drought. *Plant Cell and Environment*, *44*(9), 2898–2911. https://doi.org/10.1111/pce.14080
41. Burato, A., Tava, A., Biazzi, E., Parisi, M., Tripodi, P., Lo Scalzo, R., Bianchi, G., Picchi, V., & Ronga, D. (2025). Changes in processing tomato fruit quality in heirloom and modern varieties developed over the past decades. *Journal of Food Composition and Analysis*, *146*, 107956. https://doi.org/10.1016/J.JFCA.2025.107956
42. Carvalho, G. C., de Camargo, B. A. F., de Araújo, J. T. C., & Chorilli, M. (2021). Lycopene: From tomato to its nutraceutical use and its association with nanotechnology. *Trends in Food Science & Technology*, *118*, 447–458. https://doi.org/10.1016/J.TIFS.2021.10.015
43. Caulfield, M., Groot, J. C. J., Fonte, S. J., Sherwood, S., Oyarzun, P., Borja, R. M.,

Dumble, S., & Tittonell, P. (2020). Live barriers and associated organic amendments mitigate land degradation and improve crop productivity in hillside agricultural systems of the Ecuadorian Andes. *Wiley Online LibraryM Caulfield, JCJ Groot, SJ Fonte, S Sherwood, P Oyarzun, RM Borja, S Dumble, P TittonellLand Degradation & Development, 2020•Wiley Online Library*, *31*(13), 1650–1661. https://doi.org/10.1002/LDR.3558

44. Cen, H., Bao, Y., He, Y., & Sun, D. W. (2007). Visible and near infrared spectroscopy for rapid detection of citric and tartaric acids in orange juice. *Journal of Food Engineering*, *82*(2), 253–260. https://doi.org/10.1016/j.jfoodeng.2007.02.039
45. Čeryová, N. (2022). Total Polyphenol Content and Antioxidant Activity of Solanum lycopersicum L. *Agrobiodiversity for Improving Nutrition, Health and Life Quality*, *6*(1), 61–66. https://doi.org/10.15414/ainhlq.2022.0007
46. Chand, J. B., Hewa, G., Hassanli, A., & Myers, B. (2021). Deficit Irrigation on Tomato Production in a Greenhouse Environment: A Review. *Journal of Irrigation and Drainage Engineering*, *147*(2), 1–10. https://doi.org/10.1061/(asce)ir.1943-4774.0001529
47. Chandra, H. M., Shanmugaraj, B. M., Srinivasan, B., & Ramalingam, S. (2012). Influence of Genotypic Variations on Antioxidant Properties in Different Fractions of Tomato. *Journal of Food Science*, *77*(11). https://doi.org/10.1111/j.1750-3841.2012.02962.x
48. Chaudhary, P., Sharma, A., Singh, B., & Nagpal, A. K. (2018). Bioactivities of phytochemicals present in tomato. *Journal of Food Science and Technology*, *55*(8), 2833–2849. https://doi.org/10.1007/s13197-018-3221-z
49. Chaudhary, R. P. (2000). Forest conservation and environmental management in Nepal: A review. *Biodiversity and Conservation*, *9*(9), 1235–1260. https://doi.org/10.1023/A:1008900216876
50. Chongfa, C., Shuwen, D., Zhihua, S., Zhaoxia, L., & Chuangmu, Z. (2002). Effect of Contour Hedgerow-Intercropping System on Slope Land and Some Problems of Application in TGR. *Effect of Contour Hedgerow-Intercropping System on Slope Land and Some Problems of Application in TGR*, 1–5.
51. Costa, J. M., & Heuvelink, E. (2005). Introduction: The tomato crop and industry. *Tomatoes*, 1–19. https://doi.org/10.1079/9780851993966.0001
52. Courtois, B., Khong, N. G., Coudert, Y., Pe, C., & Gantet, P. (2010). Genetic control of root development in rice, the model cereal. *Trends in Plant Science*, *15*(4), 219–226. https://doi.org/10.1016/j.tplants.2010.01.008
53. Csambalik, L., Divéky-Ertsey, A., Pap, Z., Orbán, C., Stégerné Máté, M., Gere, A., Stefanovits-Bányai, É., & Sipos, L. (2014). Coherences of instrumental and sensory characteristics: Case study on cherry tomatoes. *Journal of Food Science*, *79*(11), C2192–C2202. https://doi.org/10.1111/1750-3841.12685
54. Csambalik, L., Orbán, C., Stéger-Máté, M., Pusztai, P., & Divéky-Ertsey, A. (2016). *Antioxidant profile of tomato landraces for freshconsumption*. *Acta Biologica Szegediensis, 2016•160.114.156.156* 60(2): 177–82. http://160.114.156.156/index.php/abs/article/view/2906
55. Csizinszky, A., & Heuvelink, E. (2005). Production in the open field. *Tomatoes*, 237–256. https://doi.org/10.1079/9780851993966.0237
56. Cui, H. (2021). Challenges and Approaches to Crop Improvement Through C3-to-C4 Engineering. *Frontiers in Plant Science*, *12*. https://doi.org/10.3389/FPLS.2021.715391/FULL
57. Dabesor, P. A., Sanni, D. M., Kolawole, A. O., Enujiugha, V. N., Lawal, O. T., & Edeh, A. T. (2022). \. *Biocatalysis and Agricultural Biotechnology*, *40*(December

2021), 102313. https://doi.org/10.1016/j.bcab.2022.102313
58. Davies, J. N., & Hobson, G. E. (1981). The constituents of tomato fruit — the influence of environment, nutrition, and genotype. *C R C Critical Reviews in Food Science and Nutrition*, *15*(3), 205–280. https://doi.org/10.1080/10408398109527317
59. Dingley, A., Anwar, S., Kristiansen, P., Warwick, N. W. M., Wang, C. H., Sindel, B. M., & Cazzonelli, C. I. (2022). Precision Pollination Strategies for Advancing Horticultural Tomato Crop Production. *Agronomy*, *12*(2). https://doi.org/10.3390/AGRONOMY12020518
60. Divéky-Ertsey, A., Ladányi, M., Biró, B., Máté, M., Drexler, D., Tóth, F., Boziné Pullai, K., Gere, A., Pusztai, P., & Csambalik, L. (2022). Tomato Landraces May Benefit from Protected Production Evaluation on Phytochemicals. *Horticulturae*, *8*(10). https://doi.org/10.3390/horticulturae8100937
61. Diver, S., Kuepper, G., Born, H., Hinman, T., Baier, A., & Riesselman, L. B. (2014). *Organic Tomato Production*.
62. Dixon, M., Simonne, E., Obreza, T., & Liu, G. (2020). Crop response to low phosphorus bioavailability with a focus on tomato. *Agronomy*, *10*(5), 1–26. https://doi.org/10.3390/agronomy10050617
63. DIXON, R. T. (2020). What Is a Fruit? *Biodiversity*, 1–4. https://doi.org/10.1016/b978-0-08-011766-9.50004-x
64. Djibrilla, A. S. M., Rabani, A., Illyassou, K. M., Issa, S. M., Abdourahimou, K. N., Abdoulkader, A. H., & Aissetou, D. Y. (2024). Improving tomatoes quality in the Sahel through organic cultivation under photovoltaic greenhouse as a climate change adaptation and mitigation strategy. *Scientific Reports*, *14*(1), 1–14. https://doi.org/10.1038/s41598-024-54427-9
65. Duma, M., Alsina, I., Dubova, L., & Erdberga, I. (2015). Chemical composition of tomatoes depending on the stage of ripening. *Chemical Technology*, *66*(1), 24–28. https://doi.org/10.5755/j01.ct.66.1.12053
66. Dumas, Y., Dadomo, M., Di Lucca, G., & Grolier, P. (2003a). Effects of environmental factors and agricultural techniques on antioxidant content of tomatoes. *Journal of the Science of Food and Agriculture*, *83*(5), 369–382. https://doi.org/10.1002/jsfa.1370
67. Dumas, Y., Dadomo, M., Di Lucca, G., & Grolier, P. (2003b). Effects of environmental factors and agricultural techniques on antioxidantcontent of tomatoes. *Journal of the Science of Food and Agriculture*, *83*(5), 369–382. https://doi.org/10.1002/JSFA.1370
68. Durmus, D. (2020). CIELAB color space boundaries under theoretical spectra and 99 test color samples. *Color Research and Application*, *45*(5), 796–802. https://doi.org/10.1002/COL.22521
69. Earnshaw, S. (2004). Hedgerows for California Agriculture. *Informe Técnico*, *95616*(530), 1–18.
70. Ehilé, S. J. E., Kouassi, N. K., Kouamé, C. A., Denis Yao, N., & Amani, G. N. guessa. (2018). Nutritional composition of five spontaneous wild plants used as human foods in Côte d'ivoire areas (West Africa), a potential role in household food security. *Pakistan Journal of Nutrition*, *17*(4), 171–178. https://doi.org/10.3923/PJN.2018.171.178
71. Enescu, C. M., Mihalache, M., Ilie, L., Dinca, L., Constandache, C., & Murariu, G. (2025). Agricultural Benefits of Shelterbelts and Windbreaks: A Bibliometric Analysis. *Agriculture*, *15*(11), 1204. https://doi.org/10.3390/AGRICULTURE15111204
72. Essomo, E. S., Arrey, B. D., Honore, B. D., Afanga, Y. A., Inès, N. T. H., & Antoine,

E. G. (2024). Evaluation of Alley-cropping Agroforestry System and Conventional System of Agriculture on the Productivity of Cabbage (*Brassica oleracea* L.) in Dschang, West Region of Cameroon. *American Journal of Agriculture and Forestry 2024, Volume 12, Page 382*, *12*(6), 382–390. https://doi.org/10.11648/J.AJAF.20241206.11
73. Fayad, J. A., Fontes, P. C. R., Cardoso, A. A., Finger, F. L., & Ferreira, F. A. (2002). Absorção de nutrientes pelo tomateiro cultivado sob condições de campo e de ambiente protegido. *Horticultura Brasileira*, *20*(1), 90–94. https://doi.org/10.1590/S0102-05362002000100017
74. Felföldi, Z., Ranga, F., Roman, I. A., Sestras, A. F., Vodnar, D. C., Prohens, J., & Sestras, R. E. (2022). Analysis of Physico-Chemical and Organoleptic Fruit Parameters Relevant for Tomato Quality. *Agronomy*, *12*(5), 1–22. https://doi.org/10.3390/agronomy12051232
75. Ferreira, S. M. R., Freitas, R. J. S. de, & Lazzari, E. N. (2004). Padrão de identidade e qualidade do tomate (Lycopersicon esculentum Mill.) de mesa. *Ciencia Rural*, *34*(1), 329–335. https://doi.org/10.1590/S0103-84782004000100054
76. Fidrianny, I., Natalia, S., Res, M. I.-I. J. P. C., (2015). Antioxidant capacities of various fruit extracts from three varieties of tomato and correlation with total phenolic, flavonoid, carotenoid content. *Hero.Epa.Gov*. Retrieved May 19, 2025, from https://hero.epa.gov/hero/index.cfm/reference/details/reference_id/8316852
77. Figás Moreno, M. del R., Arroyo, N., Casanova, C., Soler, E., Martínez Busó, M., Prohens, J., & Soler, S. (2024). Caracterització morfològica, agronòmica i de composició del germoplasma de la 'Tomata Valenciana.' *Llibre d'actes Del II Congrés de La Tomata Valenciana. L'Autèntica*. https://doi.org/10.4995/TOMAVAL2024.2024.18681
78. Foolad, M. R. (2007). Genome mapping and molecular breeding of tomato. *International Journal of Plant Genomics*, *2007*. https://doi.org/10.1155/2007/64358
79. García-Gil, J. C., Kobza, J., Soler-Rovira, P., & Javoreková, S. (2013). Soil Microbial and Enzyme Activities Response to Pollution Near an Aluminium Smelter. *Clean-Soil Air Water*, *41*(5), 485–492. https://doi.org/10.1002/CLEN.201200099
80. Gardiner, B., Berry, P., & Moulia, B. (2016). Review: Wind impacts on plant growth, mechanics and damage. *Plant Science*, *245*, 94–118. https://doi.org/10.1016/j.plantsci.2016.01.006
81. Garrett, H. E. G. (2015). North american agroforestry: An integrated science and practice: 2nd edition. *North American Agroforestry: An Integrated Science and Practice*, 1–379. https://doi.org/10.2134/2009.NORTHAMERICANAGROFORESTRY.2ED
82. Gautier, H., Diakou-Verdin, V., Bénard, C., Reich, M., Buret, M., Bourgaud, F., Poëssel, J. L., Caris-Veyrat, C., & Génard, M. (2008). How does tomato quality (sugar, acid, and nutritional quality) vary with ripening stage, temperature, and irradiance? *Journal of Agricultural and Food Chemistry*, *56*(4), 1241–1250.https://doi.org/10.1021/JF072196T
83. Geisenberg, C., & Stewart, K. (1986). Field crop management. *The Tomato Crop*, 511–557. https://doi.org/10.1007/978-94-009-3137-4_13
84. Gerszberg, A., & Hnatuszko-Konka, K. (2017). Tomato tolerance to abiotic stress: a review of most often engineered target sequences. *Plant Growth Regulation*, *83*(2), 175–198. https://doi.org/10.1007/s10725-017-0251-x
85. Getahun, D., & Bikis, D. (2015). Responses of Tomato Varieties to Intra-row Spacing Under Rain-fed Production. *Agricultural Science Research Journal*, *5*(12), 171–179. http://resjournals.com/journals/agricultural-science-research-journal.html

