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Original article

Effect of Soil-Applied Humic Amendment on Photosynthesis Rate and Lycopene Content of Tomato *Solanum lycopersicum* L. Seven Landraces, Involving Newly Characterised 'Zemplínsky'

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This research aimed to examine the effect of soil improvement based on leonardite on the intensity of photosynthesis and the lycopene content of tomatoes. Seven landraces of Hungarian and Slovakian origin were tested at two sites (Site-1, Site-2) under field conditions in the temperate continental climate of Central Europe. The treatments: (i) NPK nutrition (43.5:30:30 kg/ha NPK), and (ii) HUMAC Agro (HA), with the same nutrition and a soil-applied humic preparation from HUMAC Agro at a dose of 1,500.00 kg/ha. The lycopene content averaged 285.94 mg/kg and ranged from 6.18 to 658.54 mg/kg. The content was mainly influenced by the landraces (*F*-ratio 70,856.00, *P*-value 0.00), followed by the treatments (*F*-ratio 20,189.00, *P*-value 0.00), then by the sites (*F*-ratio 16,291.00, *P*-value 0.00), and finally by the replications (*F*-ratio 17.62, *P*-value 0.00). Lycopene orders, by: (i) landraces 'Cegléd' < 'Zemplínsky' < 'Máriapócs' < 'Fadd' < 'Tolna' ≤ 'Mátrafüredi' < 'Gyöngyös' (10.83 < 181.47 < 233.85 < 329.36 < 411.93 ≤ 413.293 < 420.85 mg/kg); (ii) treatments HA < NPK (254.96 < 316.92 mg/kg); and (iii) Site-2 < Site-1 (258.11 < 313.77 mg/kg). A phenomenon of harmonising effect of the humic amendment was observed, as the lycopene content changed from the extreme values to the medium values at both sites. Photosynthetic rate (PR) was monitored on Site-1 under two sequences: (i) TS (sequence temperature 20.3 – 41.7°C at constant FAR of 608 mmol/m^2/s) and (ii) LS (sequence light/photosynthetically active radiation, FAR 0 – 1,304.00 mmol/m^2/s at constant temperature 38.2°C). In both sequences, the higher PR was found in NPK (30.753 and 12.589 mmol/m^2/s; LS vs. TS) compared to HA (22.347 and 9.271 mmol/m^2/s). This indicates a climatic anti-stress effect of the humic treatment, which is probably related to the better-known effect of humic amendments on plant root improvement.

Key words: tomato, landraces, lycopene, photosynthesis intensity, leonardite activated

The tomato (*Solanum lycopersicum* L.) is one of the most widely produced and consumed vegetables in the world, with more than 4,000 registered cultivars in the European Union alone (FAO 2018; Plant Variety Database). The plant is considered one of the highest-yielding vegetables in the world due to its high content of vitamin C (75-300 μg/g FW fresh weight), minerals, and the particularly valuable lycopene (approx. 300 μg/g 65 FW) (Dorais *et al.* 2008).

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Lycopene, often referred to as α-carotene, is a bright red pigment carotenoid which is contained in tomatoes and fruits with a typical red colour. In terms of physiological role, lycopene works as an inhibitor that prevents external carcinogenesis (induced by viruses, pollution, radiation, and chemicals) with an antioxidant mechanism so that the oxidative stress that occurs does not cause cellular or genetic damage to DNA (Arnanda *et al.* 2019). Functionally, lycopene is an antioxidant that can neutralise free radicals, the damage of which is one of the main causes of human diseases such as heart disease, premature aging, cancer and cataracts (Setyorini 2021). Lycopene has been found throughout the fruit, but its highest concentration is found just under the skin of the fruit. It is the strongest known antioxidant of plant origin (Erdogan *et al.* 2024).

Recently, consumer demand for traditional tomato landraces, the landraces, has increased significantly due to their favourable organoleptic characteristics. However, in general, older or newly discovered wild tomato relatives are used for breeding resistance to biotic and abiotic stress factors in tomato crops, as confirmed by Koenig *et al.* (2013).

The shift from modern tomato landraces and hybrids to landraces can be observed in several places in the world, especially in the primary and secondary genetic centers of this crop and especially in organic farming (Cseperkálóné *et al.* 2015). The same need for the excellent original quality of the tomato also exists in other countries, especially in regions with traditional cultivation of this crop. In addition, the high adaptability to different climatic conditions and the nutritional properties of old cultivars and landraces are being rediscovered and are recognised to be valuable (Divéky *et al.* 2022). One of these regions is 'Zemplín' or 'Zemplén' county (Slovak and Hungarian), which even has its own tomato landrace with the folk name 'Zemplínsky'. This county is better known for its world-famous dessert wines (Tokaji aszú, mentioned in a document from 1571) produced in the historic wine region of 'Tokaj' in north-eastern Hungary and south-eastern Slovakia (with the world's first classified vineyard in 1772), the home of "Vinum Regum, Rex Vinorum", as a saying attributed to the French King Louis XIV (Balogh 2014; Hodúr *et al.* 2016; Brochot 2021).

Although 'Zemplínsky' is still cultivated in the central part of the county, albeit rarely to scattered by a few long-standing small farmers, this landrace is one of the forgotten ones, as it cannot be found in the seed collection of either the Slovak or the Hungarian gene bank. In contrast to numerous landraces collected in the aforementioned gene banks, which are historically typical of several counties in Hungary, making this country one of the known secondary genetic centers of tomato (Tóth 2023). Of the more than thirty tomato landraces tested in Hungary so far, 'Mátrafüredi' – 'Gyöngyös' – 'Fadd' – 'Máriapócs' – 'Tolna' and 'Cegléd' are currently considered the most proven (Cseperkálóné *et al.* 2015; Boziné -Pullai *et al.* 2021; Divéky *et al.* 2022). As demand is increasing, there is currently an obvious need to promote the dissemination and wider use of tomato landraces, while more in-depth scientific studies are mainly agronomic, genetic and pathogenic in nature. In order to understand the landraces as well as possible or to design the phytotechnical elements as appropriately as possible, knowledge of a physiological nature is also required. Since tomato landraces generally show moderate drought resistance (Maioli *et al*. 2023), they may benefit from humic treatment of the soil, whose ameliorative doses are suitable to promote root development as well as above-ground phytomass growth of the plants (Wilczewski *et al.* 2017; Symanowicz *et al.* 2023), which needs to be verified.

Also, Farinon *et al.* (2022) recently studied genotypes of traditional tomatoes, due to their high adaptation to the local environment. According to another recent study of Maffia *et al.* (2025), humic substances (HS), as multifunctional natural catalysts in sustainable agriculture, not only improve soil health but also increase plant productivity and environmental resilience. Unlike plant and microbial biomass, which undergo rapid mineralisation due to their active dynamics, humic substances exhibit significant resistance to biodegradation, resulting in an extended persistence time in the soil that can last for years or even centuries. In addition to their soil -improving properties, these substances positively affect microbial activities in the soil, which increase plant stress tolerance and improve yield. HS likely exhibits hormone-like properties that affect plant signalling pathways, thereby improving plant root architecture.

The study is aimed to examine the intensity of photosynthesis of the tomato landraces grown under favourable continental lowland climatic conditions in Central Europe. At the same time, the influence of humic amendment in the soil on the photosynthetic rate was investigated by in situ measurements.

MATERIAL AND METHODS

Landraces and Phytotechnics

Seven landraces of the tomato *Solanum lycopersicum* L. were tested in 2022 in a small-scale field trial in the Zemplin district under the temperate climatic conditions of the Eastern Slovakian Plain. The majority of the landraces are of Hungarian origin (‘Mátrafüredi’, ‘Gyöngyös’, ‘Fadd’, ‘Máriapócs’, ‘Tolna’, and ‘Cegléd’), and the rest is the recently rediscovered landrace ‘Zemplínsky’ of Slovakian origin. The seed of all Hungarian landraces was obtained from the Hungarian Research Institute of Organic Agriculture. The seed of the ‘Zemplínsky’ was obtained from a donor, a small grower near the town of Michalovce.

