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EFFECT OF DIFFERENT FERTILIZATION SYSTEMS ON WEED FLORA IN A TOMATO CROP IN SERBIA

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ABSTRACT

This study evaluated weed community composition and diversity in tomato crops under five fertilization regimes, including mineral fertilization (NPK) applied alone or in combination with well-decomposed cattle manure, retort beech charcoal, and their combinations.

A total of 23 weed species were recorded across all treatments. Species richness ranged from 10 to 23 species (T1 = 17, T2 = 12, T3 = 15, T4 = 23, T5 = 10). Total weed density ranged from 70.67 to 187.99 individuals per m^2. The highest Shannon diversity value was recorded in T4 (2.439), while the lowest was in T5 (1.965). Simpson's dominance index ranged from 0.116 to 0.182, with consistently high evenness across treatments. Jaccard's similarity index ranged from 31.82% to 73.91%, while Steinhaus coefficients ranged from 0.412 to 0.718.

PERMANOVA indicated significant differences in weed community composition among treatments ($p = 0.001$). NMDS ordination (stress ≈ 0.16; $R^2 = 0.973$) suggested partial separation among treatments, with T3 and T4 appearing more similar, while T5 was separated from other treatments and characterized by comparatively reduced community complexity. *Chenopodium album* and *Amaranthus retroflexus* were present in all treatments (100% frequency). Therophytes represented the dominant life form across treatments (78.26%). The results showed that the fertilization strategy influenced the frequency and abundance of the weed population in tomato crops.

Key words: NMDS, NPK, PERMANOVA, retort beech charcoal, tomato, weeds

INTRODUCTION

Tomato (*Solanum lycopersicum* L.) ranks among the most extensively grown vegetable crops worldwide and plays an important role in human nutrition. In the Republic of Serbia, tomato is grown on an area of 7,782 ha, with an average yield of 14.6 t/ha and an annual production of 113,913 t [Statistical Yearbook of the Republic of Serbia 2024]. Favorable climatic and agroecological conditions, together with the use of modern cultivars and hybrids, provide Serbia with significant potential for successful tomato production.

Organic tomato production in the Republic of Serbia is becoming increasingly important each year. Chemical weed control in tomato production is limited, even in conventional farming. Although there are clear guidelines for managing organic crops, it is often difficult to keep weed populations below the tolerance threshold. Maintaining a weed-free crop is challenging, as organic production excludes the use of herbicides for weed control

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[Edesi et al. 2012]. Weed management in organic production is based on the application of preventive (indirect) measures, unlike conventional production, which relies on a combination of agronomic, chemical, and biological measures (direct measures) aimed at eliminating weeds from the field due to their harmful effects on the cultivated plants [Awan et al. 2018, López-Correa et al. 2022].

Organic farming combines tradition, innovation, and scientific knowledge to produce healthy products while protecting the habitat. The application of activated carbons in organic farming is a strategy to preserve and enhance soil quality, thereby contributing to increased crop yields [Baronti et al. 2010, Tian et al. 2018, Yadav et al. 2018, Živković et al. 2020a, 2020b, 2023].

Activated carbon and biochar are pyrogenic carbonaceous materials (PCM), produced through the thermochemical conversion of carbon-rich feedstocks (pyrolysis and/or activation). Today, both biochar and activated carbon are employed for soil remediation, whereas in the past this practice was largely restricted to activated carbon. When activated carbon remains in the soil after application and is produced from renewable feedstocks while meeting additional specifications, it can be considered biochar [Baronti et al. 2010, Yadav et al. 2018].

Numerous studies have confirmed that soils amended with biochar can improve plant growth [Yadav et al. 2018, Tian et al. 2018, Živković et al. 2020a, 2020b, 2023]. According to Tian et al. [2018], biochar incorporation induces soil alkalization, which can increase soil nitrification and nitrogen (N) levels. Increases in soil pH are also likely to affect electrical conductivity (EC), cation exchange capacity (CEC), and the content of alkaline metal oxides (Mg^{2+}, Ca^{2+}, and K^+). Additionally, biochar reduces soluble forms of aluminum, which has been identified as a key factor influencing phosphorus (P) solubility [Yadav et al. 2018, Tian et al. 2018].

Previous studies conducted in Serbia demonstrated that retort beech charcoal significantly increased tomato and pepper yields in organic production systems [Živković et al. 2020a, 2020b]. In addition, improved vegetative growth and rooting of blueberry plants were observed following retort beech charcoal application [Živković et al. 2023]. However, weed infestation remained a major production challenge, indicating the need for further investigation of weed dynamics under different fertilization systems.

This study investigated the diversity of weed species in tomato crops subjected to five different fertilization treatments, each with three replicates, to assess how these treatments influence weed community composition. The composition of weeds in crops depends on numerous factors, including crop species, weed control measures, environmental conditions, soil fertility, and climatic characteristics [Roschewitz et al. 2005, Barroso et al. 2015, Pinke et al. 2016, Travlos et al. 2018]. Understanding the influence of crop fertilization on weed composition is a key step toward shifting from reactive to predictive weed management [Barroso et al. 2015]. In addition, climate change may alter weed composition, with certain species potentially becoming invasive [Scott et al. 2014]. Due to the dynamic nature of weed occurrence, continuous monitoring and identification of dominant weeds in tomato production, as well as an understanding of their biology and ecology, are essential for establishing effective management strategies [Ljevnaić-Mašić et al. 2022, Božić et al. 2025].

