

THESIS OF PHD DISSERTATION

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**Institute of Horticultural Sciences
Ph.D. Dissertation**

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

by

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1. INTRODUCTION

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. Tomatoes are used in soup, paste, juice, and ketchup, and are a rich source of essential minerals. Tomatoes are a rich source of metabolites, including soluble solids, flavonoids, vitamins, and minerals, providing essential nutrients. 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. Climate change, with its associated hot waves and droughts, is responsible for over 40% of yield variation globally.

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. 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. 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. Hedgerow systems enhance soil quality and modify microclimatic conditions, influencing tomato yield and fruit quality. Hedgerow side and planting distance affect genotype-specific responses to thermal stress, nutrition, and productivity. Tomato genotypes differ in their resilience to pests, diseases, and environmental stress within hedgerow systems.

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, Szentlőrinc-káta). 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. MATERIALS AND METHODS

2.1 Study area, plant material and experimental design

This study was designed to evaluate how tomato genotype and distance from a hedgerow interact to shape microclimatic conditions and plant performance under organic farming systems. Conducted over three growing seasons (2022–2024) at the Soroksár Experimental Station, the experiment used a randomized block design with three tomato genotypes (Ace55, Roma, and the Hungarian landrace Szentlőrinc-káta) cultivated at five increasing distances on both the Windy and Protected sides of a species-rich hedgerow. This design allowed a detailed assessment of spatial microclimatic gradients and genotype-specific responses to hedgerow-mediated environmental modification.

2.2 Microclimatic condition (Protected and Windy Sides)

From 2022 to 2024, a field experiment was conducted under certified organic conditions to evaluate the effect of a hedgerow system on tomato nutritional quality through microclimate modification. Wind-exposed (W1–W5) and protected (P1–P5) zones were compared along a transect perpendicular to the hedgerow. Air temperature and relative humidity were recorded at 30-minute intervals using Voltcraft DL-121TH and DL-210TH data loggers to quantify the hedgerow's role in buffering climatic extremes.

2.3 Soil analysis measurements

Soil sampling was conducted from 2022 to 2024, producing 18 composite samples per hedgerow side (six per year). Samples were collected before transplanting and after harvest to assess baseline and seasonal soil changes. Each composite sample consisted of 20 subsamples from 0–20 cm depth, following EU guidelines. Sampling was performed at 5, 10, and 15 m, with a 7.5 m control, on both Windy and Protected sides. Soil physical, chemical, and biological properties were analyzed at the Soil Department Laboratory of the Hungarian University of Agriculture and Life Sciences to evaluate spatial and temporal soil variability

2.3.1 Soil Physical, Chemical, and Biological Analyses

Soil samples collected from Windy and Protected sides at multiple distances from the hedgerow over three consecutive years were analysed for physical, chemical, and biological properties. Soil moisture content was determined gravimetrically after oven-drying at 105 °C. Soil pH concentration was measured annually in soil water suspensions using a calibrated PH probe. Organic matter content and quality were assessed using the modified Tyurin method,

including fractionation into humic and fulvic acids. Available phosphorus was determined spectrophotometrically using the molybdenum blue method, while potassium was measured by flame photometry. Soil biological activity was evaluated through assays of phosphatase, β -glucosidase, and dehydrogenase activities, based on standard enzymatic methods, to characterize microbial activity and nutrient cycling.

2.4 SPAD-502 plus chlorophyll content measurement

Leaf chlorophyll content was measured non-destructively during 2022, 2023, and 2024 using a SPAD-502 Plus meter at flowering and fruit development stages. Measurements were taken on 3–5 representative plants per plot, using fully expanded leaves from the upper and middle canopy. Each reading was repeated three times per plot, and mean SPAD values were used for analysis.

2.5 Nutrient Content Measurements of Tomato Plant Leaves

Tomato leaves were sampled from healthy, fully developed plants for chlorophyll and NPK analyses. Leaf samples were transported under cooled conditions and prepared by grinding, followed by acetone extraction. Total chlorophyll and chlorophyll a and b were determined spectrophotometrically using standard absorbance readings. Nitrogen content was measured using the Kjeldahl method, phosphorus by molybdenum–antimony spectrophotometry, and potassium by flame atomic absorption spectrophotometry, with concentrations calculated using established calibration-based equations.

2.6 Harvesting and yield parameters measurements

Tomato yield performance was evaluated over three growing seasons (2022, 2023, and 2024) at the Soroksár Experimental and Research Station. Fruits were harvested at breaker, pink, and red-ripe stages, with two main harvest periods each season (early July–mid August and late August–early September). Yield was assessed per plant and per plot across five planting distances on both Windy and Protected sides of the hedgerow. Only healthy red-ripe fruits were included in statistical analyses, with fruit number, fruit weight, and equatorial diameter measured using precision scales and calipers to characterize yield and physical attributes.