The seeds were sown on March 14, 2022, and planted on May 6, 2022 at 2 locations in the Eastern Slovakian Lowland (ESL) (Figure 1). The field trial was established at site 1 in the southern part of the ESL (100 m altitude, village Ágcsernyő) and at site 2 in the northern part of the lowlands (120 m altitude, town Michalovce). The sites are characterised by a semi-arid (Site-1) to semi-humid continental subclimate (Site-2). The experiment was conducted under irrigation conditions at both sites. Site-1 is in a hot region and offers ideal growing conditions for tomatoes under irrigation due to the optimal soil conditions (eutric fluvisol, medium soil with good nutrient content). Site-2 is in a semi-hot region, which, together with suitable soil conditions (fluvi-eutric Gleysol, heavy soil with good nutrient content) and irrigation, makes the site moderately suboptimal.

The main soil chemical properties was followed: total nitrogen content was determined by Kjeldahl method (Hrivňáková *et al.* 2011); ammoniacal nitrogen was determined by the Nessler technique, and nitrate nitrogen was determined by the colorimetric method; available P, K, Mg, and Ca were determined by Mehlich III method (Mehlich 1984); soil reaction in 1 mol/L KCl solution was determined using potentiometric method (ISO 10390 2005) (ISO 2005); soil organic carbon was determined by Tjurin method (ISO 14235 1998). The main chemical properties of the soil are shown in Tables 1 and 2, indicating the initial condition in spring 2022 (April) and the final condition (August) for the sites. The following two treatments were conducted: (i) NPK nutrition (43.5:30:30 kg/ha NPK), and (ii) HA, with the same nutrition and a soil-applied humic preparation HUMAC Agro (HA) at a dose of 1,500 kg/ha (Table 3).

From Samples to Extract Preparation and Lycopene Measurement

The tomato samples for lycopene content were collected continuously, in such a way that 12 ful-

Figure 1. The location of the trial sites (left), and measuring the photosynthesis (right).

ly ripened fruits were obtained for each landrace, which were collected from 4 plants per each of 28 trial members (7 landraces × 2 treatments × 2 sites). The number of 12 was obtained from the first two harvests, collected gradually from the middle of July to the beginning of August as the landraces matured. Other harvests were not used for lycopene analyses, nor was the total yield monitored. The slices of fruits were dried at a temperature of 35°C, to surely not degrade during the drying process (Fish *et al.* 2002; Mendelova *et al.* 2013). When the number of 12 fruits were completed, the average sample for analysis was prepared.

The samples of dried tomato fruits were ground with an electric grinder for homogenization. Always 1.0 g of the ground sample was used for extraction. The sample was placed in an Erlenmeyer flask with ground glass. For the extraction of lycopene, 25 mL of n-hexane (Sigma-Aldrich USA, Chromasolv for HPLC ≥ 97.0%) was used. The extraction reagent was added to the Erlenmeyer flask containing the tomato sample, the flask was sealed with a stopper

T a b l e 1

The average content of nutrients in the soil (layer 0 – 30 cm) initial state (spring 2022, before the trial establishment)

Locality	Nt [mg/kg]	P [mg/kg]	K [mg/kg]	Ca [mg/kg]	Mg [mg/kg]	pH/KCl	C-ox [%]	Humus [%]	C/N
Site-1	1,480.00 midle	314.80 very high	292.40 midle	3,793.00 high	271.70 high	7.29 neutral	1.235	2.128 midle	8.34
Site-2	1,570.00 midle	141.10 very high	279.20 midle	5,767.00 high	258.50 midle	7.27 neutral	1.613	2.780 midle	10.70

Note: Nt – total nitrogen. Nt evaluated with respect to the content of organic carbon, respectively C/N.

T a b l e 2

The average content of nutrients in the soil (layer 0 – 30 cm) final state (autumn 2022, after the end of the experiment)

Locality	Treatment	Nt [mg/kg]	P [mg/kg]	K [mg/kg]	Ca [mg/kg]	Mg [mg/kg]	pH/KCl	C-ox [%]	Humus [%]	C/N
Site-1	HA	1,570.00	320.9	267.0	3,685.00	238.4	7.16	1.265	2.180	8.06
	NPK	1,430.00	294.5	245.6	3,548.00	216.2	7.13	1.269	2.187	8.87
Site-2	HA	1,540.00	119.9	207.2	5,639.00	232.4	7.03	1.685	2.904	10.94
	NPK	1,430.00	294.5	245.6	5,548.00	216.2	7.13	1.269	2.761	10.97

Note: HA – HUMAC Agro; Nt – see Table 1.

T a b l e 3

The dosage of mineral fertilisers N and NPK (PK in oxide form), and humic preparation HUMAC Agro, in kg/ha (by treatments)

Treatment	N (N content 27%)	NPK (nutrient content ratio 15:15:15%)	HUMAC Agro (content 62% of humic acids)
HA	50 (13.50 kg/ha N)	200 (30:30:30 kg/ha NPK)	1,500 (40.00 g per plant)
NPK	50 (13.50 kg/ha N)	200 (30:30:30 kg/ha NPK)	0

Note: HA – see Table 2.

and wrapped with an aluminium foil. The extraction was carried out for 90 minutes by shaking on a shaker (IKA HS 260 Basic) at a speed of 150 vibrations per minute.

After extraction, the samples were filtered into dark volumetric flasks (filter KA1-M very fast). Each extract was then made up to the exact volume of 25 mL with n-hexane (approx. 1 mL per sample). The vials were sealed and immediately stored in the refrigerator until measurement.

Spectrophotometric Measurement

The absorbance of the samples was measured in a quartz cuvette with a path length of 1 cm at 503 nm in comparison to a hexane blank solution (Shimadzu UV-1800). The lycopene content of the samples was then calculated using the formula (Zechmeister *et al.* 1943; Fish *et al.* 2002) with the molar extinction coefficient of 17.2×10^{-4}/M/cm for lycopene in hexane

Lycopene (mg/100 g) = $A_{503}/(17.2 \times 10^{-4} \times d)$,

or $$\text{Lycopene} \left(\frac{mg}{100\,g}\right) = \frac{A_{503}}{17.2 \times 10^{-4} \times d}$$

where: A_{503} is the absorbance at 503 nm; 17.2×10^{-4} is the molar extinction coefficient; d is the cell thickness of 1.0 cm

Photosynthesis Measurement

The intensity of photosynthesis of tomato landraces was measured in situ on 28 and 29 June 2022 using the LCPro-SD instrument equipped with a sealable climate chamber for non-destructive testing of leaves under controlled conditions, at the phenophase of full flowering (BBCH 69). For each landrace per treatment, the fully vegetating leaf (the third leaf under the flag) was measured, and the measured leaf area was 6.25 cm^2 (2.5 cm × 2.5 cm). Each leaf was measured for a duration of 72 minutes, following a sequence of 24 three-minute steps with a gradual change in (i) photosynthetically active light (FAR) intensity at a stable temperature and (ii) then temperature at a constant FAR intensity. An overview of the controlled main accompanying parameters of the tested temperature and light sequence range is part of the evaluation (Table 9 and Figures 9 and 10).

Statistical Methods

The data on lycopene content were analysed using multifactorial ANOVA, and then Fisher's post-hoc test was performed to calculate the least significant difference for the levels of the main study, while the Statgrafics 15.2.14 program was applied.

The study evaluates a further set of 5,152 original data, of which exactly one quarter is in terms of photosynthetic rate (1,288), while the remainder is in terms of the accompanying data of (i) temperature, (ii) photosynthetically active radiation intensity and (iii) CO_2 concentration. A primary method for these data analyses is the second-order polynomial function. The dependence of photosynthetic rate on the light and temperature sequence was analysed as well.