For these reasons, this study continued with the aim of comparing weed flora in tomato crops under different fertilization systems. The analysis focused on weed composition (species richness, floristic diversity, evenness, and dominance) and weed abundance (occurrence and frequency). The findings of this study are expected to aid in the development of effective strategies for weed management.

MATERIALS AND METHODS

The experiment was conducted during the 2024 growing season in the locality of Trmčare, Kruševac municipality, Serbia (latitude: 43.50555°N; longitude: 21.35571°E; elevation: 300 m) under a continental climate. The study was carried out in field conditions using five treatments, each covering 50 m^2 (total experimental area 2,500 m^2). Each treatment was replicated three times, with 25 plants per replication. Row spacing was 70 cm, and plant spacing within a row was 40 cm. Tomato seedlings of the Optima genotype were started in a greenhouse on 20 March 2024 and transplanted to the field on 30 May 2024. Tomatoes were grown by a support (pillar) on a single tree on Vertisol soil. For many years, no herbicides have been used in the experimental field. Prior to sowing, the soil was prepared by applying burnt cow manure at a rate of 250 kg per 50 m^2 in the sowing layer. The selection of fertilization treatments and application rates was based on previous experimental studies demonstrating significant effects of retort beech charcoal on plant growth and yield parameters across different crop production systems [Živković et al. 2020a, 2020b, 2023]. Mineral fertilization (NPK 15 : 15 : 15) was included as a conventional reference treatment to enable comparison with organic and combined fertilization systems.

Seven days before planting, all five fields were further prepared according to the following treatments:
Treatment 1 (T1): 250 g of retort beech charcoal + 200 g of burnt cow manure per plant;
Treatment 2 (T2): 20 g of NPK 15 : 15 : 15 + 200 g of burnt cow manure per plant;
Treatment 3 (T3): 200 g of retort beech charcoal + 200 g of burnt cow manure per plant;
Treatment 4 (T4): 300 g of retort beech charcoal per plant;
Treatment 5 (T5): 20 g of NPK 15 : 15 : 15 per plant.

The activated charcoal used in this study was produced from natural beech wood and obtained through carbonation under strictly defined technical conditions, followed by steam activation in a static furnace.

Due to its organic origin and production process, the charcoal exhibits a defined level of physicochemical activity, with an iodine number of 233–750 mg/g, enabling effective water retention and providing the moisture required for plant uptake. The material supplies macronutrients (N, P, K), essential micronutrients (mg/kg: Ca – 8590, Mg – 1260, K – 7400, P – 380, S – 350, Mn – 32, Fe – 230, Zn – 20, Cu – 23), as well as organic compounds, humic acids, and amino acids that enhance physiological processes and improve plant health. The granulometry of 0–2.5 mm maintains soil porosity and structure, as the charcoal is chemically stable and does not dissolve in the soil. Its ash fraction is enriched with oxides of potassium, calcium, and magnesium and contains phosphates, providing an excellent source of this nutrient for plants. Due to the content of alkali metals, the material exhibits an alkaline pH ranging from 9 to 11.

Species nomenclature follows Josifović [1970a, 1970b, 1972a, 1972b, 1973, 1974, 1975, 1976, 1977] and Sarić [1986]. The invasiveness status of weeds in Europe and Serbia, as well as globally significant invasive species, was determined based on DAISIE [2018] and GISD [2019]. Taxonomic classification into families, life forms, and flowering periods was adopted from Landolt et al. [1977] and Takhtajan [2009].

Weed density (number of individuals per square meter, m^2 was assessed using the quantitative quadrat method with completely random sampling. All individual plants of each species were counted within 1 m^2 plots in three replicates for each of the five experimental tomato fields, after which the mean density was calculated (Formula 1).

Total weed density per treatment was subsequently computed according to Formula 2 [Ljevnaić-Mašić et al. 2022].

To evaluate floristic similarities and differences in weed composition, abundance, and dominance across the five tomato treatments, the following metrics were calculated: total number of species, i.e., species richness (*S*), weed density, frequency, Shannon–Weaver diversity index (*H′*), Shannon–Weaver evenness index (*E*), Simpson's dominance index (*D*), Jaccard similarity index (S_J), and Steinhaus coefficient (S_A), according to Formulas 3–8 [Shannon and Weaver 1964, Magurran 2004, Nkoa et al. 2015, Ljevnaić-Mašić et al. 2022].

$$\bar{x} = \frac{n_i/m^2}{3} \tag{1}$$

$$Weediness = \frac{\sum N}{m^2} \tag{2}$$

$$Frequency = \frac{\sum Z_i}{Z} \times 100\ (\%) \tag{3}$$

$$H' = -\sum_{i=1}^{S_t} p_i ln\ p_i, \text{ for } p_i = \frac{n_i}{N} \tag{4}$$

$$E = \frac{H'}{ln\ S} \tag{5}$$

$$D = \sum \frac{n_i(n_i-1)}{N(N-1)} \tag{6}$$

$$S_J = \frac{c}{a+b+c} \times 100\ (\%) \tag{7}$$

$$S_A = \frac{2W}{A+B} \tag{8}$$

where
$\bar{x}$ – the average number of individual plants of species i in plot measured in 3 repetitions,
n_i – number of the i^{th} species,
N – the total abundance of all species within the plot,
Z_i – number of sampling plots with species *i* present,
Z – total number of sampling plots surveyed,
p_i – a proportional abundance of i^{th} species,
ln – natural logarithm,
S – species richness (total number of species),
a – total number of species in the first population,
b – total number of species in the second population,
c – number of common species,
A – total number of individuals in population A,
B – total number of individuals in population B,
W – the sum of the lesser abundance of each species across the populations.