86. Ghazavi, G., Thomas, Z., Hamon, Y., Marie, J. C., Corson, M., & Merot, P. (2008). Hedgerow impacts on soil-water transfer due to rainfall interception and root-water uptake. *Hydrological Processes*, *22*(24), 4723–4735. https://doi.org/10.1002/HYP.7081
87. Ghorbani, R., Wilcockson, S., Koocheki, A., & Leifert, C. (2008). Soil management for sustainable crop disease control: A review. *Environmental Chemistry Letters*, *6*(3), 149–162. https://doi.org/10.1007/s10311-008-0147-0
88. Gil-Ortiz, R., Naranjo, M. Á., Atares, S., & Vicente, O. (2023). Antioxidant Responses of Water-Stressed Cherry Tomato Plants to Natural Biostimulants. *Agronomy*, *13*(9), 8–10. https://doi.org/10.3390/agronomy13092314
89. Gogo, E. O., Saidi, M., Itulya, F. M., Martin, T., & Ngouajio, M. (2012). Microclimate modification using eco-friendly nets for high-quality tomato transplant production by small-scale farmers in East Africa. *HortTechnology*, *22*(3), 292–298. https://doi.org/10.21273/horttech.22.3.292
90. Gómez-Del-Campo, M., Centeno, A., & Connor, D. J. (2009). Yield determination in olive hedgerow orchards. I. Yield and profiles of yield components in north-south and east-west oriented hedgerows. *Crop & Pasture Science*, *60*(5), 434–442. https://doi.org/10.1071/CP08252
91. Greig, J. K., Bokhari, N., Armbrust, D. V., & Anderson, L. C. (1974). Residual Effects of Wind- and Sandblast-damage on Tomato Plants at Different Stages of Development1. *Journal of the American Society for Horticultural Science*, *99*(6), 530–534. https://doi.org/10.21273/jashs.99.6.530
92. Gustavsson, T. (1995). A study of air and road-surface temperature variations during clear windy nights. *International Journal of Climatology*, *15*(8), 919–932. https://doi.org/10.1002/JOC.3370150806
93. Guzman-Plazola, R. A., Davis, R. M., & Marois, J. J. (2003). Effects of relative humidity and high temperature on spore germination and development of tomato powdery mildew (Leveillula taurica). *Crop Protection*, *22*(10), 1157–1168. https://doi.org/10.1016/S0261-2194(03)00157-1
94. Haile, S. G., Nair, V. D., & Nair, P. K. R. (2010). Contribution of trees to carbon storage in soils of silvopastoral systems in Florida, USA. *Global Change Biology*, *16*(1), 427–438. https://doi.org/10.1111/J.1365-2486.2009.01981.X
95. Hanson, P., Chen, J. T., Kuo, C. G., Morris, R., & Opeña, R. T. (2000). *Guide International Cooperators' AVRDC Suggested Cultural Practices for Tomato Figure 1. Fresh market tomatoes*. www: http://www.avrdc.org.tw
96. Hargitai, L. (1967). Effect of changes in organo-mineral complexes on the quality of soil organic matter and organic nitrogen. In Transactions of Meetings of Commissions II & IV, International Society of Soil Science, 1966 (pp. 65–71).
97. Harker, F. R., Gunson, F. A., & Jaeger, S. R. (2003). The case for fruit quality: an interpretive review of consumer attitudes, and preferences for apples. *Postharvest Biology and Technology*, *28*(3), 333–347. https://doi.org/10.1016/S0925-5214(02)00215-6
98. Harterreiten-Souza, É. S., Togni, P. H. B., Pires, C. S. S., & Sujii, E. R. (2014a). The role of integrating agroforestry and vegetable planting in structuring communities of herbivorous insects and their natural enemies in the Neotropical region. *Agroforestry Systems*, *88*(2), 205–219. https://doi.org/10.1007/s10457-013-9666-1
99. Harterreiten-Souza, É. S., Togni, P. H. B., Pires, C. S. S., & Sujii, E. R. (2014b). The role of integrating agroforestry and vegetable planting in structuring communities of herbivorous insects and their natural enemies in the Neotropical region. *Agroforestry Systems*, *88*(2), 205–219. https://doi.org/10.1007/S10457-013-9666-1/TABLES/2

100. Hassan, Abdel-Ati, & IbrahimT.A., A. (2020). Genetic Behavior of Some Fruit Characters In Crosses Between Tomato and Some Wild Species and Among Wild Species. Plant Arch, 20, pp.1056-1065.ISSN:0972-5210

101. Heisler, G. M., & Dewalle, D. R. (1988). 2. Effects of windbreak structure on wind flow. *Agriculture, Ecosystems and Environment*, *22–23*(C), 41–69. https://doi.org/10.1016/0167-8809(88)90007-2

102. Helyes, L. (2004). *The effect of daily temperature on*. *1674*(February), 1671–1674. https://doi.org/10.1002/jsfa.1858

103. Helyes, L., Dimény, J., Pék, Z., & Lugasi, A. (2006). Effect of the variety and growing methods as well as cultivation conditions on the composition of tomato (*Lycopersicon lycopersicum* (L.) karsten) fruit. *Acta Horticulturae*, *712 I*, 511–516. https://doi.org/10.17660/ACTAHORTIC.2006.712.62

104. Szalai Z. 2010. The natural, installed (constructed), and biological environment of fields, Agroinform publishing house, Budapest Sustainable field crop production 1: General crop production, Detailed plant cultivation, Cultivation of cereals. 700 p. Budapest: Agroinform Publishing House, 2010. p. 367-387. ISBN:978-963-502-924-2

105. Horváth-Mezőfi, Z., Baranyai, L., Nguyen, L. L. P., Dam, M. S., Ha, N. T. T., Göb, M., Sasvár, Z., Csurka, T., Zsom, T., & Hitka, G. (2024). Evaluation of Color and Pigment Changes in Tomato after 1-Methylcyclopropene (1-MCP) Treatment. *Sensors*, *24*(8). https://doi.org/10.3390/s24082426

106. Ilahy, R., Siddiqui, M. W., Tlili, I., Montefusco, A., Piro, G., Hdider, C., & Lenucci, M. S. (2018). When Color Really Matters: Horticultural Performance and Functional Quality of High-Lycopene Tomatoes. *Critical Reviews in Plant Sciences*, *37*(1), 15–53. https://doi.org/10.1080/07352689.2018.1465631

107. Ilić, Z., Milenković, L., & Hristov, N. (2012). *The influence of photo-selective shade nets on quality of tomatoes grown under plastic tunnels and field conditions.*

108. Jafari, S. M., Jabari, S. S., Dehnad, D., & Shahidi, S. A. (2017). Effects of thermal processing by nanofluids on vitamin C, total phenolics and total soluble solids of tomato juice. *Journal of Food Science and Technology*, *54*(3), 679–686. https://doi.org/10.1007/S13197-017-2505-Z

109. Jalpa, L., & Mylavarapu, R. (2023). Current tomato production practices and their effects on plant and soil carbon and nitrogen dynamics. *Journal of Plant Nutrition*, *46*(16), 3905–3917. https://doi.org/10.1080/01904167.2023.2220708

110. Jayasinghe, S. L., & Kumar, L. (2021). Potential impact of the current and future climate on the yield, quality, and climate suitability for tea [*camellia sinensis* (L.) O. Kuntze]: A systematic review. *Agronomy*, *11*(4), 619. https://doi.org/10.3390/AGRONOMY11040619/S1

111. Jiang, Y., Bian, B., Wang, X., Chen, S., Li, Y., & Sun, Y. (2020). Identification of tomato maturity based on multinomial logistic regression with kernel clustering by integrating color moments and physicochemical indices. *Journal of Food Process Engineering*, *43*(10). https://doi.org/10.1111/JFPE.13504

112. Jimenez, A., Creissen, G., Kular, B., Firmin, J., Robinson, S., Verhoeyen, M., & Mullineaux, P. (2002). Changes in oxidative processes and components of the antioxidant system during tomato fruit ripening. *Planta*, *214*(5), 751–758. https://doi.org/10.1007/s004250100667

113. Jolankai, M., Scientificus, M. B.-A. C., & 2007, undefined. (2007). Global climate change impacts on crop production in Hungary. *Hrcak.Srce.HrM Jolankai, M BirkásAgriculturae Conspectus Scientificus, 2007•hrcak. Srce.Hr*, *72*(1), 17–20. https://hrcak.srce.hr/clanak/19650

114. Jones, S. H. (1992). *The Landscape Ecology of Hedgerows with particular*

reference to Island Biogeography. *January*, 263.
115. Jose, S., & Gordon, A. M. (2008). *Ecological Knowledge and Agroforestry Design: An Introduction*. 3–9. https://doi.org/10.1007/978-1-4020-6572-9_1
116. Juan-Cabot, A., Galmés, J., & Conesa, M. (2022). The tomato long shelf-life fruit phenotype: Knowledge, uncertainties and prospects. *Scientia Horticulturae*, *291*. https://doi.org/10.1016/J.SCIENTA.2021.110578
117. Kacjan Maršić, N., Gašperlin, L., Abram, V., Budič, M., & Vidrih, R. (2011). Quality parameters and total phenolic content in tomato fruits regarding cultivar and microclimatic conditions. *Turkish Journal of Agriculture and Forestry*, *35*(2), 185–194. https://doi.org/10.3906/tar-0910-499
118. Kathimba, F. K., Kimani, P. M., Narla, R. D., & Kiirika, L. M. (2021). Characterization of tomato germplasm accessions for breeding research. *Journal of Agricultural Biotechnology and Sustainable Development*, *13*(2), 20–27. https://doi.org/10.5897/JABSD2021.0386
119. Kaundal, M., Sharma, K., & Anand, H. (2024). *Processing, Value Addition and Post- Harvest Technology of Tomato: A Scoping Review on Global and Indian Perspective*. *27*(11), 339–347.
120. Kessler, S., Kim, M., Pham, T., Weber, N., & Sinha, N. (2001). Mutations Altering Leaf Morphology in Tomato. *Https://Doi.Org/10.1086/320136*, *162*(3), 475–492. https://doi.org/10.1086/320136
121. Khan, T. N., Ramzan, A., Jillani, G., & Mehmood, T. (2013). Morphological Performance of Peas (Pisum Sativum) Genotypes Under Rainfed Conditions of Potowar Region. *J. Agric. Res*, *51*(1), 51.
122. Kilambi, H. V., Manda, K., Sanivarapu, H., Maurya, V. K., Sharma, R., & Sreelakshmi, Y. (2016). Shotgun proteomics of tomato fruits: Evaluation, optimization and validation of sample preparation methods and mass spectrometric parameters. *Frontiers in Plant Science*, *7*(JUNE2016), 1–14. https://doi.org/10.3389/fpls.2016.00969
123. Kimura, S., Protocols, N. S.-C. S. H., & 2008, undefined. (2008). Tomato (Solanum lycopersicum): a model fruit-bearing crop. *Cshprotocols.Cshlp.Org*. https://doi.org/10.1101/pdb.prot5084
124. Király, É., Bidló, A., Keserű, Z., & Borovics, A. (2024). Climate Benefit Assessment of Doubling the Extent of Windbreak Plantations in Hungary. *Earth 2024, Vol. 5, Pages 654-669*, *5*(4), 654–669. https://doi.org/10.3390/EARTH5040034
125. Knapp, S., & Peralta, I. E. (2016a). *The Tomato (Solanum lycopersicum L., Solanaceae) and Its Botanical Relatives*. 7–21. https://doi.org/10.1007/978-3-662-53389-5_2
126. Knapp, S., & Peralta, I. E. (2016b). *The Tomato Genome*. 7–21. https://doi.org/10.1007/978-3-662-53389-5
127. Körschens, M. (2021). *Long-Term Field Experiments (LTEs)—Importance, Overview, Soil Organic Matter*. 215–231. https://doi.org/10.1007/978-3-030-67448-9_8
128. Kotroczó, Z., Fekete, I., Juhos, K., Prettl, N., Nugroho, P. A., Várbíró, G., Biró, B., & Kocsis, T. (2023). Characterisation of Luvisols Based on Wide-Scale Biological Properties in a Long-Term Organic Matter Experiment. *Biology*, *12*(7). https://doi.org/10.3390/biology12070909
129. Kovács, K., & Vityi, A. (2022). Soil and Atmospheric Microclimate Research in Poplar Forestry Intercropping System in Hungary. *Acta Silvatica et Lignaria Hungarica*, *18*(1), 9–24. https://doi.org/10.37045/aslh-2022-0001
130. Kulkarni, M., & Deshpande, U. (2005). Comparative Studies in Stem Anatomy

and Morphology in Relation to Drought Resistance in Tomato (*Lycopersicon esculentum*). *American Journal of Plant Physiology*, *1*(1), 82–88. https://doi.org/10.3923/AJPP.2006.82.88
131. Kumari, P., Maurya, S., Meena, M., & Meena, S. (2020). Disease management by organic farming. *Journal of Pharmacognosy and Phytochemistry*.
132. Kütük, C., Çayci, G., & Heng, L. K. (2004). Effects of increasing salinity and 15N-labelled urea levels on growth, N uptake, and water use efficiency of young tomato plants. *Soil Research*, *42*(3), 345–351. https://doi.org/10.1071/SR02006
133. Lammerts Van Bueren, E. T., Jones, S. S., Tamm, L., Murphy, K. M., Myers, J. R., Leifert, C., & Messmer, M. M. (2011). The need to breed crop varieties suitable for organic farming, using wheat, tomato and broccoli as examples: A review. *NJAS - Wageningen Journal of Life Sciences*, *58*(3–4), 193–205. https://doi.org/10.1016/j.njas.2010.04.001
134. Lashkarizadeh, M., Munz, G., & Oleszkiewicz, J. A. (2016). Impacts of variable pH on stability and nutrient removal efficiency of aerobic granular sludge. *Water Science and Technology*, *73*(1), 60–68. https://doi.org/10.2166/WST.2015.460
135. Lei, P., Ni, C., Chen, F., Wang, S., Zhong, S., Tan, S., Ni, J., & Xie, D. (2021). Effects of crop-hedgerow intercropping on the soil physicochemical properties and crop yield on sloping cultivated lands in a purple soil of southwestern China. *Forests*, *12*(8), 1–16. https://doi.org/10.3390/f12080962
136. Li, N., Jia, J., Xia, C., Liu, X., & Kong, X. (2013). *Characterization and mapping of novel chlorophyll deficient mutant genes in durum wheat*. *175*, 169–175. https://doi.org/10.1270/jsbbs.63.169
137. Liedl, B., Labate, J., Stommel, J., Slade, A., & Kole, C. (2013). *Genetics, genomics, and breeding of tomato*. https://books.google.com/books
138. Ling, Q., Huang, W., & Jarvis, P. (2011a). Use of a SPAD-502 meter to measure leaf chlorophyll concentration in Arabidopsis thaliana. *Photosynthesis Research*, *107*(2), 209–214. https://doi.org/10.1007/s11120-010-9606-0
139. Ling, Q., Huang, W., & Jarvis, P. (2011b). Use of a SPAD-502 meter to measure leaf chlorophyll concentration in Arabidopsis thaliana. *Photosynthesis Research*, *107*(2), 209–214. https://doi.org/10.1007/S11120-010-9606-0
140. Liu, H., Mao, H., Zhu, W., Zhang, X., & Gao, H. (2015). Rapid diagnosis of tomato N-P-K nutrition level based on hyperspectral technology. *Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering*, *31*, 212–220. https://doi.org/10.3969/J.ISSN.1002-6819.2015.Z1.025
141. Long, R. F., Garbach, K., & Morandin, L. A. (2017). Hedgerow benefits align with food production and sustainability goals. *California Agriculture*, *71*(3), 117–119. https://doi.org/10.3733/CA.2017A0020
142. López Camelo, A. F., & Gómez, P. A. (2004). Comparison of color indexes for tomato ripening. *Horticultura Brasileira*, *22*(3), 534–537. https://doi.org/10.1590/s0102-05362004000300006
143. Ly, B. C. K., Dyer, E. B., Feig, J. L., Chien, A. L., & Del Bino, S. (2020). Research Techniques Made Simple: Cutaneous Colorimetry: A Reliable Technique for Objective Skin Color Measurement. *Journal of Investigative Dermatology*, *140*(1), 3-12.e1. https://doi.org/10.1016/j.jid.2019.11.003
144. Ma, C. H., & Kalb, T. (2006). Development of starter solution technology as a balanced fertilization practice in vegetable production. *Acta Horticulturae*, *700*, 167–172. https://doi.org/10.17660/ActaHortic.2006.700.27
145. Machado, J., Vasconcelos, M. W., Soares, C., Fidalgo, F., Heuvelink, E., & Carvalho, S. M. P. (2023). Enzymatic and Non-Enzymatic Antioxidant Responses of