2.6.1 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 and 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.

2.7 Tomato fruit quality traits measurement and sample preparation

Ripe tomato fruits were collected at the Soroksár Organic Experimental Farm and transported to the laboratory for nutritional and chemical analyses. During 2023 and 2024, 5–6 fruits per plot were sampled at two harvests from both Windy and Protected sides and across all distances and varieties. Fruits were washed, homogenized using the toss-and-chop method, blended into puree, and stored at $-18\text{ }^{\circ}\text{C}$ until analysis.

2.7.1 Determination of tomato fruit chroma (C^*) and hue angle (h°) TSS, TAC and SAR

Fruit quality was evaluated through colour, soluble solids, acidity, and sugar–acid ratio. Colour of fruit homogenates was measured using a tristimulus colorimeter, expressed as L^* , a^* , b^* values, with chroma (C^*) and hue angle (h°) calculated. Total soluble solids (TSS, $^{\circ}\text{Brix}$) were determined using a temperature-compensated refractometer, while titratable acidity (TA) was measured by titration with 0.1 N NaOH and expressed as % citric acid. The sugar–acid ratio (SAR) was calculated as the ratio of TSS to TA. All measurements were performed in triplicate to ensure accuracy.

2.7.2 Determination of ferric-reducing antioxidant power (FRAP)

The total antioxidant capacity was assessed using the FRAP assay. The FRAP reagent was prepared by combining sodium acetate buffer (300 mM, pH 3.6), ferric chloride (5.4 mg/mL), and TPTZ solution in a 10:1:1 ratio, then warmed to $37\text{ }^{\circ}\text{C}$ for 5 minutes. For analysis, 1500 μL of FRAP reagent was mixed with 50 μL of sample extract and 50 μL of distilled water, and the absorbance was recorded at 593 nm after 5 minutes. Measurements were performed in triplicate, and results were expressed as mg ascorbic acid equivalents (AAE) per 100 mg of sample.

2.7.3 Determination of total phenolic content (TPC)

Total polyphenols were measured using the colorimetric Folin–Ciocalteu method. The Folin reagent was diluted with water, sodium carbonate was prepared in aqueous solution, and gallic acid was used as the standard. Samples were mixed with Folin reagent and methanol–water (80:20) and incubated at $50\text{ }^{\circ}\text{C}$ for 5 minutes. Absorbance was measured at 750 nm against a blank, and all measurements were performed in triplicate. Results were expressed as mg gallic acid equivalents (GAE) per 100 g of sample.

3. RESULTS

3.1 Hedgerows microclimate 2022, 2023, and 2024.

Microclimatic monitoring conducted during the 2022–2024 growing seasons revealed a consistent hedgerow effect on air temperature, with clear differences between the Windy and Protected sides. Across all years, temperatures on the Protected side were consistently higher than those on the Windy side relative to the hedgerow reference, with mean deviations of +3.02 to +3.54 °C and +2.07 to +2.49 °C, respectively. Temperature increases on the Protected side intensified with distance from the hedgerow and remained evident up to 15 m, indicating effective thermal buffering, whereas the Windy side exhibited more moderate changes due to increased exposure. Seasonal trends were consistent, with lowest temperatures in May and highest in July–August, and the strongest spatial gradients observed at the outer sampling points.

Relative humidity (RH) exhibited an inverse pattern to temperature, with higher RH values on the cooler Windy side and lower values on the warmer Protected side. Using hedgerow RH as a reference, the Windy side consistently showed greater humidity retention across all years, with average deviations ranging from +5.97 to +7.44%, compared with +3.74 to +6.26% on the Protected side. Seasonally, RH was lowest in May and increased steadily toward September, when maximum values were recorded across both sides. The highest late-season RH occurred on the Windy side, while the Protected side remained comparatively drier. Overall, these patterns confirm the hedgerow's microclimatic role: the Protected side promotes warmer but drier conditions with distance from the hedge, whereas the Windy side maintains cooler and more stable humidity levels.

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

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, while protected (P) and windy (W) parcels exhibited lower values. Soil hydrogen content increased across all parcels from approximately 2.0% to 3.9–4.0% in 2023, indicating improved organic matter decomposition under hedgerow conditions. 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.