Statistical analysis

For performing statistical analysis we used the R software [R Core Team 2023]. We prepared data for analyses with the R packages readxl [Wickham and Bryan 2023] and dplyr [Wickham et al. 2023]. For manipulation of Microsoft Word document we used the R package officer [Gohel 2023a] and for tabular reporting we used the R package flextable [Gohel 2023b]. Before the analysis we transformed abundances with square-root. First, we used the function *metaMDS* from the R package vegan [Oksanen et al. 2020] for visualizing the differences between the fields in two-dimensional settings according to the non-metric multidimensional scaling (NMDS). Second, we calculated the dissimilarity matrix by using the Bray-Curtis dissimilarity coefficients [Bray and Curtis 1957, Faith et al. 1987].

$$d_{jk} = \frac{\sum_{i=1}^{23} |x_{ij} - {}_{ik}|}{\sum_{i=1}^{23} (x_{ij} + x_{ik})}, \text{where } j = 1,2,\ldots,15;\ k = 1,2,\ldots,15.$$

Multivariate homogeneity of group dispersions described in Anderson [2006] was checked with the function *betadisper* from the R package vegan [Oksanen et al. 2020]. Afterwards, following Anderson [2001] we used permutational multivariate analysis of variance (PERMANOVA), which brings the best of both worlds of non-parametric statistical tests and classical MANOVA, to test the differences among the treatments. It was performed with the function *adonis2* from the R package vegan [Oksanen et al. 2020]. Finally, for pairwise comparison between the treatments, the SIMPER procedure, also called the "Similarity percentages method", was used. It was described as a part of the general framework for non-parametric multivariate analysis of community data in Clarke [1993] and according to the suggestion given in Oksanen et al. [2020] it is sometimes hard to interpret. We used it to single out the species for which the difference among the treatments is an important ingredient for their contribution to dissimilarities. The function *simper* from the R package vegan Oksanen et al. [2020] was used with the default threshold for showing species that contribute at least 70% to the dissimilarity between the treatments according to the Bray-Curtis dissimilarity coefficients mentioned above and 999 permutations.

For further processing and analysis of our data, ChatGPT (OpenAI, GPT-5, accessed May 27, 2026) was used to assist in selecting appropriate statistical methods and their implementation. ChatGPT (OpenAI) was also used exclusively to assist with the English translation of the manuscript and grammatical corrections, as well as text editing. The authors reviewed and verified all content and assume full responsibility for the final version of the manuscript.

RESULTS

A total of 23 weed species were recorded across all fertilization treatments. Species richness varied considerably, ranging from 10 species in T5 to 23 species in T4 (T1 = 17, T2 = 12, T3 = 15, T4 = 23, T5 = 10). Mineral NPK fertilization (T5) was used as the conventional control treatment. Of the total flora, 78.26% of species belonged to *Magnoliopsida* and 21.74% to *Liliopsida*. The families *Asteraceae* and *Poaceae* each included five species, representing 21.73% for each family. The family *Polygonaceae* comprises three species, accounting for 13.04%. The *Amaran-*

thaceae and *Chenopodiaceae* families each included two weed species, representing 8.70% per family. The families *Brassicaceae*, *Convolvulaceae*, *Geraniaceae*, *Malvaceae*, *Portulacaceae*, and *Rubiaceae* were each represented by a single weed species, accounting for 4.35% each (Table 1). Therophytes were the dominant life form (78.26%) across all treatments, followed by geophytes (21.74%). The most frequent species were *Chenopodium album* and *Amaranthus retroflexus*, both present in all treatments (Table 1).

