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Irrigation effects on aromatics and phenolics of eggplant (*Solanum melongena*)

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Abstract

This research examines the impact of treated and untreated wastewater on eggplant cultivation, focusing on the aroma profile and phenolic composition. The results demonstrate significant alterations in dry matter content, pH levels, and total phenolic compounds in eggplant varieties irrigated with wastewater, compared to tap water. Regarding total phenolic content, the highest result was 120.14 mg kg^{-1} in the Kemer variety irrigated with wastewater. The amount of water-soluble dry matter in eggplant varieties irrigated with physical treatment (WW1), physical + biological treatment, and municipal (tap) water (MW) was found to vary between 7.80% and 5.20%. The aromatic analysis identifies variations in volatile compounds with higher concentrations of specific components, such as farnesene <(E, E)- alpha-> (30.60%), benzene <para-dichloro-> (22.05%), and non-(2E)-enal (26.89%), under different qualities of water irrigation treatments. An increase in the purification level of irrigation water increased the percentage of farnesene <(E, E)-, alpha->, ranging from 15.13% (Aydın Siyahi, WW1) to 30.60% (Kemer, MW). The results underline the importance of sustainable water management practices and highlight the need to quality of irrigation water in agricultural areas to ensure soil health, environmental sustainability and food safety.

Keywords: aromatic compounds; climate change; food safety; sustainable agriculture; wastewater irrigation; water scarcity

Introduction

Climate change, an escalating global issue, has significantly impacted regions globally, rapidly depleting water resources. This is evident in Turkey, where the available water resources per capita have plummeted to 1,323 m^3, classifying the country as water-scarce (Anonymous, 2018, 2023). In light of this alarming trend and the burgeoning population, the agricultural sector must urgently adopt innovative water conservation strategies, emphasizing the critical need for immediate action.

Approximately 80% of the globally available freshwater is used for agricultural activities from a farming production perspective (Francaviglia and Di Bene, 2019; Ouma *et al.*, 2024). Irrigation alone accounts for 70% of all freshwater withdrawals. Between 1961 and 2019, the land used for crop production increased by 208 million hectares (15%). Irrigated cropping expanded by 110%, while rainfed cropping increased by only 2.6%. Groundwater, which constitutes over 30% of freshwater withdrawals for irrigated agriculture, grows approximately 2.2% annually. Approximately 70% of groundwater withdrawals support food, fiber, industrial crops, and livestock. The rising demand for water in agriculture is a cause for concern because of the potential for water pollution, which directly threatens health, economic development, and food security (Food and Agriculture Organization [FAO], 2022).

Various factors, such as crop type, evapotranspiration, growth stage, climate, rainfall, and soil moisture, influence irrigation. To improve water use efficiency, agronomists often use weather station data to adjust irrigation schedules (Chen *et al*., 2019). Irrigation has several benefits, such as stress reduction on crops, increased yield, and the possibility of multiple cropping within a year. It also decouples crop production from seasonal rainfall patterns (Zafar *et al*., 2020). However, optimizing irrigation remains a challenge. Farmers often rely on guesswork when applying water, leading to wastage of already scarce water resources (Müller *et al*., 2016). Deficit irrigation practices have emerged due to the scarcity and high cost of water (Mangalassery *et al*., 2019).

Using urban and treated wastewater in agriculture is crucial for sustainable water management. Although recycling of wastewater effectively conserves valuable water resources, it also poses risks due to harmful substances and pathogens that negatively impact soil quality, the environment, and human health (Polat, 2013). However, before its controlled application to soil and plants, suitability analyses must be conducted due to the presence of heavy metals and salts. Periodic soil analyses and drip irrigation mitigate potential risks and ensure safe usage, underscoring the need for careful consideration of the benefits and risks involved. However, urban wastewater is nutrient-rich, containing nitrogen and phosphorus, which can reduce reliance on chemical fertilizers and curb water pollution (Yurtseven *et al*., 2009; Demir *et al*., 2017; Tarantino *et al*., 2017).