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 as shown in Figure 1, indicating enhanced nutrient retention at greater distances from the hedgerow. Soil moisture content showed spatial variation among parcels, with significant differences between protected and windy parcels detected only in the final year (2024). Glycosidase activity was highest at protected parcels, reaching 43.31 $\mu\text{mol/g/h}$ in 2023, reflecting enzymatic sensitivity to hedgerow conditions. 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.

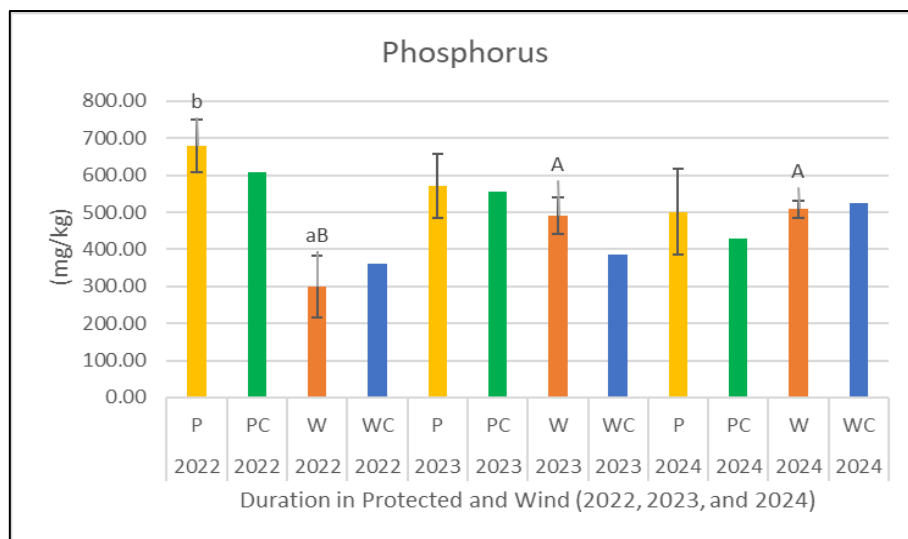


Figure 1. Soil chemical (phosphorus levels) (Mean \pm SD) Variations across parcels: P (Protected), PC (Protected Control), W (Windy), and WC (Windy Control) on the hedgerow sides for the years 2022, 2023, and 2024. Values represent annual treatment means, with error bars showing standard deviations. 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.

3.3 Nutritional quality parameters of tomato genotypes in a hedgerow System

Hedgerow technology influenced the physiological and nutritional attributes of three tomato genotypes Roma, Ace55, and Szentlőrinc-káta under open-field conditions on protected-side distances (P1, P3, P5) and windy-side distances (W1, W3, W5). Nutritional parameters, including nitrogen (N), phosphorus (P), potassium (K), chlorophyll A and B, and carotene, were analysed in relation to genotype, side, and distance from the hedgerow. The results showed significant variation in nutrient accumulation and pigment content across genotypes, sides, and distances.

The Roma genotype consistently exhibited the highest nutrient and pigment values, with nitrogen reaching 59.51 mg/100 g and potassium up to 26.33 mg/100 g, particularly at

outer distances. Roma also showed the highest pigment concentrations, with chlorophyll A and B peaking at 2106.98 mg/100 g and 1170.32 mg/100 g, respectively, on the windy side, while carotene reached maximum values at intermediate distances on both sides. In contrast, Szentlőrincskáta generally recorded lower chlorophyll levels, while phosphorus content peaked at protected-side outer distances. Significant differences were detected among genotypes and distances ($p < 0.05$), with protected-side positions favouring phosphorus and carotene accumulation and windy-side positions enhancing chlorophyll concentrations as shown in Figure 2. The findings indicate that hedgerow systems influence tomato nutritional quality and physiological performance, with responses strongly dependent on genotype and spatial position relative to the hedgerow.