Data on the main soil chemical properties are also presented; the analyses were performed with two replicates, and the average values are displayed. Data on main weather conditions were obtained from the nearest observation stations of SHMÚ (Slovak Hydrometeorological Institute) network with guaranteed record quality (the stations located up to 1,500 m as the crow flies to the trial sites).

RESULTS AND DISCUSSION

Conditions, Weather and Soil Parameters

The tomato landraces were sown on March 22, 2022 and planted on May 6, 2022; both actions were carried out under optimal agrotechnical conditions. The planting was watered regularly, and the plants were also watered regularly after planting to avoid water stress. Regarding the weather conditions in May and June, the period after sowing until the photosynthesis measurements were characterised by hot and dry conditions with higher temperatures (+1.2°C compared to the 30-year normal 1991 – 2020) and the complete absence of rainfall (Table 4). The same weather pattern was typical for the entire main vegetation period (April to September). The photosynthesis measurement was conducted on June 28 and 29, 2022 at Site-1; on both days, the average daily temperature was 31.4°C and 31.3°C, with maximum daily temperature reaching 40°C, and both days were the hottest in the vegetation period 2022 (Figure 2).

Although the experiment was not designed for nutrient balance, the differences between the initial and final nutrient status confirm some general trends regarding the main chemical properties of the soil. The difference between the initial and final nutrient status was small in general, for total nitrogen (Nt), the change in status was –30 and +95 mg/kg for HA and NPK, respectively (Figure 3). The situation was reversed for available phosphorus (P), where the change was +7.6 and –66.6 mg/kg, respectively. This can be linked to two effects of the humic treatment: higher consumption due to higher yield (Nt) and/or higher nutrient availability due to higher root activity (P). Both phenomena are consistent with previous studies on humic amendment (Olaetxea *et al.* 2018; Tóth *et al.* 2022; 2015).

Olaetxea *et al.* (2018) tested the efficacy of humic amendments and found that certain concentrations had a biostimulant effect on plants, at a concentration of 150 – 350 mg/L soil solution, which could be achieved with ameliorative doses of soil humic treatment. The effectiveness of such soil treatments on the growth of tomato landraces probably depends on the characteristics of the soil to which they are added, as well as on the conditions of nutrient management (use or non-use of fertilisers). However, the soil heterogeneity could be decisive. According to the conclusions of Tartaglia *et al.* (2020), the best effects were obtained in acidic and nutrient-poor soils.

Typology of the Tested Landraces Involving Just Rediscovered and Now First Described 'Zemplínsky' Landrace

Over the last century, the gradual replacement of landraces by modern, high-yielding cultivars has led to a dramatic decline in the diversity of cultivated plants preserved in situ in Europe. Currently, infor-

T a b l e 4

The course of the weather conditions (AT average day air temperature in °C, and SP sum of precipitation in mm) during the vegetation period 2022

Locality	April		May		June		July		August		September		IV-IX	
	AT	SP	AT	SP	AT	SP	AT	SP	AT	SP	AT	SP	AT	SP
Site-1	8.9	26.4	17.1	9.8	22.7	12.5	23.9	45.2	23.8	19.7	15.1	140.7	18.6	254.3
Site-2	8.8	37.9	16.8	12.3	22.2	17.6	23.0	63.3	23.5	24.1	14.9	140.2	18.2	295.4

Note: AT – average day air temperature; SP – sum of precipitation.

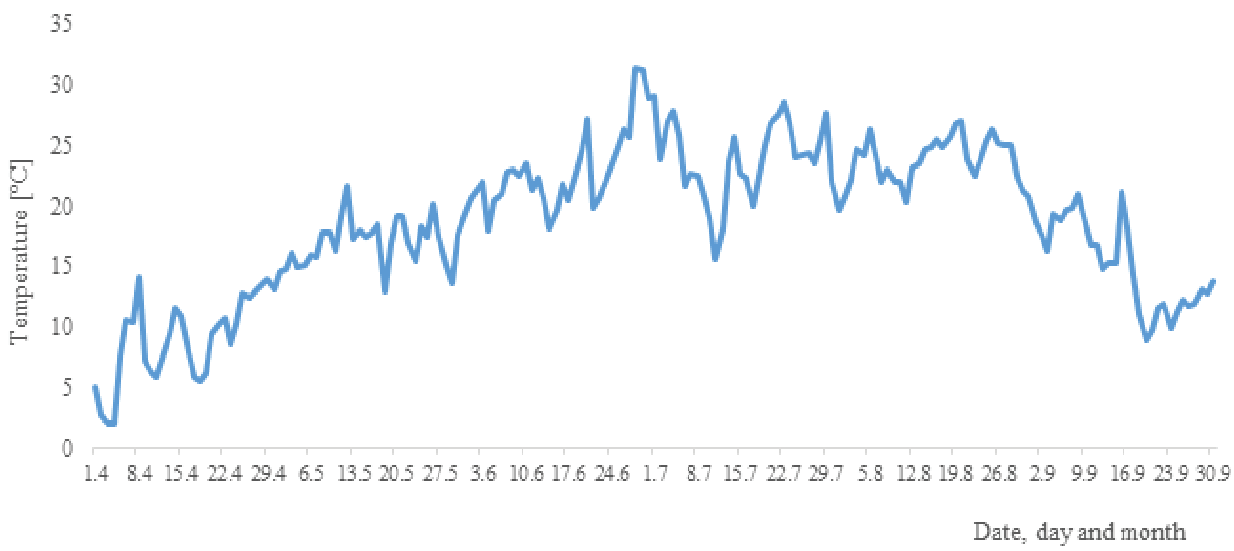


Figure 2. The course of average day temperature during the vegetation period of 2022, Site-1.

mation about landraces' cultivation places and areas is limited and scattered (Raggi *et al.* 2022; Villena *et al.* 2023). Van Andel *et al.* (2022) demonstrated that the earliest tomatoes in Europe occurred in a much wider range of colours, shapes and sizes. The landrace 'Zemplínsky' is described for the first time and compared with other landraces. It differs from the others not only in its appearance (an orange collar around the leaf stalk that turns yellow), but also in its determinate growth, which can be considered a great advantage (Table 5, Figure 4). In contrast to 'San Marzano', which is considered one of many famous landraces in Western Europe, the 'Zemplínsky' has only just been rediscovered and has not yet been studied.

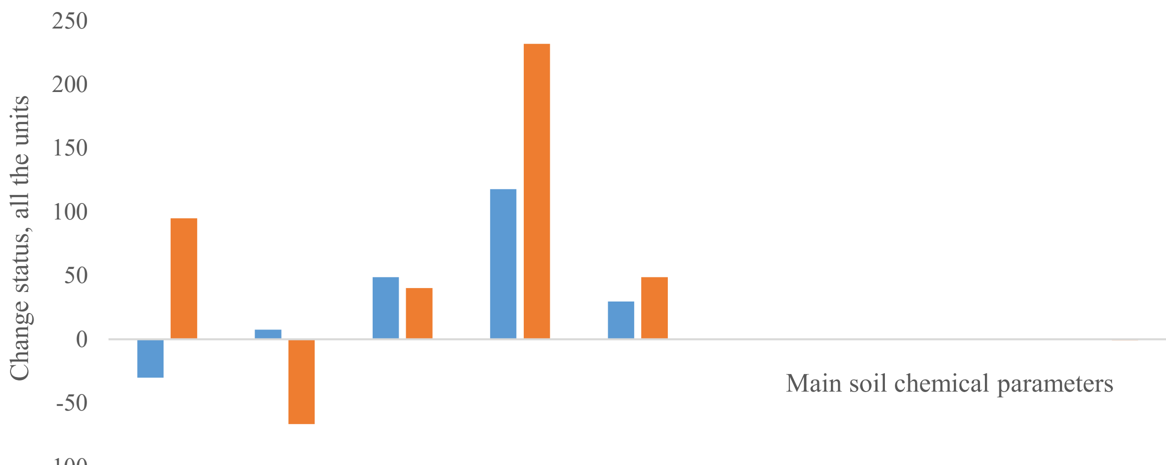
The work of Boziné-Pullai *et al.* (2021) describes some differences within the landraces in terms of disease susceptibility. Certain landraces are highly recommended, e.g., the indeterminate 'Fadd' and 'Mátrafüred', which showed correspondingly high yields under unfavourable conditions with significantly lower susceptibility to late blight *Phytophthora infestans* (Mont.) de Bary. This study indicates that landraces in organic production systems are competitive with the commercial landraces studied. Hungarian tomato landraces such as 'Balatonboglár',