Irrigation is pivotal in eggplant cultivation, impacting yield and quality. Drought significantly reduces eggplant yield and quality (Badr *et al*., 2020; Kouassi *et al*., 2021; Plazas *et al*., 2022). Additionally, eggplant varieties are sensitive to water stress and soil moisture (Cirelli *et al*., 2012). Eggplant, which belongs to the *Solanaceae* family, has a historical significance dating back to the 3rd century BC. It is cultivated in various climates and is the sixth most cultivated vegetable globally (FAO, 2019). Eggplant has a total global production of 59,312,599.76 tons, and Türkiye ranks the fourth largest eggplant producer, with 781,242 tons, following China, India, and Egypt (FAO, 2023). The eggplant (*Solanum melongena L.*) is among the vital fruit vegetables cultivated globally for its health and nutritional benefits (Abubakar *et al*., 2023). Regarding nutritional value, eggplant has a very low caloric value and is considered among the healthiest vegetables for its high content of vitamins, minerals, and bioactive compounds for human health (Taher *et al*., 2017). They are high in antioxidants, such as flavonoids and phenolic compounds, which promote health (Chumyam *et al*., 2013; Kantakhoo *et al*., 2022). The skins of black and purple eggplant varieties, in particular, contain anthocyanins, which are essential for good health (Colak *et al*., 2022; Fan *et al*., 2016). In addition, eggplant is considered beneficial to human health. It may potentially treat cardiovascular and other metabolic diseases because of the flesh's polyphenol and chlorogenic acid content (Plazas *et al*., 2013; Taher *et al*., 2017). Also, eggplant is rich in vitamins and minerals and can be consumed fresh or processed. It ranks second in iron content after spinach, especially eggplant stalks.

The objective of this study was to ascertain the impact of drip irrigation with treated and untreated domestic wastewater on the aromatic and phenolic compounds of eggplant. The vegetable was selected as the study material for its high content of aromatic and phenolic compounds and also its sensitivity to irrigation.

Material and Methods

Location and soil analysis

The experimental area for the research was established in 2023 in Kalecik District, Ankara, Türkiye. Kalecik is located at 40.10°N latitude and 33.40°E longitude, with an altitude of 780.00 m.

Soil analyses were conducted at the Laboratory of Soil Science and Plant Nutrition, Department of Ankara University. Potassium and phosphorus in soil were determined using an inductively coupled plasma–optical emission spectrometry (ICP-OES) device (Olsen and Cole, 1954; Pratt, 1965). Disturbed and undisturbed soil samples were collected from experimental plots (Anonymous, 1993). The soil samples underwent basic physical and chemical analyses (Anonymous, 1992; Jackson, 1960).

Plant and water materials

The study employed eggplant, a commonly cultivated crop by farmers in Turkey (Francaviglia and Di Bene, 2019; Ouma *et al*., 2024): Two different eggplant varieties, *Solanum Melongena L. cvs. Aydın Siyahı* and *cvs. Kemer* were used. The eggplant seedlings were planted with a row spacing of 70 cm and 50 cm between rows. The experiment was conducted with three replications in a randomized complete block design, considering edge effects.

A total of 15 plants were grown in each replication, and three different irrigation water methods were used: primary-treated wastewater (physical treatment; WW1), secondary-treated wastewater (physical + biological treatment; WW2) obtained from Ankara Kalecik Domestic Waste Water Treatment Plant, and municipal (tap) water (MW).

Climatic conditions and irrigation methods

The experiment was conducted in a region influenced by a continental climate. Summers are hot and dry, while winters are cold and rainy, resulting in high water demand in summers. The prevailing wind direction in Ankara and its surroundings is northeast, with an average annual wind speed of 2.1 m/s. Ankara has a semi-arid climate, which is classified as semi-arid climate (BSk) according to the Köppen Climate Classification. The yearly average temperature is below 18.0°C, and summer aridity is observed (Akman, 1990). Ankara experiences severe summers with water deficit and is classified as semi-arid (D s2 b3) according to the Thornthwaite Climate Classification. It also belongs to the first-degree mesothermal category and partially resembles marine climate.