Young Tomato Plants (cv. Micro-Tom) to Single and Combined Mild Nitrogen and Water Deficit: Not the Sum of the Parts. *Antioxidants*, *12*(2). https://doi.org/10.3390/antiox12020375
146. Mäder, P., Fließbach, A., Dubois, D., Gunst, L., Fried, P., & Niggli, U. (2002). Soil fertility and biodiversity in organic farming. *Science*, *296*(5573), 1694–1697. https://doi.org/10.1126/science.1071148
147. Mamatha, H., Srinivasa Rao, N. K., Laxman, R. H., Shivashankara, K. S., Bhatt, R. M., & Pavithra, K. C. (2014). Impact of elevated CO2 on growth, physiology, yield, and quality of tomato (*Lycopersicon esculentum* Mill) cv. Arka Ashish. *Photosynthetica*, *52*(4), 519–528. https://doi.org/10.1007/s11099-014-0059-0
148. Marconi, O., Floridi, S., & Montanari, L. (2007). Organic acids profile in tomato juice by HPLC with UV detection. *Journal of Food Quality*, *30*(2), 253–266. https://doi.org/10.1111/J.1745-4557.2007.00119.X
149. Marcu, I., Radu, G. L., & Dăncilă, A. M. (2025). Analysis of the Antioxidant Capacity of Whole-Fruit Tomato Powder Using the Ferric Reducing Antioxidant Power (FRAP) Assay—An Eco-Friendly Approach for the Valorization of Horticultural Products. *Horticulturae*, *11*(9). https://doi.org/10.3390/horticulturae11091145
150. Marković, K., Krbavčić, I., Krpan, M., Bicanic, D., & Vahčić, N. (2010). The lycopene content in pulp and peel of five fresh tomato cultivars. *Acta Alimentaria*, *39*(1), 90–98. https://doi.org/10.1556/AALIM.39.2010.1.9
151. Martínez-Blanco, J., Muñoz, P., Antón, A., & Rieradevall, J. (2011). Assessment of tomato Mediterranean production in open-field and standard multi-tunnel greenhouse, with compost or mineral fertilizers, from an agricultural and environmental standpoint. *Journal of Cleaner Production*, *19*(9–10), 985–997. https://doi.org/10.1016/j.jclepro.2010.11.018
152. Mcguire, R. G. (1992). *Reporting of objective color measurements.* https://doi.org/10.5555/19930322597
153. Mellidou, I., Koukounaras, A., Kostas, S., Patelou, E., & Kanellis, A. K. (2021). Regulation of vitamin c accumulation for improved tomato fruit quality and alleviation of abiotic stress. *Genes*, *12*(5). https://doi.org/10.3390/genes12050694
154. Mengel, K., Kirkby, E. A., Kosegarten, H., & Appel, T. (2001). Plant Water Relationships. *Principles of Plant Nutrition*, 181–242. https://doi.org/10.1007/978-94-010-1009-2_4
155. Meriles, J. M., Vargas Gil, S., Conforto, C., Figoni, G., Lovera, E., March, G. J., & Guzmán, C. A. (2009). Soil microbial communities under different soybean cropping systems: Characterization of microbial population dynamics, soil microbial activity, microbial biomass, and fatty acid profiles. *Soil and Tillage Research*, *103*(2), 271–281. https://doi.org/10.1016/j.still.2008.10.008
156. Moco, S., Bino, R. J., Vorst, O., Verhoeven, H. A., De Groot, J., Van Beek, T. A., Vervoort, J., & Ric De Vos, C. H. (2006). A liquid chromatography-mass spectrometry-based metabolome database for tomato. *Plant Physiology*, *141*(4), 1205–1218. https://doi.org/10.1104/pp.106.078428
157. Mohammed, S. P., Yen, J. Y., Hsu, Y. C., Chou, H. Y., Natarajan, S., & Eybishitz, A. (2025). Integrative Trait Analysis for Enhancing Heat Stress Resilience in Tomato (*Solanum lycopersicum* L.): A Focus on Root, Physiological, and Yield Adaptations. *Plants*, *14*(4), 533. https://doi.org/10.3390/PLANTS14040533/S1
158. Mostapha, B. B., Hayette, L., & Zina, M. (2014). Antioxidant Activity of Eight Tomato (Lycopersicon Esculentum L.) Varieties Grown in Algeria. *Journal of Food Technology Research*, *1*(2), 133–145.

https://doi.org/10.18488/JOURNAL.58/2014.1.2/58.2.133.145
159. Muhammed, A., Ara, N., Bashar, M., Begum, S., Kakon, S., & Oficer, S. (2006). Effect of spacing and stem pruning on the growth and yield of tomato. *International Journal of Sustainable Crop Production, 2*(3), 35–39.
160. Mustafa, M., Adjei, J. A., & Szalai, Z. (2023). *Pest and Disease Impact on Tomato Genotypes in a Hedgerow*. 1–8. https://doi.org/https://doi.org/10.3390/IECAG2023-15819
161. Mustafa, M., Szalai, Z., Divéky-Ertsey, A., Gál, I., & Csambalik, L. (2022). Conceptualizing Multiple Stressors and Their Consequences in Agroforestry Systems. *Stresses*, *2*(3), 242–255. https://doi.org/10.3390/stresses2030018
162. Mustafa, M., Szalai, Z. M., & Csambalik, L. (2023). Nutritional quality parameters of tomato genotypes in a hedgerow system. *Progress in Agricultural Engineering Sciences*, *19*(S1), 113–122. https://doi.org/10.1556/446.2023.00091
163. Nair, P. K. R. (2011). Agroforestry Systems and Environmental Quality: Introduction. *Journal of Environmental Quality*, *40*(3), 784–790. https://doi.org/10.2134/jeq2011.0076
164. Nair, P. K. R., Kumar, B. M., & Nair, V. D. (2021). Definition and Concepts of Agroforestry. *An Introduction to Agroforestry*, 21–28. https://doi.org/10.1007/978-3-030-75358-0_2
165. Nair, P. R., Nair, V., Kumar, B. M., Showalter, J. M., Ramachandran Nair, P. K., Nair, V. D., & Mohan Kumar, B. (2010). Carbon sequestration in agroforestry systems. *Elsevier*. https://doi.org/10.1016/S0065-2113(10)08005-3
166. Neață, G. (2012). *Studies concerning the extraction of chlorophyll and total carotenoids from vegetables*.
167. Nerlich, K., Graeff-Hönninger, S., & Claupein, W. (2013). Agroforestry in Europe: a review of the disappearance of traditional systems and development of modern agroforestry practices, with emphasis on experiences in Germany. *Agroforestry Systems*, *87*(2), 475–492. https://doi.org/10.1007/s10457-012-9560-2
168. Nikitin, B. (1999). *Method for soil humus determination.* https://doi.org/10.5555/20001909596
169. Nipa, J. F. (2020). Effect of Drip Irrigation over Conventional Method on the Growth and Yield of Tomato. *International Journal for Research in Applied Science and Engineering Technology*, *8*(12), 976–981. https://doi.org/10.22214/IJRASET.2020.32710
170. Nordey, T., Basset-Mens, C., De Bon, H., Martin, T., Déletré, E., Simon, S., Parrot, L., Despretz, H., Huat, J., Biard, Y., Dubois, T., & Malézieux, E. (2017). Protected cultivation of vegetable crops in sub-Saharan Africa: limits and prospects for smallholders. A review. *Agronomy for Sustainable Development*, *37*(6). https://doi.org/10.1007/s13593-017-0460-8
171. Ntagkas, N., Min, Q., Woltering, E. J., Labrie, C., Nicole, C. C. S., & Marcelis, L. F. M. (2016). Illuminating tomato fruit enhances fruit Vitamin C content. *Acta Horticulturae*, *1134*, 351–356. https://doi.org/10.17660/ACTAHORTIC.2016.1134.46
172. Ntim Amedor, E., Maalekuu, B. K., & Kofi, S. J. (2015). Effect of soil amendments on the nutritional quality of three commonly cultivated lettuce varieties in Ghana. *Academicjournals.Org*, *10*(14), 1796–1804. https://doi.org/10.5897/AJAR2014.8650
173. Ogwulumba, S., Ugwuoke, K., & Ogbuji, R. (2011). Reakcja pomidora (*Solanum lycopersicum*) - odmiany Roma vf na opanowanie przez patogeniczny nicień Meloidogyne javanica Treub w glebie potraktowanej wodnym roztworem ekstraktu z

liści roślin Vernonia amygdalina L. oraz mangowca (*Magnifera indica*; L.). *Journal of Plant Protection Research*, *51*(1), 14–17. https://doi.org/10.2478/v10045-011-0003-2
174. Olaniran and Odelade. (2014). Survey of the Post Harvest Diseases and Aflatoxin Contamination of Marketed Orange Fruit (Citrus Sp.) In Major Cities in Oyo State, Nigeria. *IOSR Journal of Agriculture and Veterinary Science*, *7*(8), 27–31. https://doi.org/10.9790/2380-07822731
175. Olaniyi, J. O., Akanbi, W. B., Adejumo, T. a, & Akande, O. G. (2010). Growth, fruit yield and nutritional quality of tomato varieties. *African Journal of Food Science*, *4*(6), 398–402.
176. Opara, U. L., Al-Ani, M. R., & Al-Rahbi, N. M. (2012). Effect of Fruit Ripening Stage on Physico-Chemical Properties, Nutritional Composition and Antioxidant Components of Tomato (*Lycopersicum esculentum)* Cultivars. *Food and Bioprocess Technology*, *5*(8), 3236–3243. https://doi.org/10.1007/S11947-011-0693-5/TABLES/3
177. Orman-ligeza, B., Parizot, B., Gantet, P. P., Beeckman, T., Bennett, M. J., & Draye, X. (2013). Post-embryonic root organogenesis in cereals: branching out from model plants. *Trends in Plant Science*, *18*(8), 459–467. https://doi.org/10.1016/j.tplants.2013.04.010
178. Pabar, S. A., Kotroczó, Z., Biró, B., & Takács, T. (2025). Regenerative soil treatments with alginite, mulch, and cover crops under minimum tillage: Impacts on soil organic matter content and quality in a 3-year study. Agronomy Journal, 117(5), 1–15. https://doi.org/10.1002/agj2.70140
179. Pandey, A., & Tiwari, P. (2022). Potential of Horticulture Crops and Trees in Agroforestry Systems in India. *International Journal on Agricultural Sciences*, *13*(02), 106–113. https://doi.org/10.53390/ijas.v13i2.8
180. Panthee, D. R., Cao, C., Debenport, S. J., Rodríguez, G. R., Labate, J. A., Robertson, L. D., Breksa, A. P., van der Knaap, E., & McSpadden Gardener, B. B. (2012). Magnitude of Genotype × Environment Interactions Affecting Tomato Fruit Quality. *Hortscience*, *47*(6), 721–726. https://doi.org/10.21273/HORTSCI.47.6.721
181. Panthee, D. R., & Chen, F. (2010). Genomics of Fungal Disease Resistance in Tomato. *Current Genomics*, *11*(1), 30–39. https://doi.org/10.2174/138920210790217927
182. Parisi, M., Lo Scalzo, R., & Migliori, C. A. (2021). Postharvest quality evolution in long shelf-life "vesuviano" tomato landrace. *Sustainability (Switzerland)*, *13*(21), 11885. https://doi.org/10.3390/SU132111885/S1
183. Paull, J. (2024). Organic Agriculture in Europe: EU Sets Goal of Growing Organic Farmland from 10% to 25% by 2030. *European Journal of Agriculture and Food Sciences*, *6*(1), 26–31. https://doi.org/10.24018/ejfood.2024.6.1.769
184. Pedro, A. M. K., & Ferreira, M. M. C. (2007). Simultaneously calibrating solids, sugars and acidity of tomato products using PLS2 and NIR spectroscopy. *Analytica Chimica Acta*, *595*(1-2 SPEC. ISS.), 221–227. https://doi.org/10.1016/j.aca.2007.03.036
185. Peralta, I. E., & Spooner, D. M. (2001). Granule-bound starch synthase (GBSSI) gene phylogeny of wild tomatoes (*Solanum L. section Lycopersicon* [Mill.] *Wettst. subsection Lycopersicon*). *American Journal of Botany*, *88*(1–12), 1888–1902. https://doi.org/10.2307/3558365
186. Peralta, I. E., & Spooner, D. M. (2005). Morphological characterization and relationships of wild tomatoes (. *A Festschrift for William G. D'arcy*, *104*, 227–257.
187. Perea-Domínguez, X. P., Hernández-Gastelum, L. Z., Olivas-Olguin, H. R., Espinosa-Alonso, L. G., Valdez-Morales, M., & Medina-Godoy, S. (2018). Phenolic