T a b l e 5

The main biometric specification of the tested landraces

Landrace	GT	Fruit colour	Fruit shape	FWR [g]	Beginning of ripening	FNpB	OR
'Mátrafüredi'	ID	red	heart	110 – 130	middle of July	2 – 3	HU
'Gyöngyös'	ID	red	longitudal	100 – 120	middle of July	3 – 4	HU
'Fadd'	ID	rose red	round	50 – 70	middle of July	5 – 7	HU
'Máriapócs'	ID	red	round	15 – 20	beginning of July	15 – 18	HU
'Tolna'	ID	orange red	kidney	150 – 180	beginning of August	2 – 3	HU
'Cegléd'	ID	yellow	rounded	80–100	end of July	3 – 4	HU
'Zemplínsky'	SD	orange red	rounded	90 – 110	end of June	4 – 5	SK

Note: GT – growing type; ID – indeterminate; SD – semideterminate; FWR – fruit weight range; FNpB – fruits number per brunch; OR – origin; HU – Hungary; SK – Slovakia.



	Nt	P	K	Ca	Mg	pH	C-ox	humus	C/N
HA	-30	7.6	48.7	118	29.7	0.19	-0.051	-0.088	-0.20
NPK	95	-66.6	40.2	232	48.9	0.15	0.155	-0.020	-0.62

Figure 3. The change in the status of the main soil chemical parameters. Note: HA – see Table 2; Nt – see Table 1.

'Fadd', 'Mátrafüred', 'Tarnaméra' and 'Tolna' can thus replace commercial landraces under organic production conditions, even if they are grown outside their place of origin.

The remarkable Hungarian tomato landraces are characterised by adaptability to the Eastern European climate. They have a juicier texture than the well-known Italian tomato landrace 'San Marzano', which defines the indeterminate growth type. The 'San Marzano' has also been studied for its photosynthesis and drought resistance. Biostimulants improved the photosynthetic accumulation of carbohydrates and the efficiency of mineral nutrient utilisation, resulting in a higher yield (Rouphael *et al.* 2021). Furthermore, Tartaglia *et al.* (2020) confirm that the addition of biochar improves vegetative growth and fruit yield while upregulating genes involved in photosynthesis. In terms of drought resistance, this plant showed increased drought tolerance by maintaining leaf turgor under drought stress by reducing transpiration through stomatal control (Fullana *et al.* 2019; Maioli *et al.* 2023).

Lycopene Content

The authentic data on the lycopene content of the tested tomato landraces are summarised in Table 6 and shown with added standard error (Figure 5). The data are presented as the average of four replicates. The statistical results of the multivariate analysis of variance (MANOVA) and Fisher's post hoc test are also integrated and displayed (Tables 7 and 8). Overall, the average lycopene content was 285.94 mg/kg and ranged from 6.18 to 658.54 mg/ha. Lycopene content was mainly influenced by the landraces (*F*-ratio 70,856.36, *P*-value 0.00), followed by the treatments (*F*-ratio 20,189.09, *P*-value 0.00), then by sites (*F*-ratio 16,291.16, *P*-value 0.00) and finally by the replications (*F*-ratio 17.62, *P*-value 0.00).

In general, lycopene content was higher at Site-1 than at Site-2 (313.77 vs. 258.11 mg/kg), Table 7. Among treatments, lycopene content decreased with increasing nutrient intensity (HA>NPK vs. 254.96 <316.92 mg/kg), but this general trend did not hold for all landraces. The order of landraces by decreasing lycopene content was as follows: 'Gyöngyös' > 'Mátrafüredi' > 'Tolna' > 'Fadd' > 'Máriapócs' > 'Zemplínsky' > 'Cegléd' (420.85 > 413.29 > 411.93 > 329.36 > 233.85 > 181.47 > 10.83 mg/ha in order of average values).

As for the interactions, according to the sum of F-ratios, they contributed 19.96% to the overall variability of the experiment, which is less than 81.04% for the superior proportion of main effects. Although the influence of replications as one of the main effects was significant (*F*-ratio 17.62, *P*-value 0.00), the contribution of replications to the total variance was small, only 0.01%, so the influence of replications is not worthy of further comment. The reason for the significance of replication could be related to the trial scale and the wide range of lycopene content resulting from the inclusion of different landraces with different values. Similarly, all six replication interactions could also be considered irrelevant, although half of them are significant. According to the *F*-ratio, all interactions of the replications on the total variability of the experiment are again only 0.01%, indicating the high quality of the in situ experiment and the laboratory analyses. Despite the replications, all remaining four interactions were significant without the replications.

The most significant interaction (by *F*-ratio) was "landraces × sites", probably indicating the need for some regionalization of the landraces or related to the different ability to tolerate less favourable growing conditions. Significant differences in lycopene content by sites were found in every combinations within the interaction, while considering *LSD* value of 0.815857 (Table 8). However, considering adequate values of standard error (displayed in Figure 6), contrasting differences were found for four landraces ('Zemplínsky', 'Mátrafüredi', 'Gyöngyös', and 'Fadd'), and only one of them ('Mátrafüredi') showed the higher values at the less favourable location-2 (Table 8, Figure 6). The second most significant interaction was "landraces × treatments", while significant differences were found in every combinations within the interaction (by *LSD*) and lycopene content by treatments were contrasting (by standard error) in only two cultivars ('Mátrafüredi' and 'Gyöngyös'), with the higher values found in the less intensive treatment in both cases (Figure 7).

The third most important interaction, "landraces × treatments × sites" is shown in Figure 5, as it is identical to the integrated data of the whole experi-

Figure 4. The landraces ‘Zemplínsky’ – ‘Mátrafüredi’ – ‘Gyöngyös’ – ‘Fadd’ – ‘Máriapócs’ – ‘Tolna’ – ‘Cegléd’ displayed from left to right as from above to down, and long drying the samples at 35°C, photo Š. Tóth (vegetation period 2022).

ment, without the replicates. The differences in lycopene content between landraces are most likely mainly genetically determined and influenced by external factors, which is confirmed by a high proportion of significant differences between landraces depending on treatment and location. The humic treatment increased the lycopene content in three landraces that had a lower content at both experimental sites ('Zemplínsky', 'Máriapócs' and 'Ceglé'), while the effect was reversed in four landraces with a generally higher lycopene content ('Mátrafüredi', 'Gyöngyös', 'Fadd', and 'Tolna'). Since the basic nutrition with NPK was the same, the humic treatment shows a harmonising effect, i.e., it balances the different values towards the middle. This harmonising phenomenon is also confirmed by the fourth most significant interaction "treatments × sites", where most of the mutual differences are significant (Figure 8).

According to Cox *et al.* (2003), who examined different tomato landraces, the lycopene content varied depending on the degree of reddening of the fruit. The study found that all tomato landraces tested, with the exception of 'Cegléd', contained more than 80 mg/kg FW (fresh weight) of lycopene. The colour of the tomatoes gave an indication of the exact lycopene content, with the variety with a yellowish hue containing less lycopene than the red landraces and two of the three red landraces containing more lycopene than the orange variety in general. In addition, they observed that up to 92.3% of the local landraces had intense red coloration of the tomato fruit, with

T a b l e 6

The content of lycopene in tomato landraces, by trial

Locality	Treatment	'Zemplínsky'	'Mátrafüredi'	'Gyöngyös'	'Fadd'	'Máriapócs'	'Tolna'	'Cegléd'
Site-I	HA	297.30	244.99	349.08	411.75	223.01	444.91	15.92
	NPK	251.19	404.69	658.54	414.89	171.61	492.92	11.99
Site-2	HA	88.74	413.61	219.62	220.44	277.65	353.14	9.24
	NPK	88.63	589.88	456.17	270.34	263.13	356.74	6.18

Note: HA – see Table 2.