Table 1. Floristic composition of weeds in five treatments

Plant species	Family	LF	LC	Weediness (average No. of individuals per m^2) in tomato crop					Total indiviuals per m^2	Weed abundance	
				T1	T2	T3	T4	T5		Average individuals per m^2	Frequency (%)
Chenopodium album L.	*Chenopodiaceae*	Th4	A	41.67	40.33	23.33	26	7.33	138.66	27.73	100
Amaranthus retroflexus L.	*Amaranthaceae*	Th4	A	33.67	13.33	20.67	15.33	15.67	98.67	19.73	100
Chenopodium polyspermum L.	*Chenopodiaceae*	Th4	A	–	11.67	8.33	11.67	6	37.67	7.53	80
Amaranthus hybridus L.	*Amaranthaceae*	Th4	A	28.00	–	12.33	7	2,67	50	10	80
Galinsoga parviflora Cav.	*Asteraceae*	Th4	A	–	16.67	9.67	8	–	34.34	6.9	60
Setaria glauca (L.) P. B.	*Poaceae*	Th4	A	16.67	5.00	–	6.67	7,67	36.01	7.20	80
Cirsium arvense (L.) Scop.	*Asteraceae*	G3	P	8.33	–	8.33	4.33	11	31.99	6.4	80
Ambrosia artemiisifolia L.	*Asteraceae*	Th4	A	3.33	–	–	4.33	–	7.66	1.53	40
Hibiscus trionum L.	*Malvaceae*	Th4	A	11.67	–	7.67	3	6	28.34	5.67	80
Agropyrum repens Beauv.	*Poaceae*	G1	P	–	4.67	4.67	5.33	5.33	20.00	4.00	80
Geranium dissectum Jusl.	*Geraniaceae*	Th2	B	8.33	6	–	5.33	–	19.66	3.93	60
Setaria viridis (L.) P. B.	*Poaceae*	Th4	A	9	11.3	–	0.67	–	20.97	4.19	60
Cynodon dactylon (L.) Pers.	*Poaceae*	G1	P	2.67	4.3	–	2	4	12.97	2.60	80
Sorghum halepence L.	*Poaceae*	G1	P	3.33	–	4	5	–	12.33	2.47	60
Polygonum convolvulus L.	*Polygonaceae*	Th4	A	2	–	7.67	5.6	–	15.27	3.05	60
Capsella bursa–pastoris (L.) Medic.	*Brassicaceae*	Th1	B	–	4	–	2.33	–	6.33	1.27	40
Portulaca oleracea L.	*Portulaceae*	Th4	A	–	–	6.33	1.67	–	8	1.6	40
Erigeron annuus (L.) Perss.	*Asteraceae*	Th4	A	–	1.67	3	2	–	6.67	1.33	60
Polygonum persicaria L.	*Polygonaceae*	Th4	A	5	6	4.67	0.67	–	16.34	3.3	80
Polygonum lapathifolium L.	*Polygonaceae*	Th4	A	3.66	–	7.33	2.67	–	13.66	2.73	60
Convolvulus arvensis L.	*Convolvulaceae*	G3	P	4	–	–	3.67	–	7.67	1.53	20
Senecio vulgaris L.	*Asteraceae*	Th1	A	3.33	–	6.33	3.67	5	18.33	3.67	80
Galium aparine L.	*Rubiaceae*	Th2	A	3.33	–	–	1.33	–	4.66	0.93	40
Species richness (S)				17	12	15	23	10	23		
Number of annual plants				12	9	12	16	7	16		
Number of biennial plants				2	1	–	2	–	2		
Number of perennial plants				5	2	3	5	3	5		
Weediness (total number sof individuals per m^2)				187.99	124.94	134.33	128.27	70.67	646.20		
H′				2.191	2.082	2.210	2.439	1.965			
E				0.892	0.892	0.823	0.890	0.911			
D				0.136	0.182	0.134	0.116	0.170			

LF – life form; LC – life cycle; T1–T5 – treatments 1–5; A – annual plants; B – biennial plants; P – perennial plants; Th1 – annual plants; germinate in autumn, fruiting in early spring; Th2 – annual plants; germinate in autumn and early spring, fruiting in early summer; Th4 – annual plants; germinate in spring, bring seeds in late summer; G1 – perennial plants with thin underground shoots (rhizomes); G3 – perennial plants with root shoots (i.e. with adventitious buds on the root); *H′* – Shannon-Weaver's diversity index; *E* – evenness; *D* – Simpson's dominance index

Total weed density varied markedly among treatments, ranging from 70.67 individuals per m^2 in T5 to 187.99 individuals per m^2 in T1 (Table 1). Diversity indices showed clear treatment-related differences. Shannon diversity (*H'*) ranged from 1.965 to 2.439, with the highest values in T3 and T4 and the lowest in T5. Evenness (*E*) ranged from 0.823 to 0.911, with the highest value in T5. Simpson's dominance index (*D*) ranged from 0.116 to 0.182, with highest dominance in T2 and T5 (Table 1). Jaccard similarity showed the highest floristic similarity between T1 and T4 (73.91%) and between T3 and T4 (65.22%), while the lowest similarity was between T1 and T2 (31.82%) – as shown in Figure 1. Steinhaus similarity indicated the highest quantitative similarity between T3 and T4 (SA = 0.718) and between T2 and T4 (SA = 0.642), while the lowest values occurred between T2 and T5 (SA = 0.412) and T1 and T5 (SA = 0.415) – as shown in Figure 2.

Perennial species such as *Cirsium arvense* and *Sorghum halepense* were widely distributed across treatments, while *Agropyron repens* and *Cynodon dactylon* were also recorded. Among annual species, *Amaranthus hybridus*, *Hibiscus trionum*, *Polygonum convolvulus*, *Polygonum lapathifolium*, and *Senecio vulgaris* were more frequent in treatments amended with retort beech charcoal.