composition of tomato varieties and an industrial tomato by-product: free, conjugated and bound phenolics and antioxidant activity. *Journal of Food Science and Technology*, *55*(9), 3453–3461. https://doi.org/10.1007/S13197-018-3269-9/FIGURES/2
188. Pérez-de-Mora, A., Burgos, P., Ortega-Calvo, J. J., Cabrera, F., & Madejón, E. (2008). Microbial Function after Assisted Natural Remediation of a Trace Element Polluted Soil. *Modern Multidisciplinary Applied Microbiology: Exploiting Microbes and Their Interactions*, 536–540. https://doi.org/10.1002/9783527611904.CH94
189. Periago, M. J., Martínez-Valverde, I., Chesson, A., & Provan, G. (2002a). Phenolic compounds, lycopene and antioxidant activity in commercial varieties of tomato (*Lycopersicum esculentum*). *Journal of the Science of Food and Agriculture*, *82*(3), 323–330. https://doi.org/10.1002/JSFA.1035
190. Periago, M. J., Martínez-Valverde, I., Chesson, A., & Provan, G. (2002b). Phenolic compounds, lycopene and antioxidant activity in commercial varieties of tomato (*Lycopersicum esculentum*). *Journal of the Science of Food and Agriculture*, *82*(3), 323–330. https://doi.org/10.1002/JSFA.1035
191. Polder, G., Van Der Heijden, G. W. A. M., Van Der Voet, H., & Young, I. T. (2004). Measuring surface distribution of carotenes and chlorophyll in ripening tomatoes using imaging spectrometry. *Postharvest Biology and Technology*, *34*(2), 117–129. https://doi.org/10.1016/j.postharvbio.2004.05.002
192. Pratt, P. F. (2016). Potassium. *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties*, 1022–1030.ISBN:978-0-89118-072-2
193. Precheur, R., Greig, J. K., & Armbrust, D. V. (1987). The Effects of Wind and Wind-Plus-Sand on Tomato Plants1. *Journal of the American Society for Horticultural Science*, *103*(3), 351–355. https://doi.org/10.21273/jashs.103.3.351
194. Quispe-Choque, G., Rojas-Ledezma, S., & Maydana-Marca, A. (2022). Diversidad morfológica de fruto de una colección de tomate (*Solanum lycopersicum* L.) mediante fenotipado basado en imágenes digitales. *Journal of the Selva Andina Research Society*, *13*(2), 51–68. https://doi.org/10.36610/J.JSARS.2022.130200051
195. Rácz, É. V. P., & Környei, L. (2023). Local Scale Wind Regime Changes and their Consequences on Sustainability in the Carpathian Basin (Hungary). *Chemical Engineering Transactions*, *107*, 475–480. https://doi.org/10.3303/CET23107080
196. Radzevičius, A., Karklelienė, R., Viškelis, P., Bobinas, Č., Bobinaitė, R., Sakalauskienė, S., & Metspalu, L. (2009). Tomato *(Lycopersicon esculentum* Mill.) fruit quality and physiological parameters at different ripening stages of Lithuanian cultivars. *Agronomy Research*.
197. Rajoria, A., Kumar, J., & Chauhan, A. (2010). Anti-Oxidative And Anti-Carcinogenic Role of Lycopene In Human Health – A Review. *Journal of Dairying, Foods and Home Sciences*.
198. Ramadan, A. A., Olfat, M. M., Nour, E. K. S., Kenta, S., Said, M. K., & Mohamed, T. R. (2017). Resistance to Phytophthora infestans in tomato wild relatives. *African Journal of Agricultural Research*, *12*(26), 2188–2196. https://doi.org/10.5897/AJAR2017.12422
199. Rambla, J. L., Tikunov, Y. M., Monforte, A. J., Bovy, A. G., & Granell, A. (2014). The expanded tomato fruit volatile landscape. *Journal of Experimental Botany*, *65*(16), 4613–4623. https://doi.org/10.1093/jxb/eru128
200. Rana, N., Kumar, M., Walia, A., & Sharma, S. (2014a). Tomato Fruit Quality under Protected Environment and Open Field Conditions. *International Journal of Bio-Resource and Stress Management*, *5*(3), 422. https://doi.org/10.5958/0976-4038.2014.00592.2

201. Rani Chandrasekaran, I., Geetha, P., Geetha, P., Indhu Rani, C., & Journal, R. (2020). Post harvest technology and value addition of tomatoes. *Researchgate.Net*, *11*(2), 2020–2217. https://doi.org/10.15740/HAS/FSRJ/11.2/217-229
202. Ravi, S., D'Odorico, P., Over, T. M., & Zobeck, T. M. (2004). On the effect of air humidity on soil susceptibility to wind erosion: The case of air-dry soils. *Geophysical Research Letters*, *31*(9). https://doi.org/10.1029/2004GL019485
203. Reszka, M., Serdiuk, I. E., Kozakiewicz, K., Nowacki, A., Myszka, H., Bojarski, P., & Liberek, B. (2020). Influence of a 4'-substituent on the efficiency of flavonol-based fluorescent indicators of β-glycosidase activity. *Organic and Biomolecular Chemistry*, *18*(38), 7635–7648. https://doi.org/10.1039/D0OB01505A
204. Riahi, A., Hdider, C., Sanaa, M., Tarchoun, N., Kheder, M. Ben, & Guezal, I. (2009). Effect of conventional and organic production systems on the yield and quality of field tomato cultivars grown in Tunisia. *Journal of the Science of Food and Agriculture*, *89*(13), 2275–2282. https://doi.org/10.1002/JSFA.3720
205. Rick, C. M., & Smith, P. G. (1953). Novel Variation in Tomato Species Hybrids. *Https://Doi.Org/10.1086/281796*, *87*(837), 359–373. https://doi.org/10.1086/281796
206. Rizhsky, L., Liang, H., Shuman, J., Shulaev, V., Davletova, S., & Mittler, R. (2004). When defense pathways collide. The response of arabidopsis to a combination of drought and heat stress 1[w]. *Plant Physiology*, *134*(4), 1683–1696. https://doi.org/10.1104/pp.103.033431
207. Rosa-Martínez, E., Bovy, A., Plazas, M., Tikunov, Y., Prohens, J., & Pereira-Dias, L. (2023). Genetics and breeding of phenolic content in tomato, eggplant and pepper fruits. *Frontiers in Plant Science*, *14*, 1135237. https://doi.org/10.3389/FPLS.2023.1135237/FULL
208. Rosales, M. A., Cervilla, L. M., Sánchez-Rodríguez, E., Rubio-Wilhelmi, M. del M., Blasco, B., Ríos, J. J., Soriano, T., Castilla, N., Romero, L., & Ruiz, J. M. (2011). The effect of environmental conditions on nutritional quality of cherry tomato fruits: evaluation of two experimental Mediterranean greenhouses. *The Journal of the Science of Food and Agriculture*, *91*(1), 152–162. https://doi.org/10.1002/JSFA.4166
209. Roy, J. C., & Boulard, T. (2005). CFD Prediction of The Natural Ventilation In A Tunnel-Type Greenhouse: Influence Of Wind Direction and Sensibility To Turbulence Models. *Acta Horticulturae*, *691*, 457–464. https://doi.org/10.17660/ACTAHORTIC.2005.691.55
210. Ruggieri, V., Calafiore, R., Schettini, C., Rigano, M. M., Olivieri, F., Frusciante, L., & Barone, A. (2019). Exploiting genetic and genomic resources to enhance heat-tolerance in tomatoes. *Agronomy*, *9*(1), 1–13. https://doi.org/10.3390/agronomy9010022
211. Ruppert, D., Welp, M., Spies, M., & Thevs, N. (2020). Farmers' Perceptions of Tree Shelterbelts on Agricultural Land in Rural Kyrgyzstan. *Sustainability 2020, Vol. 12, Page 1093*, *12*(3), 1093. https://doi.org/10.3390/SU12031093
212. Rutger, J. N., Beckham, L. S., Tucker, C. L., & Harding, J. (1977). Influence of Subsoil Acidity on Tomato Yield and Fruit Size1. *Journal of the American Society for Horticultural Science*, *102*(5), 643–645. https://doi.org/10.21273/JASHS.102.5.643
213. Rubio-Delgado, J., Schnabel, S., Lavado-Contador, J. F., & Schmutz, U. (2024). Small woody features in agricultural areas: Agroforestry systems of overlooked significance in Europe. *Agricultural Systems*, *218*(December 2023), 103973. https://doi.org/10.1016/j.agsy.2024.103973
214. Saidi, M., Gogo, E. O., Itulya, F. M., Martin, T., & Ngouajio, M. (2013).

Microclimate modification using eco-friendly nets and floating row covers improves tomato (*Lycopersicon esculentum*) yield and quality for small holder farmers in East Africa. *Agricultural Sciences*, *04*(11), 577–584. https://doi.org/10.4236/AS.2013.411078
215. Sainju, U. M., Dris, R., & Singh, B. (2003). Mineral nutrition of tomato. *Food, Agriculture & Environment*, *1*(2), 176–184.
216. Šalagovič, J., Vanhees, D., Verboven, P., Holsteens, K., Verlinden, B., Huysmans, M., Van de Poel, B., & Nicolaï, B. (2024a). Microclimate monitoring in commercial tomato (*Solanum Lycopersicum* L.) greenhouse production and its effect on plant growth, yield and fruit quality. *Frontiersin.OrgJ Šalagovič, D Vanhees, P Verboven, K Holsteens, B Verlinden, M HuysmansFrontiers in Horticulture, 2024 frontiersin. Org*, *3*, 1425285. https://doi.org/10.3389/FHORT.2024.1425285/FULL
217. Šalagovič, J., Vanhees, D., Verboven, P., Holsteens, K., Verlinden, B., Huysmans, M., Van de Poel, B., & Nicolaï, B. (2024b). Microclimate monitoring in commercial tomato (*Solanum Lycopersicum* L.) greenhouse production and its effect on plant growth, yield and fruit quality. *Frontiers in Horticulture*, *3*(October), 1–17. https://doi.org/10.3389/fhort.2024.1425285
218. Sánchez-Rodríguez, E., Leyva, R., Constán-Aguilar, C., Romero, L., & Ruiz, J. M. (2014). How does grafting affect the ionome of cherry tomato plants under water stress? *Soil Science and Plant Nutrition*, *60*(2), 145–155. https://doi.org/10.1080/00380768.2013.870873
219. Santos Neto, J., Schwan-Estrada, K. R. F., de Sena, J. O. A., & Telles, T. S. (2017). Economic Viability of Tomato Cultivation in Organic Farming System. *Brazilian Archives of Biology and Technology*, *60*(December), 1–11. https://doi.org/10.1590/1678-4324-2017161229
220. Sastre, J., Vidal, M., Rauret, G., & Sauras, T. (2001). A soil sampling strategy for mapping trace element concentrations in a test area. *Science of the Total Environment*, *264*(1–2), 141–152. https://doi.org/10.1016/S0048-9697(00)00616-1
221. Schlindwein, J. A., Bortolon, L., Fioreli-Pereira, E. C., Oliveira Bortolon, E. S., & Gianello, C. (2013). Phosphorus and potassium fertilization in no till southern Brazilian soils. *Agricultural Sciences*, *04*(12), 39–49. https://doi.org/10.4236/AS.2013.412A004
222. Schwarz, D., Thompson, A. J., & Kläring, H. P. (2014). Guidelines to use tomato in experiments with a controlled environment. *Frontiers in Plant Science*, *5*(NOV), 1–16. https://doi.org/10.3389/fpls.2014.00625
223. Schwitter, P., Detterbeck, A., & Herforth-Rahmé, J. (2022). Effect of Harvest Frequency, Seed Extraction Time Point and Post-Harvest Cooling on Organic Tomato Seed Production. *Sustainability (Switzerland)*, *14*(18). https://doi.org/10.3390/su141811575
224. Setiawan J. A., M. M. D. & N. (2016). Effects of hedgerow systems on soil moisture and unsaturated hydraulics conductivity measured by the Libardi method. *Degraded Andmining Landsmanagement*, *2*(3), 535–542. https://doi.org/10.15243/jdmlm.2016.032.491
225. Setu, H. (2022). Effect of Phosphorus and Potassium Fertilizers Application on Soil Chemical Characteristics and Their Accumulation in Potato Plant Tissues. *Applied and Environmental Soil Science*, *2022*. https://doi.org/10.1155/2022/5342170
226. Setyaningrum, D., Budiastuti, M. T. S., Purnomo, D., & Sudadi. (2024). Role of Organic Fertilizer Types on Nutrient Absorption and Soybean Yield in Teak-based Agroforestry Systems. *Agricultural Science Digest*, *44*(1), 35–40. https://doi.org/10.18805/ag.DF-574

227. Seufert, V., Ramankutty, N., & Foley, J. A. (2012). Comparing the yields of organic and conventional agriculture. *Nature*, *485*(7397), 229–232. https://doi.org/10.1038/nature11069
228. Shabani, F., Kumar, L., of, A. E.-J., (2013). Use of CLIMEX, land use and topography to refine areas suitable for date palm cultivation in Spain under climate change scenarios. *Researchnow-Admin.Flinders.Edu.Au*, *4*(4), 145. https://doi.org/10.4172/2157-7617.1000145
229. Shamshiri, R. R., Jones, J. W., Thorp, K. R., Ahmad, D., Man, H. C., & Taheri, S. (2018). Review of optimum temperature, humidity, and vapour pressure deficit for microclimate evaluation and control in greenhouse cultivation of tomato: A review. *International Agrophysics*, *32*(2), 287–302. https://doi.org/10.1515/intag-2017-0005
230. Shi, J., Maguer, M. Le, Kakuda, Y., Liptay, A., & Niekamp, F. (1999). Lycopene degradation and isomerization in tomato dehydration. *Food Research International*, *32*(1), 15–21. https://doi.org/10.1016/S0963-9969(99)00059-9
231. Shober, A. L., Gartley, K. L., & Sims, J. T. (2019). *Measurement and management of soil pH for crop production in Delaware*.https://www.udel.edu/content/dam/udelImages/canr,
232. Silva, C. A. da, Dalazen, J. R., Rodrigues, W. P., Rocha, R. B., & Partelli, F. L. (2025). Nutritional Efficiency of Coffea canephora: The Role of Genetic Variability and Nutrient Accumulation. *Plants*, *14*(10). https://doi.org/10.3390/PLANTS14101509
233. Silva, R. S., Kumar, L., Shabani, F., & Picanço, M. C. (2017). Assessing the impact of global warming on worldwide open field tomato cultivation through CSIRO-Mk3.0 global climate model. *Journal of Agricultural Science*, *155*(3), 407–420. https://doi.org/10.1017/S0021859616000654
234. Singleton, V. L., & Rossi, J. A. (1965). Colorimetry of Total Phenolics with Phosphomolybdic-Phosphotungstic Acid Reagents. *American Journal of Enology and Viticulture*, *16*(3), 144–158. https://doi.org/10.5344/AJEV.1965.16.3.144
235. Sinsabaugh, R., Klug, M., Collins, H., & Yeager, P. (1999). *Characterizing soil microbial communities*.
236. Sirieva, Y., & Daulakova, L. (2020). Современный Процесс Выращивания Томата В Защищенном Грунте. *Nauka. Issledovaniia. Praktika: Sbornik Izbrannyh Statei Po Materialam Mezhdunarodnoi Nauchnoi Konferencii (Sankt-Peterburg, Fevral` 2020)*. https://doi.org/10.37539/SRP289.2020.13.93.004
237. Smith, A. F. (1994). *The Tomato in America: Early History, Culture, and Cookery*. University of Illinois Press.
238. Smith, K. A.., & Mullins, C. E. (2000). *Soil Water Content*. 13–76. https://doi.org/10.1201/9780203908600-6
239. Sobarzo-Bernal, O., Gómez-Merino, F. C., Alcántar-González, G., Saucedo-Veloz, C., & Trejo-Téllez, L. I. (2021). Biostimulant Effects of Cerium on Seed Germination and Initial Growth of Tomato Seedlings. *Agronomy*, *11*(8). https://doi.org/10.3390/AGRONOMY11081525
240. Stevens, M. A., Kader, A. A., & Albright, M. (1979). Potential for Increasing Tomato Flavor via Increased Sugar and Acid Content1. *Journal of the American Society for Horticultural Science*, *104*(1), 40–42. https://doi.org/10.21273/JASHS.104.1.40
241. Stoutjesdijk, P. (1974). The Open Shade, An Interesting Microclimate. *Acta Botanica Neerlandica*, *23*(2), 125–130. https://doi.org/10.1111/J.1438-8677.1974.TB00927.X