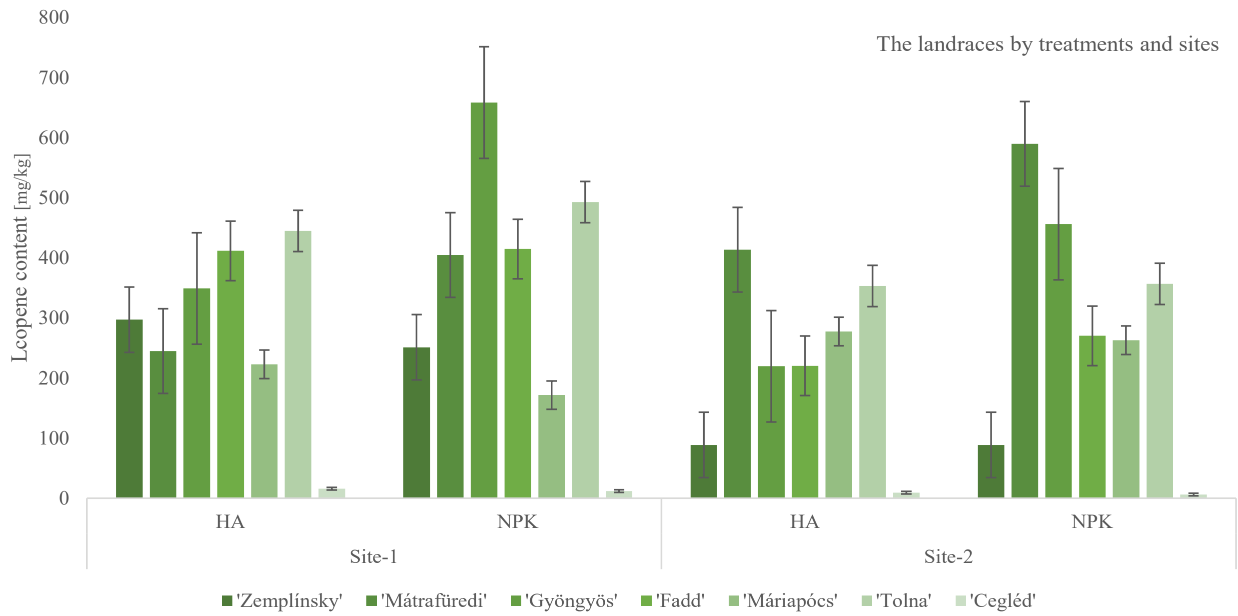


Figure 5. The content of lycopene in the tested landraces of tomatoes, by the treatments (HA, NPK) and sites (Site-1 Ágcsernyő, Site-2 Michalovce), with standard error added. Note: HA – see Table 2.

T a b l e 7

The joined MANOVA and Fisher´s test outputs of the lycopene content data for the main

IO	Source of variability	Sum of squares	*DF*	*F*-ratio	*P*-value	Homogenous groups		LS Mean	LS Sigma
1	Landraces	2,263,860.00	6	70,856.36	0.0000	B	'Zemplinsky'	181.466	0.576898
						E	'Mátrafüredi'	413.293	0.576898
						F	'Gyöngyös'	420.854	0.576898
						D	'Fadd'	329.356	0.576898
						C	'Máriapócs'	233.852	0.576898
						E	'Tolna'	411.927	0.576898
						A	'Cegléd'	10.8311	0.576898
2	Treatment	107,507.00	1	20,189.09	0.0000	A	HA	254.958	0.308365
						B	NPK	316.922	0.308365
3	Sites	86,750.20	1	16,291.16	0.0000	B	Site-1	313.770	0.308365
						A	Site-2	258.109	0.308365
4	Replications	281.529	3	17.62	0.0000	B	I	287.721	0.436094
						A	II	283.968	0.436094
						B	III	287.255	0.436094
						A	IV	284.814	0.436094
Residual		0.0	0	*5.32499	–	–	–	–	–

Note: IO – impact order, an order according to *F*-ratio; *DF* – degree of freedom; LS – least significant difference; * – main square (for residual).

T a b l e 8

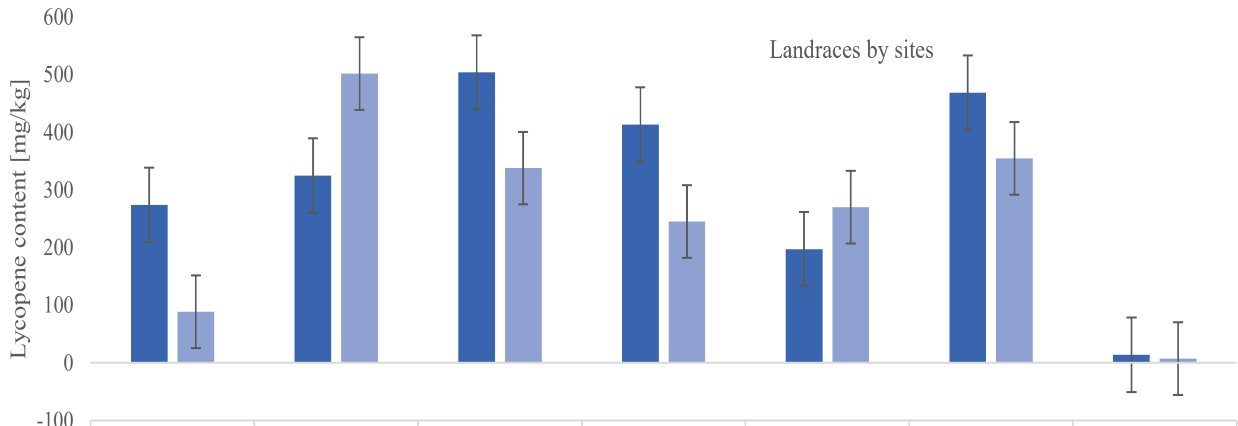
The joined MANOVA and Fisher´s test outputs of the lycopene content data for the interaction

IO	Source of variability	Sum of squares	*DF*	*F*-ratio	*P*-value	LS Sigma
2.	Landraces × treatments	315499	6	9874.81	0.0000	0.815857
1.	Landraces × sites	472555	6	14790.49	0.0000	0.815857
6.	Landraces × replications	419.993	18	4.89	0.0015	1.1538
4.	Treatments × sites	126.486	1	23.75	0.0001	0.436094
9.	Treatments × replications	19.0267	3	1.19	0.3412	0.61673
10.	Sites × replications	0.791641	3	0.05	0.9849	0.61673
3.	Landraces × treatments × sites	13096.9	6	409.92	0.0000	0.815857
7.	Landraces × treatments × replications	230.387	18	2.40	0.0354	1.1538
5.	Landraces × sites × replications	497.221	18	5.19	0.0005	1.1538
8.	Lreatments × sites × replications	37.7972	3	2.37	0.1049	0.61673
	Residual	95.8498	18	–	–	–
	Total	3260970	111	–	–	–

Note: IO – impact order, an order according to *F*-ratio; *DF* – degree of freedom; LS – see Table 7.