Drip irrigation is one method used to regulate the irrigation process to optimize water usage, decrease energy consumption, and enhance crop quality. Drip irrigation was selected as the method of irrigation in the experimental area. Several factors influence irrigation, such as crop type, evapotranspiration, growth stage, climate, effective rainfall, and soil moisture. Weather significantly affects crop water requirements, and agronomists frequently use weather station data to adjust irrigation schedules to improve irrigation water use efficiency (Chen *et al*., 2019). The CROPWAT 8.0 program calculated the amount of required irrigation water and determined irrigation scheduling and intervals. The CROPWAT 8 model computed the optimal crop water need and the best irrigation scheduling.

CROPWAT 8.0 is an FAO-developed decision-support system that uses rainfall, soil, crop, and climate data to calculate reference evapotranspiration (ET_o), crop water requirement (CWR), and irrigation schedule (Smith, 2002).

Furthermore, soil moisture content and plant phenological observations were monitored during irrigation applications.

Plant analysis

This study investigates the impact of irrigation water with varying characteristics on the aromatic compounds of eggplant varieties and their effects on soluble solid content, titratable acidity, pH, and total phenolic compounds.

The solid-phase micro-extraction (SPME) method was used to analyze the composition of aromatic compounds. Specifically, 5 g of homogenized eggplant sample was placed in 20-mL vials, the lids were closed, and the samples were mixed in the vortex for 2 s. The Supelco DVB/CAR/PDMS fiber (2 cm), which had been conditioned at 200°C for 20 min for gas chromatography–mass spectrometry (GC-MS), was attached to the vial at 55°C for 30 min. After this period, the fiber was automatically injected into GC-MS for analysis.

A Shimadzu AOC-6000 GC-MS was used for aroma analysis, with a Restek RTX-5MS (30 m × 0.25 mm × 0.25 µm) column in the device (Lau *et al*., 2018) modified their method based on the nesting of peaks. The analysis employed the following parameters: injection temperature of 250°C, pressure of 90.0 kPa, column flow rate of 1.61 mL/min, column temperature-1 of 40°C with a standby time of 3 min and a rate of increase of 4°C/min, column temperature-2 of 240°C with a holding time at final temperature of 5 min, total flow of 20.7 mL/min, and a partition ratio of 1:10. The device was used to inject C^7-C^{30} alkane series according to the determined method, and retention indices (RI) were calculated. Peaks were identified in the Flavors and Fragrances of Natural and Synthetic Compounds (FFNSC) library (which contains natural and synthetic flavor and fragrance components) to determine volatile aroma components. The volatile aroma components in eggplant samples were identified by their similarity of 90% or higher to the library. They were expressed as the percentage of the areas of identified peaks in total area.

Titratable acidity in homogenized samples was determined by titration, which was monitored using a pH meter. A specific sample was titrated using a 0.1-N standardized NaOH solution and guided by a pH meter until it attained a pH of 8.1. Titration acidity regarding tartaric acid was calculated as 'g/100 mL' (Cliff *et al*., 2007).

To measure the pH, 5 gm of eggplant samples were crunched and homogenized by mixing them with 50 mL of distilled water. The resulting mixture's pH was measured using a pH meter calibrated with buffer solutions ranging from 4.0 to 7.0 (Doğanlar *et al*., 2023).

The total content of phenolic compounds in the samples was quantified using the Folin–Ciocalteu method. This analytical approach involves reducing phenolic compounds with the Folin–Ciocalteu reagent in a basic environment and then measuring the resulting blue hue using a spectrophotometer. After preparing homogenates, the translucent supernatant was used to determine the overall phenolic content. In summary, a 2-mL sample was mixed with 10 mL of 2 N (10%) Folin–Ciocalteu reagent and incubated for 3 min in the dark. Then, 8 mL of 0.7-M sodium carbonate was added. After incubating for 2 h at room temperature without light, absorbance of the reaction mixture was measured at 765 nm using a spectrophotometer. The results were expressed as milligrams of gallic acid equivalent per kilogram of fresh eggplant, following the method described by Singleton and Rossi (1965).