242. Sudharta, K. A., Hakim, A. L., Fadhilah, M. A., Fadzil, M. N., Prayogo, C., Kusuma, Z., & Suprayogo, D. (2022). Soil organic matter and nitrogen in varying management types of coffee-pine agroforestry systems and their effect on coffee bean yield. *Biodiversitas*, *23*(11), 5884–5891. https://doi.org/10.13057/biodiv/d231142
243. Sun, G., Ding, Y., Wang, X., Lu, W., Sun, Y., & Yu, H. (2019). Nondestructive determination of nitrogen, phosphorus and potassium contents in greenhouse tomato plants based on multispectral three-dimensional imaging. *Sensors (Switzerland)*, *19*(23). https://doi.org/10.3390/s19235295
244. Suratman, M. N., & Brandle, J. R. (2023). Tree shelter belts for sustainable agroforestry. *Agroforestry for Carbon and Ecosystem Management*, *November*, 97–107. https://doi.org/10.1016/B978-0-323-95393-1.00011-7
245. Suprayogo, D., Hairiah, K., Noordwijk, M., & Cadisch, G. (2010). AGROFORESTRY Interactions In Rainfed Agriculture: Can Hedgerow Intercropping Systems Sustain Crop Yield On An Ultisol In Lampung (Indonesia)? *Agrivita : Journal of Agricultural Science*. https://doi.org/10.17503/AGRIVITA.V32I3.21
246. Suzuki, M., Umeda, H., Matsuo, S., Kawasaki, Y., Ahn, D., Hamamoto, H., & Iwasaki, Y. (2015). Effects of relative humidity and nutrient supply on growth and nutrient uptake in greenhouse tomato production. *Scientia Horticulturae*, *187*, 44–49. https://doi.org/10.1016/j.scienta.2015.02.035
247. Swinkels, R., Agriculture, S. F.-E., & 1997, undefined. (1997). Hedgerow Intercropping In Maize-Based Cropping Systems in the Highlands of Western Kenya 2. Economic And Farmers'evaluation. *Cambridge.Org*, *33*, 211–223. https://doi.org/10.1017/S0014479797000094
248. Szigeti, N., Frank, N., & Vityi, A. (2020a). The multifunctional role of shelterbelts in intensively managed agricultural land – Silvoarable agroforestry in Hungary. *Acta Silvatica et Lignaria Hungarica*, *16*(1), 19–38. https://doi.org/10.37045/aslh-2020-0002
249. Szigeti, N., Frank, N., & Vityi, A. (2020b). The Multifunctional Role of Shelterbelts in Intensively Managed Agricultural Land – Silvoarable Agroforestry in Hungary. *Acta Silvatica & Lignaria Hungarica*, *16*(1), 19–38. https://doi.org/10.37045/ASLH-2020-0002
250. Tabatabai, M. A., & Bremner, J. M. (1969). Use of p-nitrophenyl phosphate for assay of soil phosphatase activity. *Soil Biology and Biochemistry*, *1*(4), 301–307. https://doi.org/10.1016/0038-0717(69)90012-1
251. Thomsit-Ireland, F., Essah, E. A., Hadley, P., & Blanuša, T. (2020). The impact of green facades and vegetative cover on the temperature and relative humidity within model buildings. *Building and Environment*, *181*(May). https://doi.org/10.1016/j.buildenv.2020.107009
252. Thorne, S. N., & Efiuvwevwere, B. J. O. (1988). Changes in organic acids in chilled tomato fruit (*Lycopersicon esculentum* Mill). *Journal of the Science of Food and Agriculture*, *44*(4), 309–319. https://doi.org/10.1002/JSFA.2740440404
253. Tigist, M., Workneh, T. S., & Woldetsadik, K. (2013). Effects of variety on the quality of tomato stored under ambient conditions. *Journal of Food Science and Technology*, *50*(3), 477–486. https://doi.org/10.1007/S13197-011-0378-0/TABLES/7
254. Townsend, T. J., Ramsden, S. J., & Wilson, P. (2016). How do we cultivate in England? Tillage practices in crop production systems. *Soil Use and Management*, *32*(1), 106–117. https://doi.org/10.1111/sum.12241
255. Tracy, S. R., Black, C. R., Roberts, J. A., Sturrock, C., Mairhofer, S., Craigon, J., & Mooney, S. J. (2012). Quantifying the impact of soil compaction on root system architecture in tomato (Solanum lycopersicum) by X-ray micro-computed

tomography. *Annals of Botany*, *110*(2), 511–519. https://doi.org/10.1093/aob/mcs031
256. Tuylu, M. (2018). Examination of Anatomical Features of Tomato (*Lycopersicon Esculentum* Mill.) Varieties Cultivated Under Hydroponic System. *Journal Of Ecology and Environmental Research*, *16*(3), 3381–3391. https://doi.org/DOI: http://dx.doi.org/10.15666/aeer/1603_33813391
257. Ugwu, K. C., Mbajiorgu, C. C., Okonkwo, W. I., & Ani, A. O. (2018). Design, fabrication and performance evaluation of a portable hand-held refractometer. *Nigerian Journal of Technology*, *37*(2), 537. https://doi.org/10.4314/NJT.V37I2.33
258. Valšíková-Frey, M., Komár, P., & Rehuš, M. (2017). The Effect of Varieties and Degree of Ripeness to Vitamin C Content in Tomato Fruits. *Acta Horticulturae et Regiotecturae*, *20*(2), 44–48. https://doi.org/10.1515/ahr-2017-0010
259. van Bruggen, A. H. C., Gamliel, A., & Finckh, M. R. (2016). Plant disease management in organic farming systems. *Pest Management Science*, *72*(1), 30–44. https://doi.org/10.1002/PS.4145
260. Vanneste, T., Govaert, S., Spicher, F., Brunet, J., Cousins, S. A. O., Decocq, G., Diekmann, M., Graae, B. J., Hedwall, P. O., Kapás, R. E., Lenoir, J., Liira, J., Lindmo, S., Litza, K., Naaf, T., Orczewska, A., Plue, J., Wulf, M., Verheyen, K., & De Frenne, P. (2020). Contrasting microclimates among hedgerows and woodlands across temperate Europe. *Agricultural and Forest Meteorology*, *281*, 107818. https://doi.org/10.1016/J.AGRFORMET.2019.107818
261. Vavrina, C. S., & Orzolek, M. D. (2018). Tomato Transplant Age: A Review. *HortTechnology*, *3*(3), 313–316. https://doi.org/10.21273/horttech.3.3.313
262. Vicente, M. H., Zsögön, A., de Sá, A. F. L., Ribeiro, R. V., & Peres, L. E. P. (2015). Semi-determinate growth habit adjusts the vegetative-to-reproductive balance and increases productivity and water-use efficiency in tomato (*Solanum lycopersicum*). *Journal of Plant Physiology*, *177*, 11–19. https://doi.org/10.1016/j.jplph.2015.01.003
263. Vijayalakshmi, M., of, K. R.-||| B. J., & 2016, undefined. (2016). Ferric reducing antioxidant power assay in plant extract. *Bdpsjournal.Org*, *11*, 570–572. https://doi.org/10.3329/bjp.v11i3.27663
264. Viscarra Rossel, R. A., Minasny, B., Roudier, P., & McBratney, A. B. (2006). Colour space models for soil science. *Geoderma*, *133*(3–4), 320–337. https://doi.org/10.1016/j.geoderma.2005.07.017
265. Wang, Q., Xu, Z., Hu, T., Ur Rehman, H., Chen, H., Li, Z., Ding, B., & Hu, H. (2014). Allelopathic activity and chemical constituents of walnut (*Juglans regia*) leaf litter in walnut–winter vegetable agroforestry system. *Http://Dx.Doi.Org/10.1080/14786419.2014.913245*, *28*(22), 2017–2020. https://doi.org/10.1080/14786419.2014.913245
266. Weese, T., botany, L. B.-S., & 2007, undefined. (2007). A three-gene phylogeny of the genus Solanum (Solanaceae). *Ingentaconnect.Com*. https://doi.org/10.1600/036364407781179671
267. Wilkerson, E. D., Anthon, G. E., Barrett, D. M., Sayajon, G. F. G., Santos, A. M., & Rodriguez-Saona, L. E. (2013). Rapid assessment of quality parameters in processing tomatoes using hand-held and benchtop infrared spectrometers and multivariate analysis. *Journal of Agricultural and Food Chemistry*, *61*(9), 2088–2095. https://doi.org/10.1021/jf304968f
268. Willey, R. W., Reddy, & Natarajan, M. (1987). *Conventional Cropping Systems for Alfisols and Some Implications for Agroforestry Systems*.
269. Workman, S. W., Thevathasan, N. V, & Gordon, A. M. (2002). Book review: North American Agroforestry: An Integrated Science and Practice. H. *Agroforestry*

Systems, *54*, 83–85.
270. Xu, Y., Teng, Y., Dong, X., Wang, X., Zhang, C., Ren, W., Zhao, L., Luo, Y., & Greening, C. (2021). Genome-resolved metagenomics reveals how soil bacterial communities respond to elevated H2 availability. *Soil Biology and Biochemistry*, *163*. https://doi.org/10.1016/J.SOILBIO.2021.108464
271. Zampieri, M., Ceglar, A., Dentener, F., & Toreti, A. (2017). Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales. *Environmental Research Letters*, *12*(6). https://doi.org/10.1088/1748-9326/aa723b
272. Zhou, R., Jiang, F., Liu, Y., Yu, X., Song, X., Wu, Z., & Cammarano, D. (2024). Environmental changes impact on vegetables physiology and nutrition – Gaps between vegetable and cereal crops. *Science of the Total Environment*, *933*(May). https://doi.org/10.1016/j.scitotenv.2024.173180

Internet references

1. FAOSTAT 2020 – 2025: https://www.fao.org/faostat/en/#home
2. CLIFF, G.2005. Glossary of Plant Terms. Accessed 01 April 2025. http://grandpacliff.com/Plants/Glossary-Plants.htm
3. Foord, K. (2014). Pollination Vegetable garden -1-2 - Tomato, pepper, eggplant - Karl Foord - Mentha Group. Mentha Group. Accessed 01 April 2023. letstalkscience.ca/educational-resources/backgrounders/life-cycle-a-tomato-plant.
4. OECD (2008), "Consensus document on compositional considerations for new varieties of tomato: Key food and feed nutrients, toxicants and allergens", *Series on the Safety of Novel Foods and Feeds*, No. 17, OECD, Paris, www.oecd.org/env/ehs/biotrack/46815296.pdf.
5. OECD. (2017) . Tomato (*Solanum lycopersicum*), in Safety Assessment of Trans-genic Organisms in the Environment, Volume7: OECD Consensus Docu ments, OECD Publishing, Paris, www. oecd.org/env/ehs.
6. EU organic farming framework (https://agriculture.ec.europa.eu/farming/organic

11. APPENDICES

Appendix table 1. Mean ± SD of the soil health properties proximity of hedgerows from 2022, 2023, and 2024.

Soil measurements	parcels	2022	2023	2024
		Mean ± SD	Mean ± SD	Mean ± SD
Organic matter stability coefficient	P	0.223 ± 0.035	0.433±0.153	0.363 ± 0.201
	W	0.190± 0.026	0.170±0.053	0.250± 0.044
	PC	0.27	0.36	0.27
	WC	0.15	0.64	0.16
Organic matter quality (Q)	P	0.437± 0.067 ^{A}	1.733±0.699 ^{B}	1.437 ± 0.791 ^{A}
	W	0.340 ± 0.052 ^{A}	0.687 ±0.191 ^{B}	0.970 ± 0.149 ^{B}
	PC	0.54	1.42	1.06
	WC	0.36	2.57	0.62
H%	P	2.007 ± 0.474 ^{A}	3.947±0.177 ^{B}	3.967 ± 0.123 ^{B}
	W	1.820± 0.234 ^{A}	3.977±0.117^{B}	3.903 ± 0.127^{B}
	PC	2.05	3.96	3.91
	WC	2.48	3.99	3.97
pH (H2O)	P	8.947 ± 0.015 ^{B}	7.567±0.231 ^{A}	8.100 ± 0.100 ^{A}
	W	8.957 ± 0.015 ^{B}	7.933 ±0.231 ^{A}	8.167 ± 0.153 ^{A}
	PC	8.84	7.70	7.90
	WC	8.93	8.10	8.10
Potassium	P	199.067 ± 12.703 ^{A}	435.41±120.225 A^{B}	588.400 ± 51.842 ^{B}
	W	97.467 ± 18.287 ^{A}	3376.000 ±35.967 ^{B}	555.667± 24.399 ^{B}
	PC	229.40	511.00	530.60
	WC	201.20	367.80	675.60
Phosphorus	P	678.45 ± 70.791 ^{b}	570.53±86.713	500.91 ± 115.629
	W	298.94 ± 83.313 ^{aB}	489.91±49.143 ^{A}	508.7567 ± 23.410 ^{A}
	PC	608.65	556.70	428.25
	WC	360.05	384.72	524.96
Dehydrogenase Activity	P	0.659 ± 0.319	1.174±0.157	0.672 ± 0.196
	W	0.636 ± 0.066 ^{B}	0.913 ±0.197 ^{B}	0.165± 0.014 ^{A}
	PC	0.64	0.55	0.30
	WC	0.48	1.14	0.23
Glicosidase Activity	P	8.241 ± 1.121 ^{A}	43.309±9.014 ^{bB}	5.840 ± 1.471 ^{A}
	W	7.019 ± 0.774 ^{A}	18.344±3.497 ^{Ab}	9.691± 3.716 AB
	PC	3.26	31.30	9.06
	WC	4.57	16.93	15.78
Phosphatase Activity	P	14.610 ± 3.858 ^{B}	2.209±0.886 ^{A}	4.888 ± 1.063 ^{A}
	W	12.189 ± 1.987^{B}	4.596 ±2.224 ^{A}	3.464 ± 0.671 ^{A}
	PC	8.18	1.52	3.72
	WC	8.22	4.18	3.55
Soil moisture (%)	P	14.277 ± 1.384 ^{AB}	19.857±5.157 ^{AB}	19.420 ± 1.492 ^{bB}
	W	12.730 ± 0.122 ^{AB}	16.200 ±3.815 ^{AB}	15.417 ± 0.713 ^{aB}
	PC	12.32	13.65	19.14
	WC	10.54	20.34	15.89

Legend: P (Protected), PC (Protected Control), W (Windy), and WC (Windy Control). Different uppercase letters mean significant differences between years of the same side ($p < 0.05$). Different lowercase letters mean significant differences among sides within a year ($p < 0.05$).