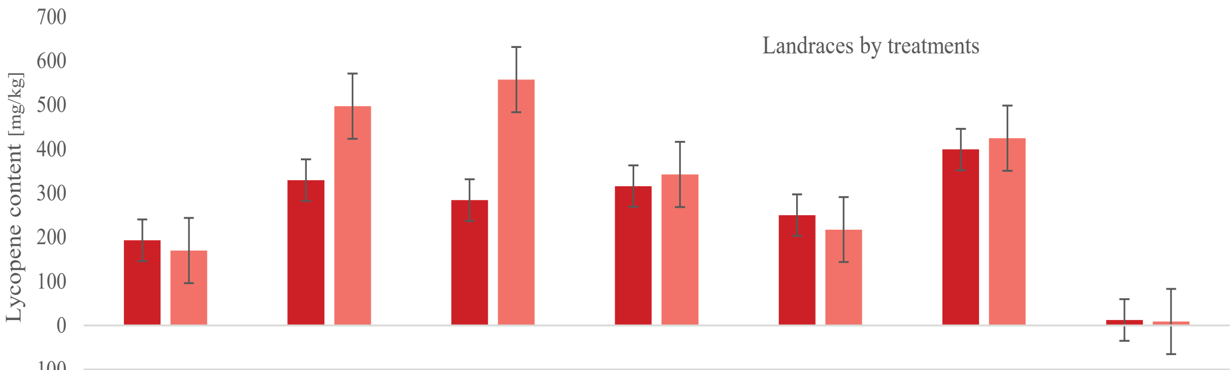
lycopene content ranging from 19.93 to 126.4 mg/kg body weight. This is consistent with the list of 7 landraces, in which the lowest lycopene content of 10.81 mg/kg was found in the cultivar 'Cegléd', which is characterised by yellow fruits. Maxim *et al.* (2022) also observed that up to 70% of the 35 local landraces showed an intense red colouration of the tomato fruits, and the lycopene content was also above 50 mg/kg bw.

Setyorini (2021) describes that the lycopene content of tomatoes grown in greenhouses is 40% higher than that of tomatoes grown outdoors. Shading by foliage could be important to maximise the lycopene content of tomato plants grown in warm areas with high solar radiation. Sensitivity to shade depends on plant genetics. In general, light activates photosynthesis, but the plants do not produce more fruit. The intensity of the sunlight has a great influence on the temperature in the plant's environment. Studies on lycopene content show that the temperature of the fruit surface predicts the lycopene content of the fruit better than the air temperature, especially when the fruit is exposed to direct, intense sunlight. The more direct sunlight the fruit is exposed to, the higher the surface temperature of the fruit, resulting in a lower lycopene content of the fruit (Helyes *et al.* 2007).



	'Zemplínsky'	'Mátrafüredi'	'Gyöngyös'	'Fadd'	'Máriapócs'	'Tolna'	'Cegléd'
Site-1	274.25	324.84	503.81	413.32	197.31	468.91	13.95
Site-2	88.68	501.75	337.90	245.39	270.39	354.94	7.71

Figure 6. The content of lycopene in the tested landraces of tomatoes, by the sites (Site-1 Ágcsernyő, Site-2 Michalovce), with standard error added.



	'Zemplínsky'	'Mátrafüredi'	'Gyöngyös'	'Fadd'	'Máriapócs'	'Tolna'	'Cegléd'
HA	193.02	329.30	284.35	316.10	250.33	399.02	12.58
NPK	169.91	497.28	557.36	342.62	217.37	424.83	9.08

Figure 7. The content of lycopene in the tested landraces of tomatoes, by the treatments (HA, NPK), with standard error added.
Note: HA – see Table 2.

Air temperatures below 12°C and temperatures above 32°C can also reduce antioxidant levels (Dumas *et al.* 2003), which generally protect plant cells from oxidative stress caused by sunlight, drought and environmental stressors. As for tomato diseases related to lycopene, some wild tomato species with higher secondary metabolites (including carotenoids) show better tolerance to pathogens, although lycopene itself is not a direct antifungal agent, its presence is associated with overall plant health and stress resistance.

Research by Maxim *et al.* (2022) discovered the properties of landraces with resistance to *Phytophthora infestans,* setting the stage for environmental protection by reducing the number of pesticides. In addition, they have identified landraces with a high content of carotenoids that support human health in the face of the alarming increase in degenerative diseases in countries with advanced economies.

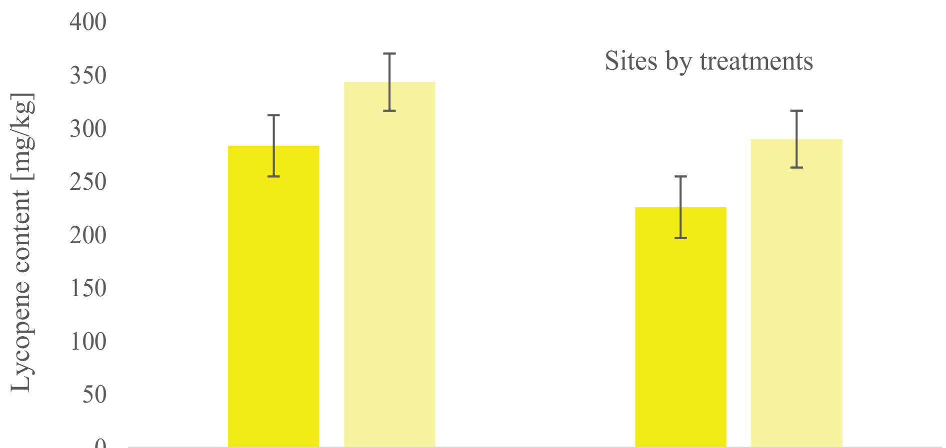
Concerning the treatments, humic treatment caused slightly lower lycopene content in general, which can be explained by the plants' lower need to protect themselves from environmental stress. According to Magdaong *et al.* (2018) and Dreuw *et al.* (2005), concerning the carotenoids, where lycopene belongs, it can be noted that they participate in light absorption and also have a photoprotective function, which consists of rapidly quenching the excited state of chlorophyll to prevent damage to photosynthetic membranes after absorbing large amounts of light.

Photosynthesis Rate

The photosynthetic rate (PR) of the tested landraces reached an average of 26.341 mmol/m^2/s in the temperature sequence and 10.926 mmol/m^2/s in the FAR sequence, with marked differences between the landraces and the treatments (Table 9). In both sequences, the higher photosynthetic rate was measured in the treatment with NPK (30.753 and 12.589 mmol/m^2/s) compared to the treatment with HA (22.347 and 9.271 mmol/m^2/s). Overall, a higher photosynthetic rate was measured in most landraces within both sequences when treated with NPK compared to HA.

The above-mentioned status applies in relation to the average values, but not only, and even more correlations become clearer when the obtained photosynthetic rate data are analysed directly according to the exact conditions of the sequence of temperature and FAR, which is processed by the landraces together in Figures 9 and 10.

Stoyanova *et al.* (2019) describe photosynthesis as the most important physiological process of plants, the speed and effectiveness of which determines the productivity of the tomato. The rate of photosynthesis is significantly related to irrigation



	Site-1	Site-2
HA	283.85	226.06
NPK	343.69	290.15

Figure 8. The content of lycopene in the tested landraces of tomatoes, by the treatments (HA, NPK), and sites (Site-1 Ágcsernyő, Site-2 Michalovce), with standard error added. Note: HA – see Table 2.