Statistical analyses

The study used a randomized complete block design with 15 plants in each plot. Variance analysis was performed with a significance level of $p = 0.05$, and differences between mean values were analyzed using the least significant difference (LSD) test.

Results and Discussion

Soil and irrigation water characteristics

The results of soil analysis showed that the soil structure was clayey, slightly alkaline, nonsaline, and moderately rich in organic matter, with a high content of lime (Table 1).

The irrigation water used in the experiment was obtained from the Kalecik Domestic Waste Water Treatment Plant, which has a daily capacity of 2.500 m^3. The results of analysis are provided in Table 2.

Irrigation planning

The irrigation scheduling for Kalecik was planned using climatic data from Esenboğa Station, the nearest meteorological station (Table 3). Irrigation was carried out from May to September, with 14 applications. A net irrigation water requirement of 498.10 mm was fulfilled throughout the growing period. Figure 1 depicts the amount of irrigation water used.

Results of plant analysis

The dry matter content of vegetables and fruits is crucial in determining their harvest date and maturity period. The dry matter content in this study ranged from 5.77% to 7.80%. The eggplant varieties irrigated with wastewater were observed to have high dry matter content (Table 4). Tzortzakis *et al.* (2020) reported an increase in soluble solids content with wastewater applications, compared to clean water applications in their study. Another study reported that eggplant varieties irrigated with tap water, treated wastewater, and wastewater had a high content of soluble solids (Zambi, 2022).

The pH levels of eggplant varieties ranged from 5.13 to 5.80. The highest pH level was observed in the Kemer

Table 1. Soil characteristics of trial parcels (Kalecik, Ankara, Turkiye).

Depth (cm)	Texture	Sand (%)	Silt (%)	Clay (%)	Clay + silt (%)	OM (%)	$CaCO_3$	pH	EC (dS m^{-1})
0–30	Clay	28.10817	24.90601	46.98581	71.89183	3.16	22.78	8.44	0.397
30–60	Clay	24.07214	22.94990	49.97796	72.92786	2.53	19.88	8.63	0.439

OM: organic matter; $CaCO_3$: calcium carbonate; EC: conductibility.

Table 2. Water utilized in the study conducted in Kalecik, Ankara, Turkiye.

Wastewater (WW) Analysis parameters	WW1	WW2	Municipal water (MW) Analysis parameters	MW
pH	7.50	7.10		
Total hardness ($CaCO_3$) (mg L^{-1})	341	307	Turbidity (NTU)	0.30
Conductibility (EC) (25°C, mS m^{-1})	124.70	90.30	Chlorine (mg L^{-1})	0.20
Total suspended solid matter(TSS) (mg L^{-1})	451	<10	Conductibility (EC) (25°C, mS m^{-1})	57
Total dissolved solids (TDS) (mg L^{-1})	8,119	9,247		
K (mg L^{-1})	13.20	13.10	Ammonium (mg L^{-1})	<0.06
Na (mg L^{-1})	108	111.00	Nitrite (mg L^{-1})	<0.006
SO_4 (mg L^{-1})	73.10	81.30	SO_4 (mg L^{-1})	47.1
Total N (T-N) (mg L^{-1})	53.20	21.40		
Total P (T-P) (mg L^{-1})	0.88	0.93		

WW1: physical treatments; WW2: physical + biological treatment; K: potassium; Na: sodium; SO_4: sulfate; N: nitrogen; P: phosphorus; mS m^{-1}: milliSiemens per meter.

Table 3. Long-term average meteorological data for the research area of Kalecik.