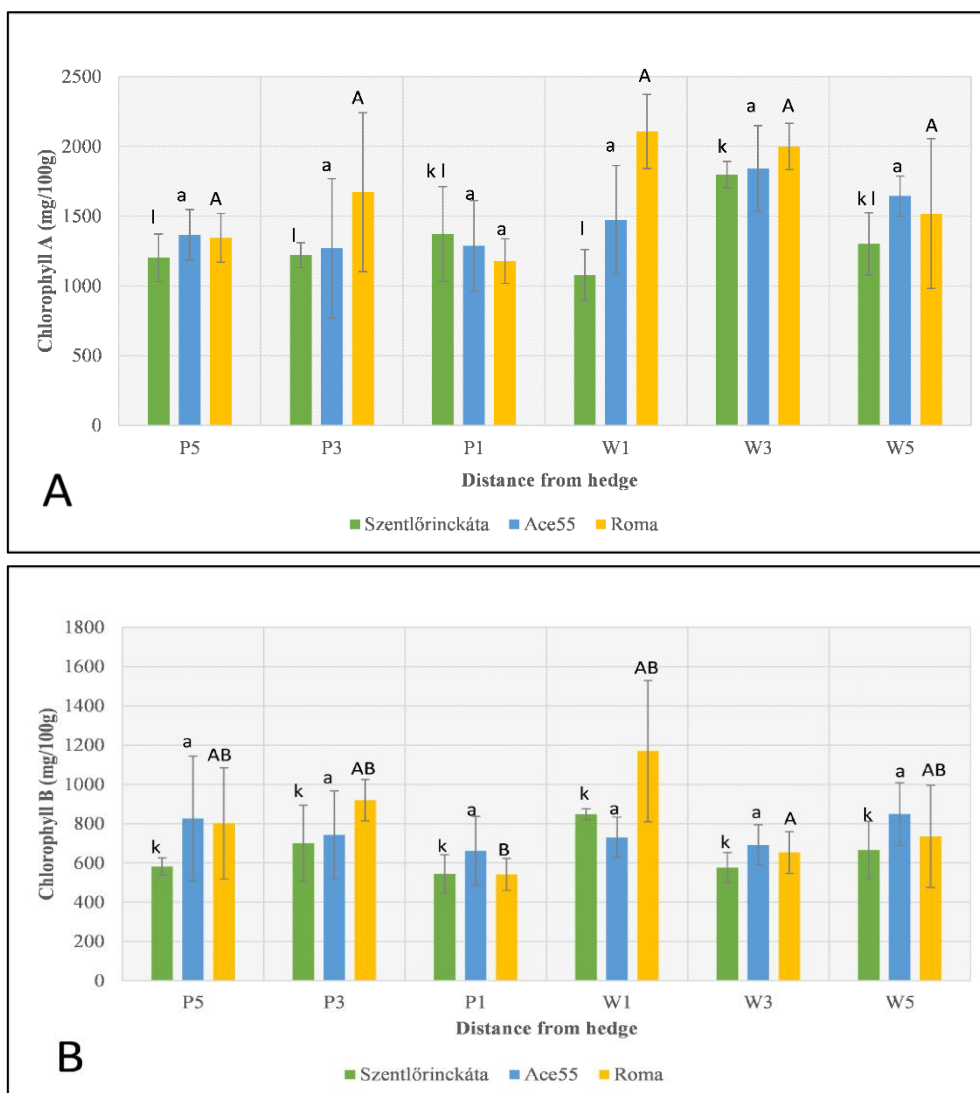


Figure 2 A and B. Chlorophyll A and B content (mean and SD) of tomato plant leaf samples produced on the protected and the windy side of a hedge, at three distances for each side in (2023). Ascending numbers mean higher distances from the hedgerow. Differing letters mean a significant difference ($p < 0.05$) among samples of the same variety (Mustafa, Szalai, et al., 2023).

3.4 Tomato fruit yield across hedgerow sides and distances

Tomato yield was significantly influenced by hedgerow orientation (windy versus protected sides), planting distance, and varietal response. The hedgerow system acted as a microclimatic regulator by modifying wind exposure, light availability, and temperature, thereby affecting fruit development. Roma and Szentlőrinc-káta consistently responded positively to windy-side conditions, particularly at outer distances (W3–W5), whereas Ace55 showed a clear preference for protected intermediate distances. In the first experimental year, Roma achieved its highest fruit number at W5 (111 fruits) with a corresponding yield of 2.81 kg. Szentlőrinc-káta also performed well on the windy side, producing 66.75 fruits and 2.19 kg at W3, while maintaining adaptability on the protected side with 2.59 kg at P5. Ace55 showed optimal performance at P3, with 79.88 fruits and 2.94 kg, indicating sensitivity to wind exposure and a preference for buffered conditions. During the second year, Roma recorded its highest fruit weight at W4 (5.98 kg) and W3 (5.13 kg), while Szentlőrinc-káta achieved its highest yield at W2 (8.11 kg), followed by W3 (6.34 kg). Ace55 remained low-yielding, with its best fruit number at P3 (18.50 fruits) and highest fruit weight at W4 (0.62 kg). The productivity peaked in the second year, likely reflecting favourable growing conditions and optimal microclimatic balance, as presented in Figure 3.