Figure 1. Jaccard's similarity index (SJ, %). T1 – Treatment 1; T2 – Treatment 2; T3 – Treatment 3; T4 –Treatment 4; T5 – Treatment 5

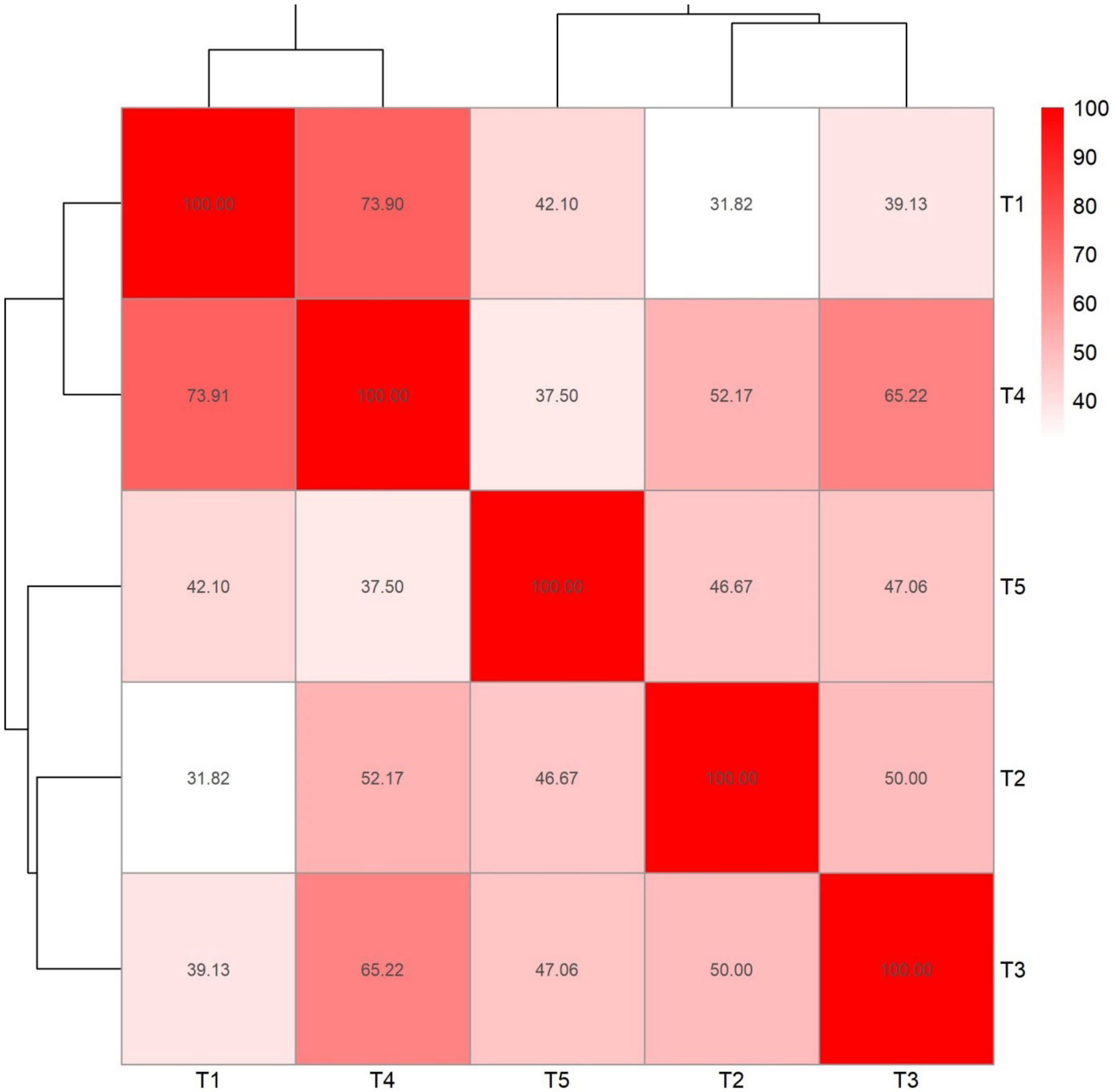
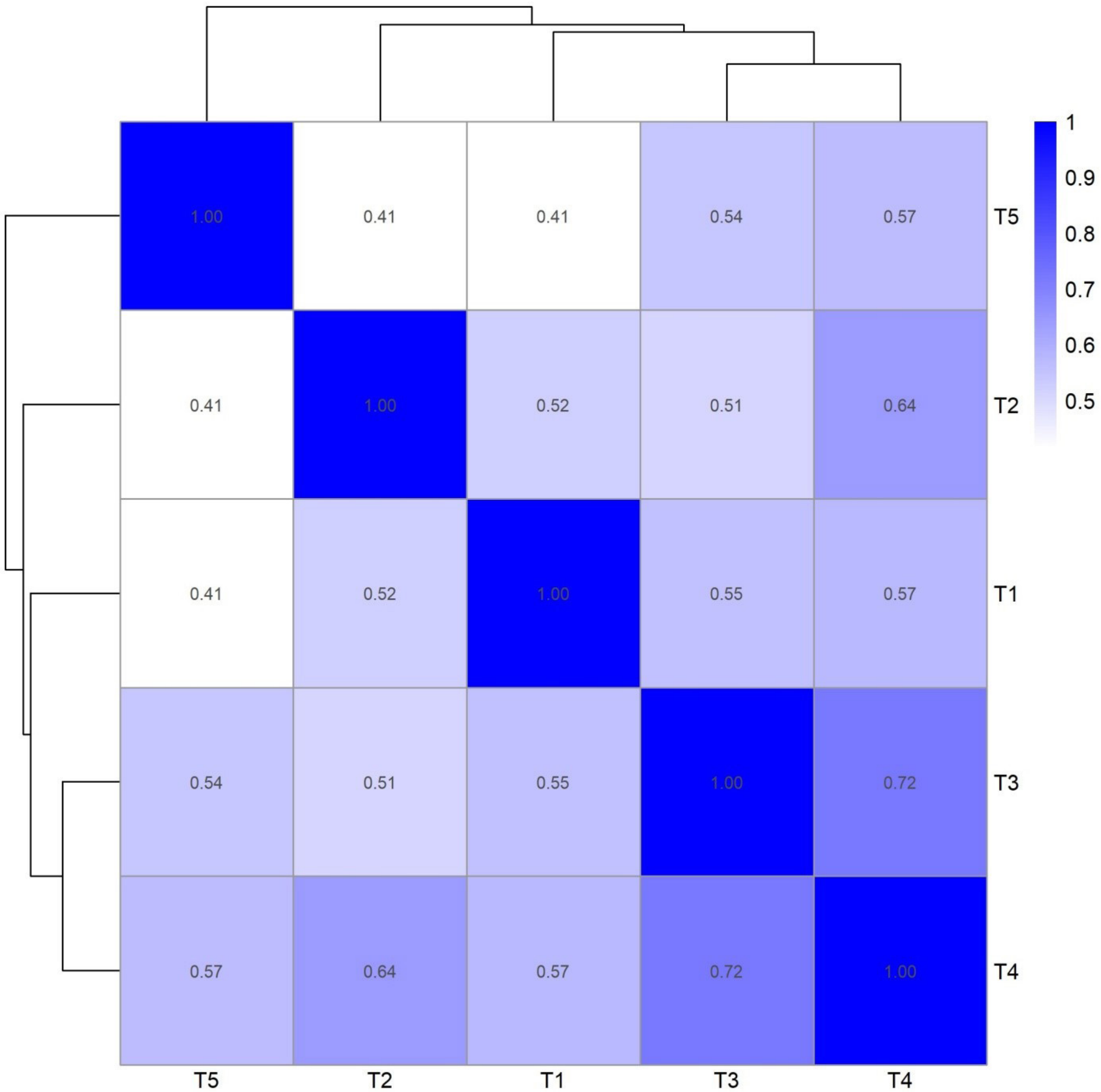