T a b l e 9

Photosynthesis rate (PR, mmol/m2/s1), photosynthetically active radiation (FAR, mmol/m^2/s) and accompanying parameters of temperature and light sequence

Landrace/Treatment		Sequence of temperature					Sequence of light				
		FAR	CO_2 concentration	Temperature range [°C]	Average temperature [°C]	PR average	Temperature [°C]	CO_2 concentration, vpm	FAR range	FAR average	PR average
‘Zemplínsky’	NPK	608	410	20.9-39.4	28.3	23.819	30.4	423	0-1304	499	13.279
	HA	608	422	23.1-40.0	29.4	9.889	32.6	416	0-1304	487	5.214
‘Mátrafüredi’	NPK	608	404	25.9-41.3	31.4	40.286	37.4	407	0-1304	487	19.403
	HA	608	414	23.9-40.6	30.2	32.659	35.3	411	0-1304	488	16.374
‘Gyöngyös’	NPK	608	400	25.9-41.1	31.5	40.579	37.7	402	0-1304	486	16.445
	HA	608	402	26.0-41.2	31.9	24.470	39.2	410	0-1304	479	10.860
‘Fadd’	NPK	608	403	27.9-41.7	33.3	25.359	39.2	404	0-1304	480	7.049
	HA	608	416	26.8-41.3	32.5	32.491	41.2	412	0-1304	480	8.036
‘Máriapócs’	NPK	608	404	27.6-41.7	33.1	33.094	38.5	403	0-1304	486	14.197
	HA	608	406	27.6-41.6	33.1	34.486	40.1	403	0-1304	487	12.941
‘Tolna’	NPK	608	402	28.0-41.3	32.8	17.757	41.4	408	0-1304	486	7.172
	HA	608	409	26.8-41.1	32.7	15.424	41.6	407	0-1304	486	6.437
‘Cegléd’	NPK	608	413	24.8-39.5	30.3	29.776	39.1	405	0-1304	486	10.852
	HA	608	409	26.5-40.8	32.1	16.305	41.3	402	0-1304	486	4.949
Average	NPK	608	405	20.9-41.7	31.7	30.753	37.6	407	0-1304	487	12.589
	HA	608	411	23.1-41.7	31.8	22.347	38.8	409	0-1304	485	9.271
Average		608	408	20.3-41.7	31.8	26.341	38.2	408	0-1304	486	10.926

Note: HA – see Table 2; FAR – photosyntethically active radiation.

and nutrition of tomato plants, with water availability having a stronger effect on photosynthesis than fertilisation. Soil moisture had greater effects on fruit yield, plant biomass and root/shoot ratio than fertiliser applications. According to Zhu *et al.* 2012, a balanced water-fertiliser combination correlated positively with yield. The high amount of fertiliser increased the content of photosynthetic pigments in the leaves, gas exchange and chlorophyll fluorescence in the leaves when the soil moisture in the field was 95%. However, complementary to these conclusions, our previous studies confirm that the intensity of photosynthesis was higher in the control treatment, which was characterised by lower plant growth, smaller root mass volume and lower yield compared to the treatments with intensive nutrition and/or humic amendment. Therefore, the increased photosynthetic rate could indicate a stress response of the plants. In contrast, despite the lower intensity of photosynthesis (power per unit area of leaf), the treatments were characterised by a higher yield, which was related to the higher total photosynthetic power due to the greater assimilation in the plants with promoted growth. In addition, the slowing of the photosynthetic rate was also associated with a better formation of secondary metabolites, which were present to a greater extent under the treatments (Tóth *et al.* 2022). According to Nardi *et al.* (2024) root exudates have the potential to change molecular conformation, with humic acids influencing important exudates such as phytosiderophores in stressed plants.

Sequence of FAR

The main photosynthetic rate data of the tested landraces in the FAR sequence are listed in Table 9, while the dependency lines are shown in Figure 9. Subfigures A−H (Figure 9) are configured by landrace and optimised to contain the full set of clustered data, including for the treatments. It is typical for the reliability indices of the second-order polynomial trends to reach high values, ranging from 0.7837 to 0.9911, depending on landrace and treatment.

Many factors jointly contribute to photosynthesis, including genetic factors as well as external environmental factors such as light, temperature, humidity, CO_2 concentration, mineral elements, hormones and leaf development. Leaf photosynthesis is the overall best source of energy for the tomato during its growth and development (Dong *et al.* 2024). Their study on the effects of light on tomato photosynthesis showed that a high level of red light improves the efficiency of photosynthesis through higher iron uptake, resulting in an increase in photosynthetic capacity that promotes tomato growth and development.

The photosynthetic rate averaged 10.926 mmol/m^2/s, while in most of the observed cultivars, the photosynthetic rate had a decreasing character depending on the light intensity under NPK treatment, except for the landrace cultivar 'Fadd'. The carotenoids, to which lycopene belongs, also have a photoprotective function in light absorption, which includes of quickly extinguishing the excited state of chlorophyll to prevent damage to photosynthetic membranes after absorbing large amounts of light.

Sequence of Temperature

In the temperature sequence, the photosynthetic rate averaged 26.341 mmol/m^2/s (Table 9). For most of the observed cultivars, the photosynthetic rate decreased under the HA treatment, except for the landraces 'Fadd' and 'Máriapócs' at an average air temperature of 31.8°C (Figure 10). This finding could be related to the fact that humic acids improve tolerance to drought, salinity and/or stress caused by extreme temperatures, thus preventing photosynthesis disruption. In terms of sensitivity to temperature stress, the yellow-coloured cultivars are also more resistant, including the cultivar 'Zemplínsky'.

Riga *et al.* (2008) described that tomato quality depends more on temperature than on photosynthetically active radiation, which indeed correlates with this experiment. Pompeiano *et al.* (2025) compared the drought adaptability of the original tomato variety 'Ciettaicale' (CE) with 'Moneymaker' (MM), a commercial variety. Both genotypes responded to drought with increasing non-photochemical quenching (NPQ), while PSII electron transport rate and CO2 uptake capacity decreased. Drought limits photosynthesis mainly through diffusion resistance in CE and metabolic damage in MM. The ability of CE to resist drought lies in the activation of cellular processes to partially control oxidative stress to induce drought acclimation.