Parameter	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Av. temp. (°C)	1.30	4.80	7.80	12.70	17.60	21.30	24.90	25.40	20.70	14.10	7.20	2.80	13.40
Highest temp. (°C)	19.10	22.70	25	31.90	35.90	37.50	41.70	39.80	40.80	34.10	25.40	17.60	41.70
Lowest temp. (°C)	–19.30	–13.20	–8.40	–3.40	3.40	6.10	9.60	11.20	0	–1.90	–9.60	–12.90	–19.30
Av. number of rainy days (mm)	11.80	8.40	9.40	8.10	12.40	12.50	2.90	4.40	4.20	6.80	5.10	9	95
Monthly Av. total precipitation (mm)	5.37	23.05	42.40	18.62	57.68	68.71	8.53	20.84	19.13	18.59	19.51	33.61	376.04

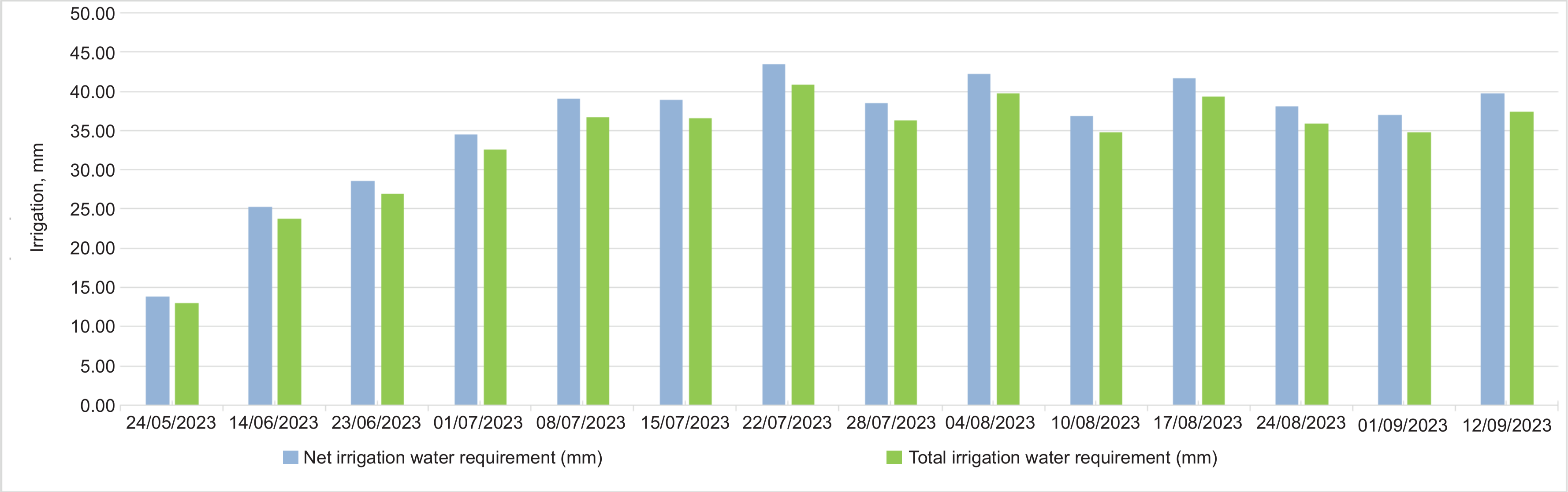

Figure 1. Total and net irrigation water requirements throughout the eggplant growth period.

Table 4. Effect of wastewater applications on chemical properties.

Irrigation water	Total phenolic matter (mg kg-1)	Water-soluble dry matter (%)	pH	Titratable acidity (%)
Kemer				
MW	99.47^{b}	5.77^{c}	5.13^{b}	0.92
WW2	114.04^{a}	6.63^{b}	5.56^{a}	0.90
WW1	120.14^{a}	7.80^{a}	5.64^{a}	0.86
LSD 5%	6.58	0.68	0.31	NS
Aydin Siyahi				
MW	80.50^{b}	5.97^{b}	5.57	0.93
WW2	106.44^{a}	6.87^{a}	5.68	0.94
WW1	114.28^{a}	7.37^{a}	5.44	0.90
LSD 5%	12.77	0.60	0.42	NS

Data are provided as mean values ± standard error, n = 3. Different superscript letters in each column indicate they are statistically different ($p \leq 0.05$; least significant difference [LSD] test). Non-letters are not statistically significant ($p > 0.05$; LSD test). MW: municipal water; WW1: physical treatments; WW2: physical + biological treatment; NS: nonsignificant.

variety irrigated with wastewater. For the Aydın Siyahı variety, wastewater applications did not significantly affect pH (Table 4). Ouansafi *et al.* (2021) conducted a study on the effect of different levels of treated wastewater on eggplant varieties. The pH was found to range from 4.7 to 5.7. Zambi (2022) found that different wastewater applications had no statistically significant effect on the pH of Kemer and Aydın Siyahı varieties, which was consistent with the results of our study.