Appendix table 2. Macronutrient and photosynthetic pigment levels (mean ± SD) of tomato leaves collected from different distances and sides of a hedge at (2023).

Measurement Parameters	Treatments Distances	Measured quantity, mean ± SD		
		Szentlőrinckáta	ACE55	Roma
Nitrogen (N)	P5	31.03 ± 0.88	42.73 ± 1.53	48.83 ± 3.18
	P3	44.25 ± 0.88	45.78 ± 1.76	36.62 ± 4.04
	P1	31.54 ± 3.18	28.99 ± 0.88	46.29 ± 2.33
	W1	29.50 ± 1.76	33.06 ± 5.36	59.51 ± 6.65
	W3	30.52 ± 1.53	59.01 ± 0.88	57.48 ± 1.76
	W5	55.95 ± 2.33	51.88 ± 3.18	59.51 ± 6.65
Phosphorus (P)	P5	5.48 ± 0.54	2.07 ± 0.05	3.57 ± 0.29
	P3	5.13 ± 0.11	4.97 ± 0.17	3.89 ± 0.21
	P1	2.78 ± 0.08	2.88 ± 0.16	2.64 ± 0.13
	W1	3.24 ± 0.28	4.09 ± 0.32	4.81 ± 0.08
	W3	4.26 ± 0.25	3.45 ± 0.46	4.39 ± 0.46
	W5	3.36 ± 0.08	2.72 ± 0.08	3.87 ± 0.23
Potassium (K)	P5	18.00 ± 0.00	24.67 ± 0.58	26.33 ± 0.58
	P3	22.33 ± 0.58	26.00 ± 1.73	18.33 ± 0.29
	P1	18.83 ± 1.04	15.83 ± 0.58	17.00 ± 0.87
	W1	15.17 ± 0.29	24.67 ± 0.58	26.00 ± 1.00
	W3	14.67 ± 0.58	18.33 ± 0.29	22.33 ± 0.58
	W5	26.67 ± 1.15	29.33 ± 0.58	25.33 ± 0.58
Chlorophyll A	P5	1201.13 ± 170.35	1365.22 ± 181.77	1344.68 ± 175.20
	P3	1220.06 ± 89.31	1269.53 ± 499.29	1671.12 ± 569.06
	P1	1371.91 ± 339.93	1287.34 ± 324.38	1177.87 ± 159.10
	W1	1077.03 ± 183.22	1474.69 ± 387.98	2106.98 ± 265.58
	W3	1797.91 ± 94.27	1841.72 ± 305.71	1999.08 ± 165.70
	W5	1301.64 ± 221.74	1644.35 ± 143.76	1518.43 ± 536.81
Chlorophyll B	P5	581.50 ± 44.09	826.38 ± 317.03	801.71 ± 282.93
	P3	700.65 ± 194.36	743.11 ± 224.37	920.04 ± 105.41
	P1	543.42 ± 98.44	661.94 ± 176.13	542.09 ± 81.50
	W1	848.69 ± 27.56	730.57 ± 102.82	1170.32 ± 359.39
	W3	576.32 ± 76.58	692.20 ± 101.94	653.40 ± 106.58
	W5	666.87 ± 146.15	849.77 ± 159.47	735.26 ± 259.92
Carotene	P5	342.06 ± 33.62	302.79 ± 37.40	415.27 ± 56.28
	P3	311.97 ± 27.80	400.16 ± 93.62	481.29 ± 149.29
	P1	294.33 ± 30.54	346.15 ± 90.33	332.58 ± 30.55
	W1	279.68 ± 42.84	368.03 ± 113.58	447.08 ± 42.06
	W3	449.09 ± 33.12	403.39 ± 64.22	485.62 ± 105.06
	W5	322.19 ± 27.75	359.56 ± 37.18	289.91 ± 108.99

Appendix table 3. Mean and Std. deviation and post hoc for total fruit weight in (2022, 2023, 2024).

Variety	Distances	Total weight of the tomato fruit (2022, 2023, and 2024).		
		2022	2023	2024
Roma	P5	1.35 ± 0.67	4.69 ± 1.76	0.56 ± 0.06
	P4	2.11 ± 0.83	4.55 ± 0.74	0.61 ± 0.07
	P3	1.45 ± 0.48	5.79 ± 1.72	0.75 ± 0.05
	P2	1.18 ± 0.63	4.69 ± 1.70	0.61 ± 0.07
	P1	1.22 ± 0.36	4.57 ± 1.67	0.68 ± 0.03
	W1	2.08 ± 1.30	3.60 ± 0.89^{B}	0.54 ± 0.22
	W2	1.97 ± 1.75	4.99 ± 1.04^{aB}	0.56 ± 0.54

	W3	0.92 ± 0.24	5.13 ± 1.34^{A}	1.66 ± 1.40
	W4	1.42 ± 0.69	5.98 ± 0.73^{A}	1.16 ± 0.32
	W5	2.81 ± 1.57	5.10 ± 1.04^{A}	1.98 ± 1.73
Ace55	P5	1.02 ± 0.27^{A}	0.52 ± 0.28	0.89 ± 0.00
	P4	1.01 ± 0.41^{aB}	0.55 ± 0.28	1.02 ± 0.21
	P3	2.94 ± 0.99^{Ab}	0.54 ± 0.31	3.96 ± 0.00
	P2	1.38 ± 0.78^{B}	0.47 ± 0.14	0.75 ± 0.30
	P1	0.81 ± 0.11^{B}	0.44 ± 0.12	0.73 ± 0.59
	W1	1.99 ± 0.86	0.30 ± 0.10^{B}	0.32 ± 0.15
	W2	0.89 ± 0.01	0.43 ± 0.06^{aB}	1.38 ± 0.71
	W3	2.08 ± 1.37	0.50 ± 0.16^{AB}	0.88 ± 0.82
	W4	2.48 ± 1.18	0.62 ± 0.18^{A}	1.31 ± 1.82
	W5	0.83 ± 0.08	0.45 ± 0.12^{A}	0.81 ± 0.57
Szentlőrinckáta	P5	2.59 ± 1.45	4.95 ± 2.59	0.60 ± 0.17
	P4	2.10 ± 0.27	8.11 ± 2.14	0.55 ± 0.36
	P3	0.75 ± 0.02	4.62 ± 1.69	0.43 ± 0.33
	P2	2.28 ± 1.00	4.13 ± 0.96	0.81 ± 0.16
	P1	1.58 ± 0.49	4.69 ± 2.09	0.66 ± 0.00
	W1	1.28 ± 0.73^{B}	3.44 ± 0.71^{B}	0.00 ± 0.00
	W2	1.24 ± 0.64^{B}	6.34 ± 2.54^{aB}	1.10 ± 0.45
	W3	2.19 ± 1.05^{B}	4.42 ± 1.48^{AB}	1.08 ± 0.15
	W4	0.74 ± 0.08^{B}	5.17 ± 0.79^{A}	1.76 ± 1.37
	W5	2.05 ± 1.08^{B}	4.24 ± 0.93^{A}	1.93 ± 0.62

Appendix table 4. Mean and Std. deviation and post hoc for total fruit numbers in (2022, 2023, 2024).

Variety	Distances	Total of the tomato fruit numbers (2022, 2023, and 2024).		
		2022	2023	2024
Roma	P5	6.88 ± 3.76	62.13 ± 32.96	2.00 ± 0.00
	P4	37.33 ± 35.76	63.13 ± 11.85	3.00 ± 2.83
	P3	16.00 ± 12.31	61.63 ± 22.19	3.33 ± 1.53
	P2	14.00 ± 16.61	51.25 ± 17.47	2.00 ± 1.41
	P1	27.00 ± 21.19	44.88 ± 19.79	2.00 ± 1.41
	W1	43.43 ± 37.80	39.00 ± 9.20^{b}	4.33 ± 1.53^{b}
	W2	44.00 ± 48.69	49.50 ± 14.26^{B}	6.38 ± 2.33^{B}
	W3	7.13 ± 9.34	46.50 ± 14.18^{aB}	17.13 ± 7.70^{aB}
	W4	38.83 ± 33.46	66.50 ± 18.23^{AB}	10.00 ± 4.87^{AB}
	W5	111.00 ± 133.01	56.13 ± 11.05^{A}	12.40 ± 7.30^{A}
Ace55	P5	15.13 ± 17.32^{B}	17.88 ± 6.33	9.00
	P4	6.20 ± 6.98^{B}	17.50 ± 8.09	3.00 ± 1.63
	P3	79.88 ± 54.33^{aB}	18.50 ± 9.01	9.00
	P2	15.50 ± 14.22^{aB}	15.13 ± 4.22	4.33 ± 1.53
	P1	2.25 ± 1.50^{A}	12.88 ± 6.60	2.67 ± 1.53
	W1	42.75 ± 20.02	10.38 ± 4.72^{A}	3.75 ± 0.96
	W2	1.50 ± 0.71	11.50 ± 2.98^{A}	10.88 ± 3.31
	W3	56.00 ± 63.77	16.13 ± 5.67^{A}	7.43 ± 4.96
	W4	22.50 ± 14.30	17.13 ± 6.51^{A}	6.75 ± 3.01
	W5	3.33 ± 0.58	11.75 ± 3.69^{A}	8.25 ± 5.68

Szentlőrinckáta	P5	36.13 ± 24.08^{B}	58.63 ± 20.65	4.33 ± 4.93
	P4	25.50 ± 8.19^{aB}	78.13 ± 21.57	3.33 ± 1.53
	P3	1.33 ± 0.58^{A}	66.00 ± 28.66	4.00 ± 1.41
	P2	44.88 ± 31.26^{A}	68.13 ± 13.62	3.50 ± 2.12
	P1	15.33 ± 9.52^{A}	59.75 ± 27.68	1.00
	W1	3.33 ± 3.21^{B}	44.38 ± 18.52^{b}	0
	W2	14.13 ± 13.85^{B}	88.88 ± 25.32^{B}	7.75 ± 2.75
	W3	66.75 ± 41.72^{A}	48.63 ± 26.73^{B}	4.00 ± 0.00
	W4	3.25 ± 1.71^{A}	58.00 ± 15.50^{Ab}	7.83 ± 5.60
	W5	58.25 ± 27.99^{A}	51.13 ± 21.98^{A}	5.50 ± 0.71

Appendix table 5**.** Mean and Std. deviation and post hoc for Chroma (C*) in (2023–2024).

Variety	Distances	Chroma (C*) year (2023)		Chroma (CYear (2024)	
		First harvest	Second harvest	First harvest	Second harvest
	P5	37.69 ± 0.07^{cb}	32.74 ± 0.03^{Ab}	20.30 ± 0.04^{Aa}	0
	P4	32.79 ± 1.79^{Aab}	33.00 ± 0.20^{Ab}	20.31 ± 0.14^{Aa}	32.73 ± 0.11^{B}
Roma	P3	31.88 ± 2.96^{ABab}	31.27 ± 0.06^{Aa}	34.01 ± 2.55^{Bb}	32.17 ± 0.44^{A}
	P2	33.90 ± 0.04^{Bab}	36.20 ± 0.07^{Bc}	38.11 ± 0.70^{cb}	31.80 ± 0.37^{B}
	P1	35.46 ± 2.19^{ABa}	33.13 ± 0.01^{Ab}	0	0
	W1	37.99 ± 0.05^{Bb}	35.63 ± 1.64^{ABabcd}	30.91 ± 0.34^{Ad}	38.22 ± 0.06^{b}
	W2	38.18 ± 0.20^{Abc}*	33.99 ± 0.07^{Ab}	20.71 ± 0.23^{Aa}	38.01 ± 0.02^{b}
	W3	33.47 ± 0.02^{Ba}	37.79 ± 0.06^{cd}	32.73 ± 0.13^{Be}	37.18 ± 0.04^{a}
	W4	38.40 ± 0.08^{cc}*	33.60 ± 0.05^{Aa}	28.01 ± 0.08^{cb}	38.91 ± 0.05^{Bc}
	W5	35.48 ± 2.53^{Aabc}	35.60 ± 0.05^{Bc}	28.55 ± 0.09^{Bc}	36.09 ± 0.42^{Aa}
Ace55	P5	37.69 ± 0.07^{cb}	33.38 ± 0.04^{Bb}*	27.36 ± 0.06^{cd}	36.09 ± 0.42^{a}
	P4	32.79 ± 1.79^{Aab}	34.92 ± 0.03^{Bc}	26.93 ± 0.09^{Bc}*	38.79 ± 0.05^{cc}*
	P3	31.88 ± 2.96^{ABab}	35.61 ± 2.16^{ABabc}	26.87 ± 0.28^{ABcd}*	36.92 ± 0.03^{Bb}
	P2	33.90 ± 0.04^{Bab}	32.67 ± 0.09^{Aa}	23.76 ± 0.11^{Aa}*	34.76 ± 0.15^{ca}
	P1	35.46 ± 2.19^{ABa}	33.48 ± 1.78^{ABab}	25.25 ± 0.16^{b}	35.13 ± 1.19^{abc}
	W1	37.99 ± 0.05^{Bb}	31.24 ± 0.05^{Ab}	33.73 ± 0.54^{Bc}*	0
	W2	38.18 ± 0.20^{Abc}*	36.03 ± 1.55^{ABbc}*	21.30 ± 0.14^{Aa}	0
	W3	33.47 ± 0.02^{Ba}	32.93 ± 0.04^{Ac}	25.50 ± 0.48^{Ab}	0
	W4	38.40 ± 0.08^{cc}*	34.00 ± 0.66^{Abc}	21.12 ± 0.20^{Ba}	24.69 ± 0.23^{A}
	W5	35.48 ± 2.53^{Aabc}	29.03 ± 0.27	35.12 ± 0.47^{cc}*	35.86 ± 0.09^{A}
Szentlőrinckáta	P5	37.69 ± 0.07^{cb}	36.44 ± 0.84^{cabcd}	21.82 ± 0.12^{Ba}*	36.49 ± 0.13^{c}
	P4	32.79 ± 1.79^{Aab}	36.40 ± 0.06^{cb}*	22.10 ± 1.47^{ABabc}	28.26 ± 0.38^{Ab}
	P3	31.88 ± 2.96^{ABab}	39.39 ± 0.05^{Bd}*	25.92 ± 0.08^{Ab}	36.59 ± 0.48^{Bc}*
	P2	33.90 ± 0.04^{Bab}	33.05 ± 0.15^{Aa}	27.04 ± 0.03^{Bc}*	24.68 ± 0.18^{Aa}
	P1	35.46 ± 2.19^{ABa}	36.92 ± 0.02^{Bc}*	24.07 ± 0.13^{c}	0
	W1	37.99 ± 0.05^{Bb}	35.53 ± 0.12^{Ba}	34.38 ± 1.00^{Bb}*	0
	W2	38.18 ± 0.20^{Abc}*	36.68 ± 0.14^{Bb}*	18.83 ± 0.56^{Ba}	35.83 ± 0.01
	W3	33.47 ± 0.02^{Ba}	35.33 ± 0.05^{Ba}	33.47 ± 0.28^{Bb}*	30.41 ± 0.19^{a}
	W4	38.40 ± 0.08^{cc}*	36.23 ± 0.05^{Bb}	20.20 ± 0.06^{Aa}	39.44 ± 0.06^{cd}*
	W5	35.48 ± 2.53^{Aabc}	38.33 ± 3.28	20.09 ± 0.25^{Aa}	37.65 ± 0.14^{Bc}*

Appendix table 6**.** Mean and Std. deviation and post hoc for Hue (h°) in (2023–2024).