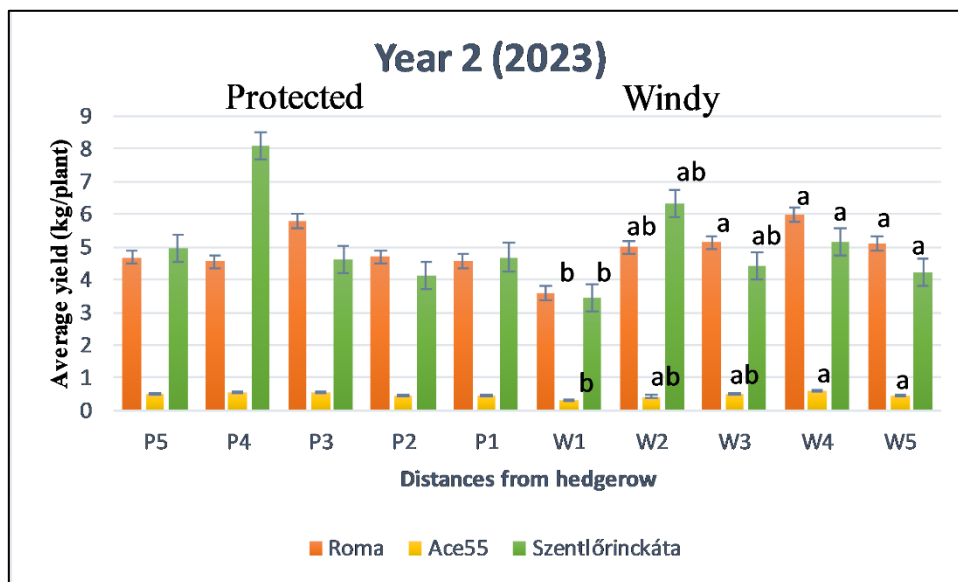


Figure 3. Tomato average yield results (mean \pm SD) from the second year (2023). Interaction plots show the effects of distance from a hedgerow (W1–W5: Windy side; P1–P5: Protected side) in Soroksár, Hungary. Differing letters denote significant differences between values within side, harvest and variety ($p < 0.05$)

In the third year, yield declined across all varieties, likely due to cumulative environmental stress and elevated temperatures. Roma continued to perform best at W3 and W5, while Szentlőrinc-káta maintained moderate yields at W2 and W4. Ace55 again showed a

single high-yield response at P3, reinforcing its preference for protected intermediate spacing, as shown in Figure 4. Fruit numbers decreased substantially across all genotypes in the final year. The results demonstrate that hedgerow systems exert a strong influence on tomato yield components, with windy-side exposure benefiting wind-tolerant varieties and protected-side conditions favouring more sensitive genotypes. The consistent varietal responses across years highlight the importance of aligning planting layout and cultivar selection with hedgerow-induced microclimatic gradients to optimize yield and system resilience.

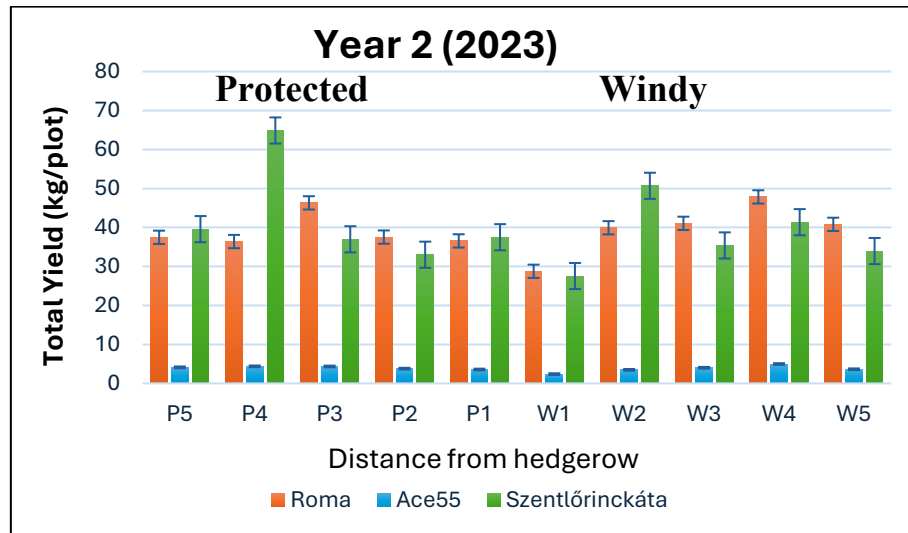


Figure 4. Tomato total fruit yield (kg/plot) results (mean \pm SD) from the second year (2023), summarized by plots within varieties and distances. Interaction plots show the effects of distance from a hedgerow (W1–W5: Windy side; P1–P5: Protected side) in Soroksár, Hungary.