Figure 2. Steinhaus coefficient index (SA). T1 – Treatment 1; T2 – Treatment 2; T3 – Treatment 3; T4 –Treatment 4; T5 – Treatment 5



In contrast, in mineral fertilization treatments (T2 and T5), *Sorghum halepense* and *Convolvulus arvensis* were absent. Several annual species, including *Ambrosia artemisiifolia*, *Polygonum convolvulus*, *Portulaca oleracea*, *Polygonum lapathifolium*, and *Galium aparine*, were not recorded in these treatments.

Statistical analysis

NMDS ordination (Bray–Curtis, stress ≈ 0.16) indicated differentiation among treatments in two-dimensional space. T3 and T4 were positioned closer in ordination space, while T1 and T2 occupied intermediate positions and T5 was separated along the ordination axes. The ordination had a high goodness-of-fit (non-metric $R^2 = 0.973$) – as shown in Figures 1, 2, 3, 4.

Homogeneity of multivariate dispersions was not significant ($p = 0.286$), indicating no evidence of differences in dispersion among treatments. PERMANOVA revealed significant differences in weed community composition among treatments ($p = 0.001$). SIMPER analysis identified species contributing most to observed dissimilarities (Table S1 – available on the journal's website).

Figure 3. Visualization of community composition based on the NMDS in two dimensions. T1 – Treatment 1; T2 – Treatment 2; T3 – Treatment 3; T4 –Treatment 4; T5 – Treatment 5