Variety	Distances	Hue (h°) **Year of (2023)**		Hue (h°) **Year of (2024)**	
		First harvest	Second harvest	First harvest	Second harvest
	P5	38.58 ± 0.16^{Aa}	38.76 ± 0.13^{Aa}	48.17 ± 0.22^{cc}	0
	P4	49.37 ± 3.82^{ABab}*	43.02 ± 0.25^{Bc}	46.44 ± 0.04^{Bb}	34.00 ± 0.03^{Ba}

Roma	P3	49.67 ± 3.86^{ABab}*	41.71 ± 0.20^{Bb}	40.18 ± 2.88^{Babc}	33.64 ± 0.75^{Aa}
	P2	51.27 ± 0.10^{Ab}*	45.80 ± 0.04^{cdistcomp}	32.54 ± 0.70^{Aa}	33.75 ± 0.47^{Aa}
	P1	47.27 ± 3.02^{Aab}	39.95 ± 0.50^{Aab}	0	0
	W1	44.35 ± 0.02^{Ac}	45.06 ± 2.47^{ABabcd}	38.03 ± 0.58^{Babc}	37.48 ± 0.13^{c}
	W2	41.29 ± 2.60^{Aabc}	39.80 ± 0.15^{Bc}	35.35 ± 0.15^{Aa}	30.44 ± 0.10^{a}
	W3	43.25 ± 0.03^{Ab}	35.99 ± 0.13^{Aa}	39.09 ± 0.32^{Ac}	33.74 ± 0.09^{b}
	W4	41.01 ± 0.09^{Ba}	41.33 ± 0.02^{Bd}	36.94 ± 0.16^{Ab}	38.71 ± 0.07^{Bd}
	W5	42.31 ± 1.14^{Aabc}*	37.12 ± 0.05^{Ab}	35.97 ± 0.03^{Ba}	39.77 ± 0.56^{cd}
Ace55	P5	38.58 ± 0.16^{Aa}	42.79 ± 0.21^{Ba}	34.45 ± 0.21^{Ac}	39.77 ± 0.56^{c}*
	P4	49.37 ± 3.82^{ABab}*	42.66 ± 0.16^{Ba}	32.41 ± 0.06^{Ab}	33.46 ± 0.10^{Aa}*
	P3	49.67 ± 3.86^{ABab}*	41.95 ± 3.16^{ABa}	28.57 ± 0.19^{Aa}	32.60 ± 0.05^{Aa}
	P2	51.27 ± 0.10^{Ab}*	43.21 ± 0.14^{Ba}	34.74 ± 0.05^{ABc}	36.84 ± 0.17^{Bb}
	P1	47.27 ± 3.02^{Aab}	46.06 ± 2.71^{Aa}	32.64 ± 0.14^{b}	32.58 ± 0.97^{a}
	W1	44.35 ± 0.02^{Ac}	52.33 ± 0.31^{Bc}*	32.77 ± 1.22^{Aa}	0
	W2	41.29 ± 2.60^{Aabc}	42.08 ± 2.80^{ABabc}	43.65 ± 0.11^{Bb}*	0
	W3	43.25 ± 0.03^{Ab}	45.51 ± 0.06^{cb}	53.06 ± 0.30^{cd}*	0
	W4	41.01 ± 0.09^{Ba}	43.70 ± 1.29^{Bab}	46.74 ± 0.21^{cc}*	30.39 ± 0.31^{Aa}
	W5	42.31 ± 1.14^{Aabc}*	42.33 ± 0.27^{Ba}	35.49 ± 0.48^{ABa}*	32.05 ± 0.13^{Aa}
Szentlőrinckáta	P5	38.58 ± 0.16^{Aa}	39.78 ± 1.24^{ABabcd}	37.88 ± 0.07^{Bb}*	35.64 ± 0.23^{a}*
	P4	49.37 ± 3.82^{ABab}*	41.86 ± 0.12^{Ac}*	40.89 ± 3.35^{ABabcd}	39.60 ± 0.61^{cb}*
	P3	49.67 ± 3.86^{ABab}*	39.91 ± 0.12^{Aa}*	35.32 ± 0.25^{Ba}	37.81 ± 0.50^{Bb}*
	P2	51.27 ± 0.10^{Ab}*	42.43 ± 0.17^{Ad}*	50.18 ± 0.20^{Bd}*	51.47 ± 1.25
	P1	47.27 ± 3.02^{Aab}	40.56 ± 0.04^{Ab}	55.19 ± 0.26^{c}*	0
	W1	44.35 ± 0.02^{Ac}	40.39 ± 0.22^{Ad}	36.49 ± 0.06^{ABb}	0
	W2	41.29 ± 2.60^{Aabc}	37.59 ± 0.06^{Ab}	49.71 ± 0.03^{ce}	36.88 ± 0.11^{d}
	W3	43.25 ± 0.03^{Ab}	38.22 ± 0.14^{Bc}	42.97 ± 0.30^{Bd}*	36.00 ± 0.22^{c}
	W4	41.01 ± 0.09^{Ba}	36.05 ± 0.17^{Aa}	41.16 ± 0.04^{Bc}	30.28 ± 0.05^{Aa}
	W5	42.31 ± 1.14^{Aabc}*	38.90 ± 5.29^{ABabcd}	34.26 ± 0.43^{Aa}	33.62 ± 0.13^{Bb}

Appendix Table 7**.** Mean and Std. deviation and post hoc for Total Soluble Solids TSS in (2023–2024).

Variety	Distances	TSS Year (2023)		TSS Year (2024)	
		First harvest	Second harvest	First harvest	Second harvest
Roma	P5	5.17 ± 0.06^{Bc}*	4.37 ± 0.06^{Aab}	5.77 ± 0.12^{a}	0
	P4	4.57 ± 0.06^{Ab}	4.47 ± 0.06^{Bb}	5.80 ± 0.00^{a}	6.50 ± 0.26^{B}
	P3	4.33 ± 0.06^{Aa}	4.23 ± 0.06^{Aa}	6.80 ± 0.10^{Bb}	6.10 ± 0.20
	P2	4.50 ± 0.10^{Aab}	4.53 ± 0.06^{Bb}	5.83 ± 0.06^{a}	5.93 ± 0.06
	P1	4.40 ± 0.10^{Aab}	4.67 ± 0.06^{Bb}	0	0
	W1	4.47 ± 0.06^{Aa}	4.37 ± 0.12^{Aa}	5.73 ± 0.06^{Ac}	6.80 ± 0.56
	W2	4.63 ± 0.06^{Aab}	4.57 ± 0.06^{Aa}	4.63 ± 0.06^{Aa}	6.37 ± 0.29
	W3	4.93 ± 0.12^{Ab}*	4.43 ± 0.06^{Aa}	5.53 ± 0.06^{bc}	5.33 ± 0.40
	W4	4.47 ± 0.12^{Aa}	4.37 ± 0.06^{Aa}	5.50 ± 0.00^{bc}	5.73 ± 0.06^{A}
	W5	4.50 ± 0.00^{Aab}	4.47 ± 0.06^{Aa}	5.20 ± 0.10^{Ab}	5.70 ± 0.10^{A}
Ace55	P5	5.17 ± 0.06^{Bc}*	4.83 ± 0.15^{Ba}	5.70 ± 0.00	5.67 ± 0.06
	P4	4.57 ± 0.06^{Ab}	4.70 ± 0.10^{Ba}	5.67 ± 0.06	5.73 ± 0.21^{A}
	P3	4.33 ± 0.06^{Aa}	4.70 ± 0.10^{ca}	5.60 ± 0.00^{A}	5.77 ± 0.12
	P2	4.50 ± 0.10^{Aab}	5.23 ± 0.21^{ca}	5.77 ± 0.12	5.63 ± 0.21
	P1	4.40 ± 0.10^{Aab}	5.00 ± 0.10^{ca}*	5.60 ± 0.00	5.90 ± 0.20
	W1	4.47 ± 0.06^{Aa}	4.20 ± 0.10^{Aa}	7.00 ± 0.00^{Bc}	0
	W2	4.63 ± 0.06^{Aab}	5.17 ± 0.21^{Ab}	6.70 ± 0.10^{cbc}*	0
	W3	4.93 ± 0.12^{Ab}*	5.30 ± 0.10^{Bb}*	5.80 ± 0.10^{a}	0
	W4	4.47 ± 0.12^{Aa}	5.27 ± 0.06^{Bb}*	5.97 ± 0.21^{ab}	6.43 ± 0.06
	W5	4.50 ± 0.00^{Aab}	5.20 ± 0.00^{Bb}	5.83 ± 0.06^{Ba}	6.20 ± 0.20^{AB}

Szentlőrinckáta	P5	5.17 ± 0.06^{Bc}*	5.47 ± 0.06^{cb}*	5.83 ± 0.06	6.67 ± 0.15^{b}*
	P4	4.57 ± 0.06^{Ab}	4.27 ± 0.06^{Aa}	5.63 ± 0.06	5.73 ± 0.06^{Aa}
	P3	4.33 ± 0.06^{Aa}	4.43 ± 0.06^{Ba}	5.80 ± 0.00^{A}	5.73 ± 0.15^{a}
	P2	4.50 ± 0.10^{Aab}	4.33 ± 0.06^{Aa}	6.17 ± 0.32	5.80 ± 0.10^{a}
	P1	4.40 ± 0.10^{Aab}	4.43 ± 0.06^{Aa}	5.73 ± 0.06*	0
	W1	4.47 ± 0.06^{Aa}	4.53 ± 0.15^{Aa}	6.10 ± 0.20^{A}	0
	W2	4.63 ± 0.06^{Aab}	4.63 ± 0.12^{Aa}*	5.70 ± 0.00^{B}	5.50 ± 0.00
	W3	4.93 ± 0.12^{Ab}*	4.60 ± 0.00^{Aa}*	5.63 ± 0.06	6.23 ± 0.40^{ab}
	W4	4.47 ± 0.12^{Aa}	4.47 ± 0.06^{Aa}*	5.70 ± 0.10	6.63 ± 0.12^{Bb}*
	W5	4.50 ± 0.00^{Aab}	4.53 ± 0.06^{Aa}	5.73 ± 0.06^{B}	6.37 ± 0.06^{Bb}

Appendix table 8**.** Mean and Std. deviation and post hoc for Titratable Acidity (TA) in (2023–2024).

Variety	Distances	(TA) Year (2023)		(TA) Year (2024)	
		First harvest	Second harvest	First harvest	Second harvest
Roma	P5	0.54 ± 0.06^{AB}	0.57 ± 0.06^{AB}	0.55 ± 0.08	0
	P4	0.53 ± 0.01	0.48 ± 0.05	0.58 ± 0.16	0.58 ± 0.08
	P3	0.49 ± 0.07	0.41 ± 0.01	0.59 ± 0.11	0.57 ± 0.07
	P2	0.43 ± 0.04	0.44 ± 0.02^{A}	0.70 ± 0.05	0.41 ± 0.13
	P1	0.49 ± 0.03	0.49 ± 0.06^{AB}	0	0
	W1	0.51 ± 0.02^{a}	0.40 ± 0.03^{a}	0.63 ± 0.03	0.60 ± 0.16
	W2	0.52 ± 0.05^{ab}	0.49 ± 0.05^{ABab}	0.47 ± 0.11	0.68 ± 0.04
	W3	0.54 ± 0.07^{ab}	0.53 ± 0.02^{Bb}	0.71 ± 0.05	0.68 ± 0.07
	W4	0.54 ± 0.04^{ABab}	0.42 ± 0.08^{ab}	0.67 ± 0.02	0.59 ± 0.11
	W5	0.62 ± 0.03^{Bb}	0.56 ± 0.06^{Bab}	0.58 ± 0.03	0.56 ± 0.12
Ace55	P5	0.54 ± 0.06^{AB}	0.61 ± 0.03^{Bb}*	0.55 ± 0.04	0.60 ± 0.05 ^{ab}
	P4	0.53 ± 0.01	0.49 ± 0.05^{ab}	0.54 ± 0.13*	0.57 ± 0.03 ^{b}
	P3	0.49 ± 0.07	0.58 ± 0.09^{ab}	0.70 ± 0.04	0.48 ± 0.06 ^{ab}
	P2	0.43 ± 0.04	0.52 ± 0.02^{Ba}*	0.56 ± 0.14	0.61 ± 0.02 ^{b}
	P1	0.49 ± 0.03	0.54 ± 0.03^{Bab}	0.57 ± 0.02	0.48 ± 0.02 ^{a}
	W1	0.51 ± 0.02^{a}	0.46 ± 0.06	0.56 ± 0.03	0
	W2	0.52 ± 0.05^{ab}	0.38 ± 0.02^{A}	0.54 ± 0.02	0
	W3	0.54 ± 0.07^{ab}	0.48 ± 0.06	0.58 ± 0.04	0
	W4	0.54 ± 0.04^{ABab}	0.48 ± 0.04	0.59 ± 0.06	0.94 ± 0.04
	W5	0.62 ± 0.03^{Bb}	0.40 ± 0.04^{A}	0.47 ± 0.11	0.69 ± 0.03
Szentlőrinckáta	P5	0.54 ± 0.06^{AB}	0.50 ± 0.04^{A}	0.48 ± 0.08	0.52 ± 0.03
	P4	0.53 ± 0.01	0.43 ± 0.03	0.44 ± 0.13	0.69 ± 0.14
	P3	0.49 ± 0.07	0.50 ± 0.05	0.38 ± 0.13	0.55 ± 0.10
	P2	0.43 ± 0.04	0.46 ± 0.06^{AB}	0.46 ± 0.12	0.60 ± 0.04
	P1	0.49 ± 0.03	0.40 ± 0.05^{A}	0.40 ± 0.09	0
	W1	0.51 ± 0.02^{a}	0.40 ± 0.01^{a}	0.54 ± 0.08	0
	W2	0.52 ± 0.05^{ab}	0.52 ± 0.01^{Bb}	0.39 ± 0.11	0.65 ± 0.22
	W3	0.54 ± 0.07^{ab}	0.45 ± 0.00	0.55 ± 0.11	0.75 ± 0.21
	W4	0.54 ± 0.04^{ABab}	0.41 ± 0.03^{ab}	0.59 ± 0.12	0.67 ± 0.14
	W5	0.62 ± 0.03^{Bb}	0.45 ± 0.02^{ABab}	0.47 ± 0.15	0.70 ± 0.14

Appendix table 9. Mean and Std. deviation and post hoc for Sugar Acid Ratio (SAR) in (2023–2024).