3.5 Tomato fruit quality traits: soluble solids, acidity, color traits, and antioxidant profiles

The comparative performance of the tomato genotypes Roma, Ace55, and Szentlőrinc-káta across windy and protected hedgerow sides, multiple distances, and two harvest periods revealed strong genotype \times environment and temporal interactions affecting fruit quality traits, including color parameters (Chroma and hue), total soluble solids (TSS), and titratable acidity (TA).

3. 3.1 Chroma (C*) analysis and Hue (h°) analysis

Fruit colour characteristics were primarily genotype dependent, with high Chroma and stable hue values observed across both years, indicating well-developed pigmentation. Roma and Ace55 showed consistently saturated fruit colour, while Szentlőrinc-káta exhibited greater variability. No consistent effects of hedgerow side or distance on colour traits were detected, suggesting limited influence of hedgerow proximity on fruit coloration.

3.3.2 Total soluble solid (TSS, °Brix) Titratable acidity (TA) Sugar acid ratio (SAR)

TSS accumulation varied significantly among genotypes and years, with Ace55 generally exhibiting higher values, particularly under windy conditions. TSS levels were lower across all genotypes in the second year, although second harvests showed slight late-season increases. Roma and Szentlőrincáta displayed more moderate TSS responses, with improved performance at intermediate distances. Titratable acidity was highest in Roma, particularly under protected-side conditions, while Ace55 showed reduced acidity during later harvests. Szentlőrincáta exhibited moderate and more variable acidity responses. Tomato quality traits varied by genotype, harvest timing, and microclimatic exposure, particularly for sugar–acid ratio (SAR) and antioxidant capacity (FRAP). In 2024, Roma showed a balanced SAR under both protected and windy conditions, with the highest values recorded at intermediate and near-windy positions. Ace55 consistently benefited from second harvest timing, showing improved SAR between harvests, while Szentlőrincáta exhibited high potential but marked variability across positions.

3.3.3 Ferric reducing antioxidant power (FRAP)

Ferric reducing antioxidant power (FRAP) varied significantly among tomato genotypes, years, hedgerow sides, distances, and harvest times. Roma consistently exhibited higher FRAP values under Windy conditions across both years, with peak activity in 2024 at W4 (24.17 ± 18.06 mg AAE 100 g^{-1}), followed by elevated values at W5. On the Protected side, Roma showed lower but more stable FRAP levels across distances. Ace55 displayed a distinct late-season response, with FRAP values consistently increasing during second harvests. In 2024, Ace55 recorded a marked increase at P4, rising from 4.04 to 10.45 mg AAE 100 g^{-1} between harvests, with enhanced FRAP activity also observed at mid-distance windy positions. This pattern indicated strong genotype-specific responsiveness to environmental conditions. Szentlőrincáta showed pronounced inter-annual variability in FRAP. In 2023, higher antioxidant activity was recorded across several positions, whereas in 2024 FRAP values declined sharply, particularly at W5 during the second harvest, decreasing from 13.77 to 1.66 mg AAE 100 g^{-1} . Overall, FRAP values increased between years by approximately 2.1- to 2.8-fold across genotypes, with peak antioxidant accumulation shifting from near-hedge positions in 2023 to intermediate distances in 2024.

3.3.4 Total phenolic content (TPC)

Total phenolic content (TPC) varied significantly among genotypes, years, hedgerow sides, distances, and harvest times, as shown in Figure 5. In 2023, Roma recorded its highest TPC on the Windy side at W5 (144.00 ± 23.30 mg GAE 100 g^{-1}), while Ace55 reached a similar maximum at W5 (145.33 ± 9.57 mg GAE 100 g^{-1}). In contrast, W4 consistently showed lower TPC across genotypes, with Ace55 recording 79.67 ± 17.13 mg GAE 100 g^{-1} . Szentlőrincskáta exhibited the highest and most stable TPC values, peaking at P1 (158.17 ± 9.45 mg GAE 100 g^{-1}) in 2023. In 2024, TPC increased substantially across all genotypes. Ace55 showed a pronounced increase at P2, reaching 188.33 ± 6.01 mg GAE 100 g^{-1} , while Szentlőrincskáta recorded the highest overall values at P2 (192.50 ± 11.46 mg GAE 100 g^{-1}) and elevated levels at W3 (151.67 ± 18.82 mg GAE 100 g^{-1}). Across all genotypes and years, TPC consistently declined during second harvests, indicating reduced phenolic accumulation at harvest stages.