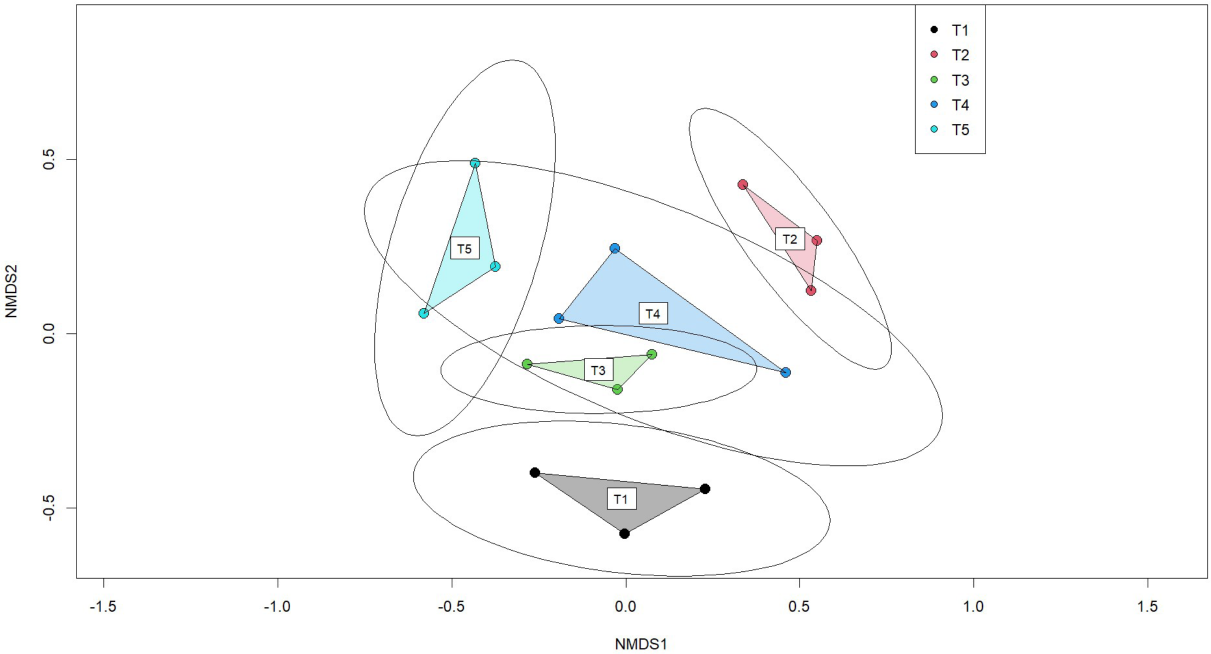
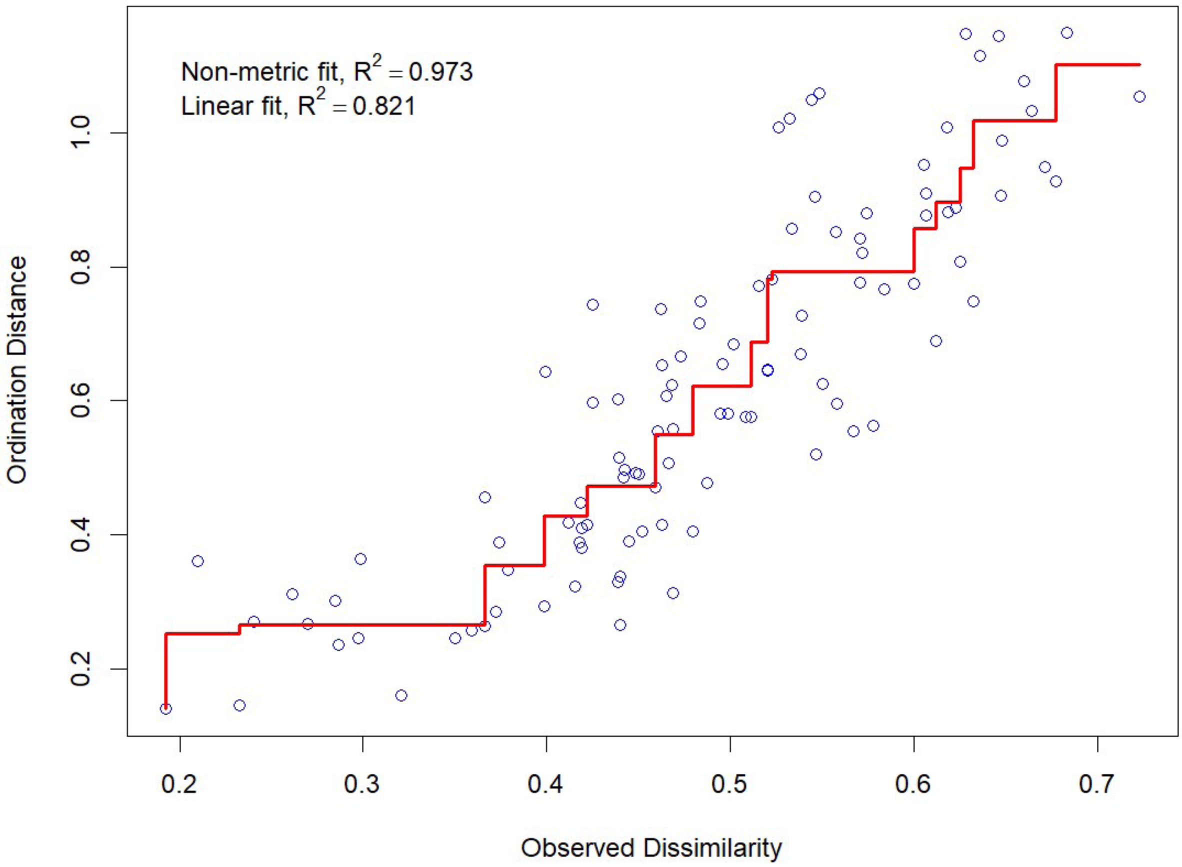


Figure 4. Shepard diagram, i.e., scatter plot of all ordination distances from the NMDS of Figure 1 (y-axis) against the corresponding observed dissimilarity (x-axis) with the fitted monotonic regression line



DISCUSSION

In this study, the fertilization regime significantly influenced weed community structure in tomato agroecosystems, as confirmed by PERMANOVA analysis (p = 0.001). Mineral NPK

fertilization (T5) was used as the control treatment, representing conventional fertilization practice in intensive crop production. Compared with this treatment, organic amendments induced changes in weed community composition and diversity [Roschewitz et al. 2005, MacLaren et al. 2020, Nyawade et al. 2021, Kousta et al. 2023]. Organic amendments, including retort beech charcoal alone or in combination with well-decomposed cattle manure, altered weed species composition and diversity compared with mineral fertilization. Similar effects of organic inputs have been reported in previous studies, mainly related to changes in soil fertility and micro-environmental conditions [Roschewitz et al. 2005, MacLaren et al. 2020, Nyawade et al. 2021, Kousta et al. 2023]. However, responses differed among diversity indices, suggesting context-dependent effects influenced by soil and management conditions [Jeffery et al. 2011, Lehmann and Joseph 2015].