Varie	Distances	Sugar Acid Ratio (SAR), year (2023)		Sugar Acid Ratio (SAR), Year (2024)	
		First harvest	Second harvest	First harvest	Second harvest
	P5	8.83 ± 0.06^{AB}	7.73 ± 0.69^{Aa}	10.59 ± 1.84	0
Roma	P4	9.83 ± 1.03	9.43 ± 0.96^{ab}	10.57 ± 3.39	11.41 ± 2.00
	P3	9.21 ± 1.11	10.38 ± 0.38^{b}	11.69 ± 2.14	10.80 ± 1.06
	P2	9.11 ± 0.84^{AB}	10.28 ± 0.65^{b}	8.38 ± 0.69	15.33 ± 4.10
	P1	9.76 ± 0.84^{AB}	9.62 ± 1.15^{ab}	0	0
	W1	9.88 ± 1.21^{AB}	10.92 ± 1.08	9.17 ± 0.51^{A}	12.12 ± 4.28
	W2	9.56 ± 1.01	9.31 ± 1.07^{A}	10.32 ± 2.83	9.36 ± 0.82
	W3	8.87 ± 0.93^{A}	8.40 ± 0.47^{A}	7.79 ± 0.51^{A}	7.83 ± 0.75
	W4	7.68 ± 0.41^{A}	10.76 ± 2.32	8.20 ± 0.18	9.90 ± 2.01
	W5	9.85 ± 0.78^{B}	8.11 ± 0.94^{A}	8.94 ± 0.69	10.53 ± 2.43
Ace55	P5	13.73 ± 0.79^{B}*	7.94 ± 0.51^{Aa}	10.34 ± 0.76^{b}	9.47 ± 0.92 ^{ab}
	P4	12.04 ± 1.92	9.70 ± 1.14^{ab}	10.99 ± 3.09^{ab}	9.98 ± 0.44 ^{ab}*
	P3	11.83 ± 1.02	8.25 ± 1.28^{ab}	8.08 ± 0.49^{a}	12.18 ± 1.64 ^{ab}
	P2	12.71 ± 0.72^{B}	10.02 ± 0.14^{b}	10.67 ± 2.85^{ab}	9.26 ± 0.64 ^{a}
	P1	12.15 ± 0.18^{B}	9.24 ± 0.45^{ab}	9.91 ± 0.39^{ab}	12.40 ± 1.07 ^{b}
	W1	12.48 ± 1.10^{B}	9.34 ± 1.56	12.48 ± 0.68^{B}*	0
	W2	9.98 ± 0.28	13.66 ± 1.44^{B}*	12.51 ± 0.50	0
	W3	12.45 ± 1.15^{B}	11.19 ± 1.13	9.96 ± 0.65^{B}*	0
	W4	10.59 ± 0.36^{B}	10.98 ± 0.94	10.19 ± 1.20	6.84 ± 0.34
	W5	9.81 ± 0.82^{B}	13.04 ± 1.41^{B}*	12.78 ± 3.11	8.98 ± 0.06
Szentlőrinckáta	P5	9.69 ± 1.10^{A}	11.02 ± 0.83^{B}	12.28 ± 2.04	12.89 ± 0.89 ^{b}*
	P4	8.62 ± 0.21	9.92 ± 0.63	13.50 ± 3.52	8.51 ± 1.60 ^{ab}
	P3	9.05 ± 1.36	8.85 ± 0.90	16.35 ± 5.41	10.63 ± 1.54 ^{ab}
	P2	10.43 ± 0.95^{AB}	9.48 ± 1.28	14.29 ± 4.83	9.73 ± 0.64 ^{a}
	P1	8.92 ± 0.74^{A}	11.15 ± 1.19	14.77 ± 3.62	0
	W1	8.70 ± 0.41^{Ab}	11.28 ± 0.26	11.48 ± 1.19^{AB}	0
	W2	8.90 ± 0.72^{ab}	8.83 ± 0.20^{Aa}	15.52 ± 4.10	9.09 ± 2.66
	W3	9.33 ± 1.29^{ABab}	10.29 ± 0.06^{Bb}	10.49 ± 2.49^{AB}	8.89 ± 3.42
	W4	8.28 ± 0.65^{Aab}	10.84 ± 0.91^{ab}	9.86 ± 2.04	10.17 ± 2.29
	W5	7.26 ± 0.35^{Aa}	10.01 ± 0.51^{ABab}	13.29 ± 4.93	9.28 ± 1.85

Appendix Table 10**.** Mean and Std. deviation and post hoc for (FRAP) in (2023–2024).

Variety	Distances	FRAP Year (2023)		FRAP Year (2024)	
		First harvest	Second harvest	First harvest	Second harvest
	P5	9.64 ± 0.25^{Ba}	11.31 ± 1.17^{Aab}	7.62 ± 1.27^{AB}	0
	P4	10.65 ± 0.67^{cab}	10.05 ± 2.02^{ab}	6.81 ± 1.15	5.91 ± 0.81^{Aa}
Roma	P3	14.49 ± 0.21^{cc}	11.11 ± 1.65^{ABab}	6.73 ± 1.22	8.66 ± 1.08^{Ba}
	P2	11.99 ± 1.36^{abc}	15.43 ± 0.20^{Bb}	10.08 ± 1.88	15.31 ± 1.26^{Bb}
	P1	12.44 ± 0.72^{Bbc}	12.94 ± 0.09^{Aa}	0	0
	W1	19.89 ± 2.39^{Babc}*	19.64 ± 0.50^{Bb}	5.06 ± 0.47^{A}	6.11 ± 0.69^{b}
	W2	12.90 ± 1.51^{ABab}	18.70 ± 1.09^{b}	4.36 ± 0.79	3.22 ± 0.47^{Aa}
	W3	14.00 ± 0.74^{Bb}	15.91 ± 0.84^{Aab}	4.79 ± 0.95^{A}	3.10 ± 0.68^{Aa}
	W4	10.34 ± 0.46^{Aa}	14.25 ± 0.64^{Aa}	3.89 ± 0.28^{A}	3.23 ± 0.09^{Bab}
	W5	19.00 ± 0.73^{Bc}*	16.28 ± 0.17^{Bab}	4.38 ± 0.75^{A}	2.91 ± 0.59^{ABa}
Ace55	P5	9.64 ± 0.25^{Ba}	19.27 ± 1.66^{Bc}*	4.61 ± 0.98^{A}	5.31 ± 0.16^{Bb}*
	P4	10.65 ± 0.67^{cab}	11.16 ± 1.11^{ab}	4.04 ± 0.62	10.45 ± 1.17^{Bc}*
	P3	14.49 ± 0.21^{cc}	9.15 ± 0.40^{Aa}	4.46 ± 1.24	5.85 ± 1.28^{Aab}
	P2	11.99 ± 1.36^{abc}	12.28 ± 0.32^{Ab}	3.81 ± 0.09	3.61 ± 0.52^{Aab}

	P1	12.44 ± 0.72^{Bbc}	14.26 ± 1.44^{Ac}	3.81 ± 0.09^{A}	3.53 ± 0.41^{a}
	W1	19.89 ± 2.39^{Babc}*	17.80 ± 0.15^{Aa}*	4.35 ± 0.19^{Ab}*	0
	W2	12.90 ± 1.51^{ABab}	19.74 ± 2.04^{ab}*	4.66 ± 0.91^{ab}	0
	W3	14.00 ± 0.74^{Bb}	20.63 ± 0.66^{Bb}*	8.61 ± 0.70^{Bc}*	0
	W4	10.34 ± 0.46^{Aa}	16.63 ± 1.08^{ABa}*	3.43 ± 0.18^{Aa}	7.68 ± 0.34^{cb}
	W5	19.00 ± 0.73^{Bc}*	13.73 ± 2.10^{ABab}	8.76 ± 1.25^{Babc}*	3.70 ± 0.60
Szentlőrinckáta	P5	9.64 ± 0.25^{Ba}	11.87 ± 1.52^{Aab}	8.03 ± 0.40^{Bbc}	1.13 ± 0.15^{Aa}
	P4	10.65 ± 0.67^{cab}	11.73 ± 0.25^{ab}	3.80 ± 0.96^{a}	3.89 ± 0.28^{Ab}*
	P3	14.49 ± 0.21^{cc}	14.77 ± 0.81^{Bb}	6.81 ± 1.09^{abc}*	4.87 ± 0.78^{Aab}*
	P2	11.99 ± 1.36^{abc}	11.51 ± 0.50^{Aa}	5.94 ± 0.93^{ab}*	4.15 ± 0.31^{Ab}*
	P1	12.44 ± 0.72^{Bbc}	21.12 ± 0.72^{Bc}	13.48 ± 1.99^{Bc}	0
	W1	19.89 ± 2.39^{Babc}*	23.67 ± 1.73^{Bc}	10.91 ± 1.46^{Bb}	0
	W2	12.90 ± 1.51^{ABab}	18.78 ± 0.98^{bc}*	3.33 ± 0.33^{a}	2.59 ± 0.52^{A}
	W3	14.00 ± 0.74^{Bb}	16.78 ± 1.53^{ABab}	3.27 ± 0.59^{Aa}	3.09 ± 0.61^{A}
	W4	10.34 ± 0.46^{Aa}	16.88 ± 0.09^{Bbc}*	8.21 ± 0.45^{Bb}*	1.87 ± 0.30
	W5	19.00 ± 0.73^{Bc}*	13.67 ± 0.18^{Aa}	13.77 ± 1.81^{cb}*	1.66 ± 0.46^{A}

Appendix table 11**.** Mean and Std. deviation and post hoc for (TPC) in (2023–2024).

Variety	Distances	TPC, Year (2023)		TPC, Year (2024)	
		First harvest	Second harvest	First harvest	Second harvest
	P5	66.33 ± 9.87^{ab}	66.33 ± 9.87^{ab}	148.5 ± 15.26^{ab}	0
	P4	65.67 ± 0.76^{Ba}	65.67 ± 0.76^{Ba}	122.17 ± 9.12^{a}	135.50 ± 13.81^{b}
Roma	P3	78.00 ± 7.05^{ab}	78.00 ± 7.05^{ab}	116.83 ± 13.99^{Aab}	74.50 ± 8.26^{Aa}
	P2	84.83 ± 4.91^{a}	84.83 ± 4.91^{a}	150.33 ± 5.35^{Ab}	171.00 ± 21.78^{b}
	P1	106.50 ± 0.50^{Bb}	106.50 ± 0.50^{Bb}	0	0
	W1	105.67 ± 7.75^{b}	105.67 ± 7.75^{b}	222.33 ± 29.69^{Bbc}	135.33 ± 12.10^{ab}
	W2	72.83 ± 6.93^{a}	72.83 ± 6.93^{a}	65.17 ± 9.75^{a}	102.67 ± 3.82^{Ba}
	W3	86.50 ± 12.68^{ab}	86.50 ± 12.68^{ab}	100.67 ± 5.13^{Ab}	143.83 ± 9.50^{Bb}
	W4	71.00 ± 4.27^{a}	71.00 ± 4.27^{a}	244.17 ± 18.06^{Bc}	125.00 ± 11.69^{ABab}
	W5	110.67 ± 5.86^{Bb}*	110.67 ± 5.86^{Bb}*	144.0 ± 23.3^{ABab}	125.83 ± 15.22^{ab}
Ace55	P5	66.33 ± 9.87^{ab}	66.33 ± 9.87^{ab}	116.5 ± 13.53	133.67 ± 10.56^{Ba}*
	P4	65.67 ± 0.76^{Ba}	65.67 ± 0.76^{Ba}	120.0 ± 9.37*	173.00 ± 13.61^{ab}*
	P3	78.00 ± 7.05^{ab}	78.00 ± 7.05^{ab}	118.5 ± 7.7^{A}	141.00 ± 24.89^{ABab}
	P2	84.83 ± 4.91^{a}	84.83 ± 4.91^{a}	119.33 ± 16.07^{A}	131.33 ± 5.97^{a}
	P1	106.50 ± 0.50^{Bb}	106.50 ± 0.50^{Bb}	135.0 ± 9.34^{A}	188.33 ± 6.01^{b}
	W1	105.67 ± 7.75^{b}	105.67 ± 7.75^{b}	143.17 ± 3.18^{Bab}	0
	W2	72.83 ± 6.93^{a}	72.83 ± 6.93^{a}	89.33 ± 5.39^{a}	0
	W3	86.50 ± 12.68^{ab}	86.50 ± 12.68^{ab}	102.67 ± 15.77^{ABab}	0
	W4	71.00 ± 4.27^{a}	71.00 ± 4.27^{a}	79.67 ± 17.13^{Aa}	95.00 ± 11.26^{A}
	W5	110.67 ± 5.86^{Bb}*	110.67 ± 5.86^{Bb}*	145.33 ± 9.57^{b}*	97.50 ± 7.37
Szentlőrinckáta	P5	66.33 ± 9.87^{ab}	66.33 ± 9.87^{ab}	116.0 ± 5.29^{a}*	148.83 ± 6.03^{ab}*
	P4	65.67 ± 0.76^{Ba}	65.67 ± 0.76^{Ba}	111.17 ± 13.29^{ab}	166.67 ± 8.02^{b}
	P3	78.00 ± 7.05^{ab}	78.00 ± 7.05^{ab}	144.5 ± 5.77^{Bbc}	123.83 ± 13.38^{Ba}
	P2	84.83 ± 4.91^{a}	84.83 ± 4.91^{a}	192.5 ± 11.46^{Bc}*	132.33 ± 22.19^{ab}*
	P1	106.50 ± 0.50^{Bb}	106.50 ± 0.50^{Bb}	158.17 ± 9.45^{Bc}*	0
	W1	105.67 ± 7.75^{b}	105.67 ± 7.75^{b}	115.33 ± 8.52^{Ab}	0
	W2	72.83 ± 6.93^{a}	72.83 ± 6.93^{a}	117.0 ± 21.63^{ab}	75.83 ± 5.62^{Aa}
	W3	86.50 ± 12.68^{ab}	86.50 ± 12.68^{ab}	138.67 ± 9.8^{Bb}	111.50 ± 7.76
	W4	71.00 ± 4.27^{a}	71.00 ± 4.27^{a}	120.83 ± 4.73^{Bb}	151.67 ± 18.82^{b}
	W5	110.67 ± 5.86^{Bb}*	110.67 ± 5.86^{Bb}*	86.33 ± 5.48^{Aa}	98.67 ± 3.82^{b}