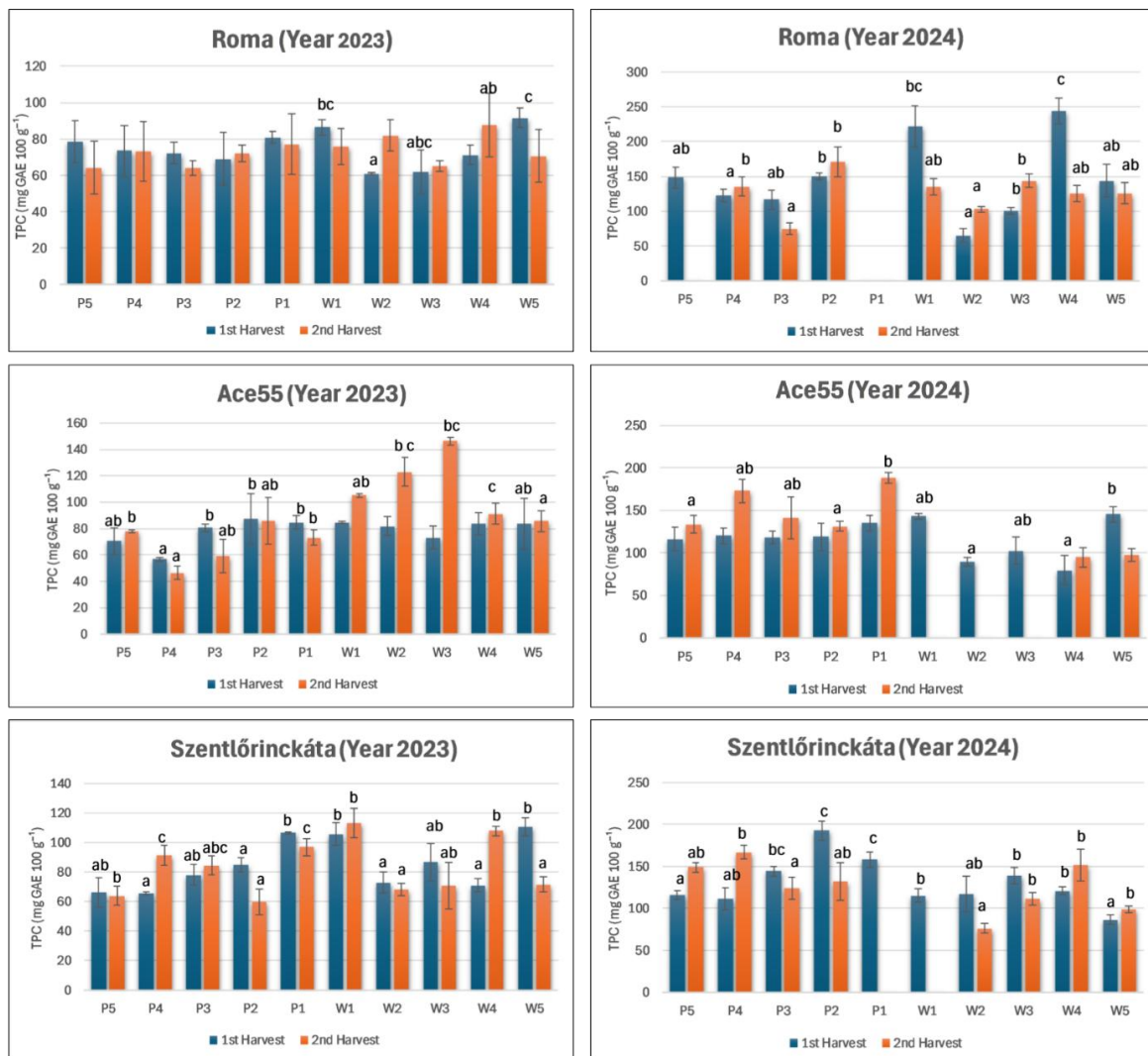


Figure 5. TPC, Analysis across hedgerow distances reveal significant variation between protected and windy sides in Soroksár, Hungary (2023 – 2024). Differing letters denote significant differences between values within side, harvest and variety ($p < 0.05$).

4. 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 Szentlőrinc-káta 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, hydrogen content, 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, Szentlőrinc-káta 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 Szentlőrinc-káta. 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 Szentlőrinc-káta 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 Szentlőrinc-káta 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.

5. 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. Szentlőrincákata 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 Szentlőrincákata.
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 Szentlőrincákata 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.