Biochar treatments generally increased species richness and diversity compared with mineral fertilization. This may be associated with improved soil heterogeneity and changes in resource distribution, which can favor establishment of additional weed species. Biochar effects, however, depend on feedstock, pyrolysis conditions, application rate, and soil properties. Temporary reductions in plant-available nitrogen due to adsorption processes may also influence early plant development and competition [Clough and Condron 2010, Spokas et al. 2012].

The dominance of *Chenopodium album* and *Amaranthus retroflexus* across all treatments indicates that these species are well adapted to intensively managed systems. Their persistence is associated with high competitiveness and strong response to nitrogen availability, which allows them to dominate under different fertilization regimes [Blackshaw and Brandt 2008, Storkey and Neve 2018, Allen et al. 2024].

Organic amendments also influenced the presence of several perennial and structurally more complex weed species, including *Cirsium arvense*, *Sorghum halepense*, and species of the genus *Polygonum*. In contrast, mineral fertilization was associated with lower species richness and greater dominance of a limited number of competitive species, indicating a simplified weed community structure under conventional fertilization [Baker et al. 2018, Travlos et al. 2018, Kousta et al. 2023].

Therophytes were dominant in all treatments, reflecting the disturbed conditions typical of intensive agricultural systems. Their dominance is related to life-history traits such as rapid growth, short life cycles, and high reproductive capacity, which allow them to persist under frequent soil disturbance [Storkey and Neve 2018, Travlos et al. 2018, Ljevnaić-Mašić et al. 2022, Božić et al. 2025]

Multivariate analyses provided broadly consistent indications of treatment-related differences. Jaccard similarity suggested moderate to relatively high similarity among selected treatment pairs (notably T1–T4 and T3–T4), while Steinhaus coefficients (SA = 0.412–0.718) indicated quantitative variation in community structure. NMDS ordination (stress ≈ 0.16; $R^2 = 0.973$) suggested partial separation among treatments, with T3 and T4 appearing more similar, while T5 was separated from other treatments and characterized by comparatively reduced community complexity. PERMANOVA indicated statistically significant differences among treatments; however, interpretation of these results should consider both statistical and ecological relevance. SIMPER analysis was used descriptively to identify taxa contributing to observed dissimilarities. Overall, diversity indices, similarity measures, and ordination results showed consistent patterns, supporting the reliability of the findings.

Several methodological limitations should be considered when interpreting the present results. The experiment was conducted under field conditions with three replicates per treatment (each covering 50 m^2, total experimental area 2,500 m^2), which may reduce statistical power and increase sensitivity to spatial heterogeneity typical of agroecosystems. In addition, the study did not include a non-fertilized control treatment, as mineral NPK fertilization was used as a conventional reference for comparison among fertilization systems. Consequently, the observed patterns should be interpreted as relative differences among fertilization regimes rather than absolute fertilization effects under non-fertilized conditions. These limitations should be considered when interpreting and extrapolating the results to broader agroecological contexts. In conclusion, organic amendments modified weed community structure compared with mineral fertilization, particularly by increasing species richness and altering community composition [Roschewitz et al. 2005, MacLaren et al. 2020, Nyawade et al. 2021, Kousta et al. 2023]. Dominant nitrophilous species remained stable across treatments, while changes were mainly observed in secondary species [Blackshaw and Brandt 2008, Barroso et al. 2015, Travlos et al. 2018, Kousta, et al. 2023]. These results highlight the importance of fertilization strategy in shaping weed communities in tomato production systems.

CONCLUSION

The results of this study demonstrate that fertilization regime significantly affects weed community structure in tomato agroecosystems. Mineral NPK fertilization produced a more simplified weed community, while organic amendments resulted in increased species richness and altered community composition. Retort beech charcoal, applied alone or in combination with well decomposed cattle manure, contributed to higher weed diversity compared with mineral fertilization. However, the response of weed communities varied depending on diversity measures and environmental context, indicating that the effects of organic amendments are not uniform. Dominant species such as *Chenopodium album* and *Amaranthus retroflexus* were present across all treatments, suggesting strong ecological adaptation to intensive agricultural conditions and stability under different fertilization regimes. In contrast, organic amendments influenced the occurrence of less competitive and structurally more diverse weed species. Multivariate analyses confirmed consistent differences among fertilization treatments, supporting the reliability of the observed patterns. However, interpretation of the results should consider the field-based experimental design, limited replication, and absence of an unfertilized control, which restricts conclusions to relative differences among treatments.

In conclusion, fertilization strategy is an important driver of weed community structure in tomato production systems. Organic amendments may increase weed diversity and modify species composition compared with conventional mineral fertilization, but their effects remain context-dependent and influenced by environmental conditions.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding this work.

DECLARATION OF THE USE OF GENERATIVE AI IN THE PROCESS OF PREPARING THE PAPER

For further processing and analysis of our data, ChatGPT (OpenAI, GPT-5, accessed May 27, 2026) was used to assist in selecting appropriate statistical methods and their implementation. ChatGPT (OpenAI) was also used exclusively to assist with the English translation of the manuscript and grammatical corrections, as well as text editing. The authors reviewed and verified all content and assume full responsibility for the final version of the manuscript.

AUTHORS' CONTRIBUTIONS

S.P.Ž. – conceptualization and study design; S.P.Ž., T.P.V. – methodology development; S.P.Ž., T.P. V., D.R.J. – investigation; M.Z.P. – statistical analysis.

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