Since the outside temperature affects the pho-

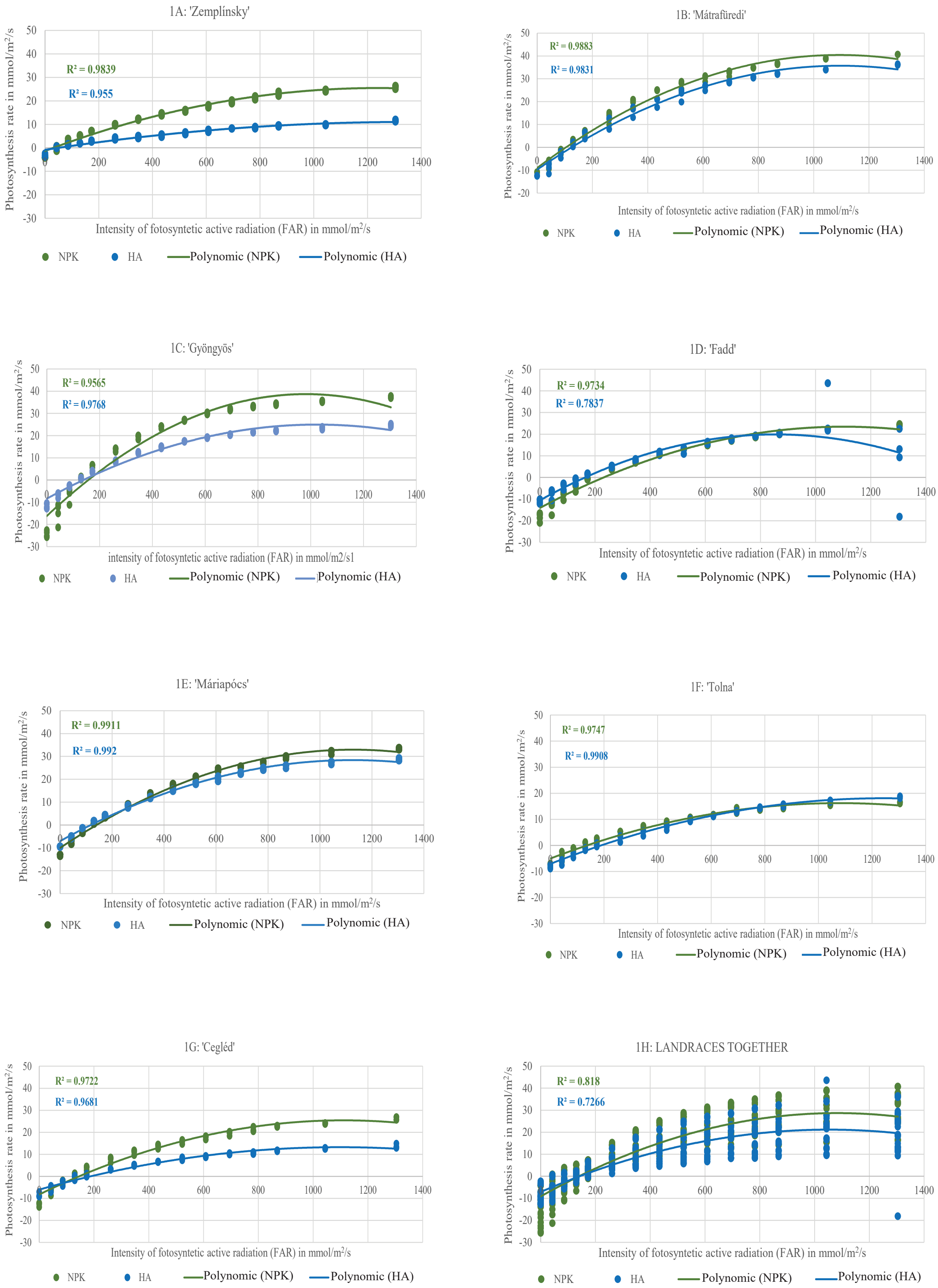


Figure 9. Photosynthesis rate (mmol/m²/s) of tomato landraces (BBCH 69 – full flowering) according intensity of FAR and treatments. Note: BBCH – plant phenology scale; HA – see Table 2; FAR – see Table 9.

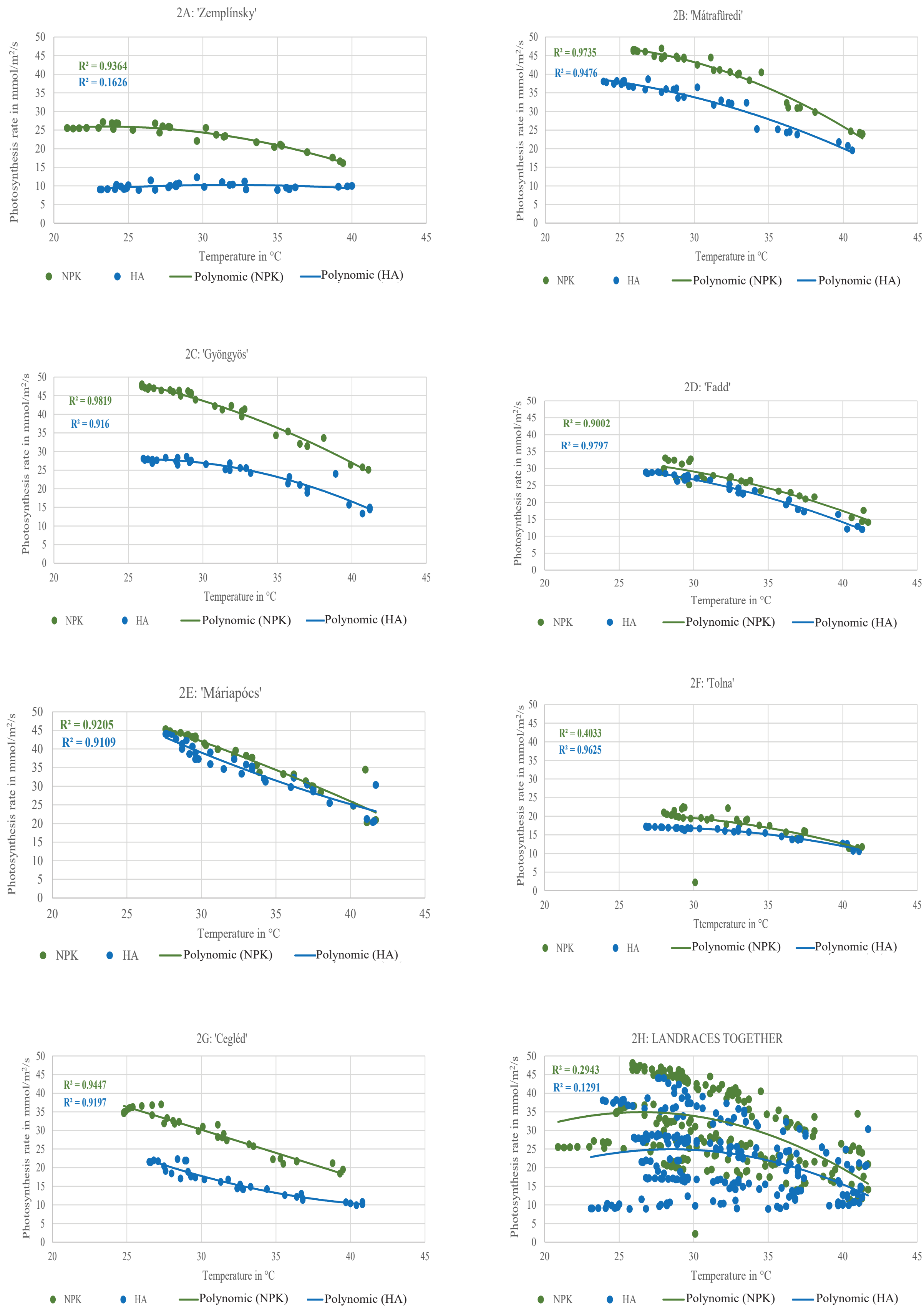


Figure 10. Photosynthesis rate (mmol/m^2/s) of tomato landraces (BBCH 69 - full flowering) according to temperature and treatments. Note: BBCH – see Figure 9; HA – see Table 2; FAR – see Table 9.

tosynthetic capacity of tomatoes by regulating several enzymatic reactions important for photosynthesis, tomatoes growing below 25°C showed lower electrolyte loss, less hydrogen peroxide and higher maximum photochemical efficiency of PSII than those growing below 4°C in the study by Xu *et al.* (2023), suggesting that low temperatures cause weaker photosynthetic capacity.

The highest photosynthetic efficiency (12.50–12.88%) was observed by Stoyanova *et al.* (2019) in the treatment without fertilisation during the growing season at 100% irrigation, which is due to the low transpiration intensity despite the relatively high photosynthetic rate. Good plant condition was observed when fertilised with 50% of the fertiliser rate and reduced irrigation. The plants were tolerant of water shortage.

Biermann *et al.* (2022) tested the diversity of 14 tomato genotypes (Mediterranean landraces) for their tolerance to long-term heat stress. Due to climate change, crops will be exposed to more severe abiotic conditions in the future. In addition, the intensity of photosynthesis varies depending on temperature, with stomatal regulation playing a key role in the stress response (Giorio *et al.* 2018). In addition, humic treatment can increase photosynthetic activity and lycopene synthesis and thus improve fruit quality.

CONCLUSIONS

The influence of soil humic amendment on seven tomato landraces was tested with intensive nutrition as a control treatment, with the investigations focusing on the lycopene content and the intensity of photosynthesis. Among the landraces, most of which were of Hungarian origin, was a newly discovered and first described ‘Zemplínsky’ of Slovakian origin.

The results on lycopene content confirmed that there are contrasting differences between the landraces, which are most likely due to genetic differences. However, a statistically significant influence of treatments and sites was also found, demonstrating the conditioning effect of cultivation practices. In addition, a phenomenon of harmonising effect of humic amendment addition was also observed, as lycopene content generally shifted from extreme values towards intermediate values in both locations.

As for the measurement of photosynthetic intensity, the humic treatment reduced the photosynthetic rate of leaves per unit area, which could indicate an anti-stress effect. This anti-stress effect could most likely be related to a better-known ameliorative effect of humic amendment related to plant root development.

Concerning the recently rediscovered landrace of ‘Zemplínsky’, it can be concluded that the main advantage can be seen in the early ripening of the fruit. Like the preferences of the Louis IX of French for Tokaj wine, which is still referred to by many as “Vinum Regum, Rex Vinorum”, the landrace could be described by many as “the tomato of kings, the king of tomatoes” as an expressive parallel in terms of flavour characteristics. The preferred taste characteristics should be quantified through sensory evaluation and targeted testing procedures. attracts consumers should be parameterised through testing and sensory.

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