6. PUBLICATIONS AND CONFERENCE RELATED TO THE DESERTATION

Journal article publications

Mustafa, M., Mwangi, R.W., Szalai, Z., Kappel, N. and Csambalik, L., 2025. Sustainable responses to open field tomato (*Solanum lycopersicum* L.) stress impacts. *Journal of Agriculture and Food Research*, p.101825. <https://doi.org/10.1016/j.jafr.2025.101825>

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Mustafa, M., Szalai, Z.M. and Csambalik, L., 2023. Nutritional quality parameters of tomato genotypes in a hedgerow system. *Progress in Agricultural Engineering Sciences*, 19(S1), pp.113-122. <https://doi.org/10.1556/446.2023.00091>

Mustafa, M., Adjei, J.A., Menyhárt, L., Csambalik, L. and Szalai, Z., 2023, November. Pest and Disease Impact on Tomato Genotypes in a Hedgerow System. In *Biology and Life Sciences Forum* (Vol. 27, No. 1, p. 47). MDPI. <https://doi.org/10.3390/IECAG2023-15819>

Mustafa, M., Szalai, Z., Divéky-Ertsey, A., Gál, I. and Csambalik, L., 2022. Conceptualizing multiple stressors and their consequences in agroforestry systems. *Stresses*, 2(3). <https://doi.org/10.3390/stresses2030018>

Mustafa, M.; Szalai, Z.M.; Márta Ladányi; Mónika Máté.; Gergely Simon.; Gitta Ficzek.; György Végvári.; Csambalik, L.2026. Agroforestry Hedgerows Influence Tomato Fruit Quality Traits Including Soluble Solids, Acidity, and Antioxidant Profiles. *Horticulturae*, *Under Review (resubmission in progress)*.

Mustafa, M.; Zsolt Kotroczó.; Szalai, Z.M.; Márta Ladányi; Csambalik, L. 2026. Hedgerow Microclimates and Soil Health: Physical, Chemical, and Biological Properties. *Land*, *Under preparation (Authors invited)*.

Conferences abstract publications

Mustafa, M., Szalai, Zita Magdolna; Csambalik, László Orbán, The Role of Hedgerows in Enhancing Microclimate and Multifunctionality in Organic Tomato Cultivation (Oral Presentation), Sustainability and Resilience International Scientific Conference (SRISC), MATE Károly Róbert Campus, Gyöngyös, Hungary, April 10–11, 2025 ISBN: 978-963-623-118-7.

Mustafa, M., Szalai, Zita; Máté, Mónika; Pék, Zoltán; Csambalik, László, Distance from Hedges Slightly Influences the Antioxidant Status of Open Field Tomato Genotypes (Poster Presentation), XVII International Symposium on Processing Tomato – XV World Processing Tomato Congress, ISHS, Budapest, Hungary, 2024, Abstract No. 58, Symposium No. 796.

Mustafa, M., Szalai, Zita; Csambalik, László Orbán, Study of Microclimate Influencing Effect of Hedgerow in Organic Tomato Production System (Poster Presentation), EURAF 2024, Mendel University in Brno, Czech Republic, May 28–31, 2024, pp. 92–95 ISBN: 978-807509-982-2.

Mustafa, M., Szalai, Zita Magdolna; Csambalik, László Orbán, The Impact of Hedge Microclimate on the Qualitative and Quantitative Parameters of Different Tomato (*Solanum lycopersicum* L.) Genotypes (Oral Presentation), János Lippay – Imre Ormos – Károly Vas (LOV) Scientific Meeting, Hungarian University of Agriculture and Life Sciences, Buda Campus, Budapest, Hungary, Nov 16, 2023, p. 98 ISBN: 978-615-020-252-5.

Mustafa, M., Szalai, Zita Magdolna; Csambalik, László Orbán, Assessment of the Nutritional Parameters of Tomato (*Solanum lycopersicum* L.) Genotypes under Hedgerow Conditions, Preliminary Study (Poster Presentation), 5th International Conference on Biosystems and Food Engineering, Budapest, Hungary, Sept 6, 2023, Paper E548, 8 p. ISBN: 34007775.

Csambalik, László Orbán; **Mustafa, M.**; Szalai, Zita, Influence of Hedgerows on Microclimate Preliminary Studies (Poster Presentation), 18th International Scientific Days: The 'Green Deal' Challenges and Opportunities, MATE Károly Róbert Campus, Gyöngyös, Hungary, May 5–6, 2022, pp. 129–135 ISBN: 978-963-623-032-6.

Mustafa, M., Csambalik, László Orbán; Szalai, Zita Magdolna, Comparing Production Systems for Field Production of Germination, Vegetative, and Reproductive Growth Yield and Quality of Tomato (*Solanum lycopersicum* L.) Plants (Poster Presentation), LOV Scientific Session, Hungarian University of Agriculture and Life Sciences, Buda Campus, Budapest, Nov 29, 2021, ISBN 978-615-013-738-4.