Titratable acidity was not statistically significant in eggplant varieties (Table 4). In a separate study, where tomatoes were irrigated with wastewater, detectable acidity was observed, although it was not statistically significant. Our study found that irrigation with tap water slightly increased titratable acidity in eggplant varieties (Cirelli *et al.*, 2012).

The total values of phenolic compounds in eggplant varieties ranged from 80.50 to 120.14 mg/kg and were found to be statistically significant. The highest value was observed in the Kemer variety, irrigated with wastewater. With an increase in irrigation water levels, a decrease in total phenolic compounds was observed. The lowest values were observed in the varieties rinsed with tap water (Table 4). A study conducted on tomatoes under greenhouse conditions found that plants irrigated with treated wastewater had a higher total phenolic compound content than those irrigated with tap water (Tzortzakis *et al.*, 2020). Phenolic compounds in plants act as a defense mechanism against environmental pollution. The amount of phenolic compounds increases with environmental pollution (Dučić *et al.*, 2008). Heavy metals are present in wastewater, and the use of domestic wastewater in agriculture is one of the causes of heavy metal accumulation in soil (Rehman *et al.*, 2018). A high amount of total phenolic compounds in the species and varieties irrigated with wastewater during trial is attributed to the high metal content of wastewater.

Analyzing the distribution of aroma components using GC-MS method, 36 volatile aroma components were identified in eggplant samples (Table 5).

In all eggplant samples, volatile aroma components, such as benzene <para-dichloro->, non-(2E)-enal, Hexadecane <n->, and farnesene <(E,E)-, alpha->, were discovered, characterizing the aromatic structure with mothball-like, powerful fried fatty odor with a citrus-like background, and woody and green vegetative with a hint of a floral nuance aroma (Table 5 and Figure 2).

The Kemer variety was found to have a higher percentage of volatile aroma component, farnesene <(E,E)-, alpha->, which imparts a woody and green vegetative aroma with a hint of floral nuance, compared to the Aydın Siyahı variety. Additionally, an increase in the purification level of irrigation water resulted in a higher percentage of this component.

The aroma compound non-(2E)-enal has aroma of aldehydic, citrus, and cucumber. The lowest values were found in the samples both varieties irrigated with wastewater, while the highest values were observed in the samples irrigated with treated wastewater (Table 5 and Figure 3).

Limonene is a volatile compound with a pleasant and intense fragrance. It is commonly used in cleaning products because of its stain-removing properties and exhibits antifungal and antibacterial activity (Yaşar *et al.*, 2017). However, when applied to fruit peels, it causes

Table 5. Volatile aromatic compounds in eggplant samples %.

Aromatic compounds	Aydın Siyahı			Kemer		
	MW	WW2	WW1	MW	WW2	WW1
Farnesene <(E,E)-, alpha->	24.11	16.21	15.13	30.60	23.16	20.70
Hexadecane <n->	8.60	18.12	3.43	15.40	3.53	7.21
Benzene <para-dichloro->	11.25	22.05	3.95	6.85	15.11	2.91
Non-(2E)-enal	19.26	26.89	7.27	11.75	26.71	6.03
Limonene	3.07	1.97		3.90		
Hexanal <n->	2.99		12.35		11.57	
Octen-1-al<2E->	2.53		3.77		5.15	
Nona-(2E,6Z)-dienal	6.42		12.90		10.38	2.30
Non-(2E)-enoic acid <methyl-> ester	4.18				2.55	
Tridecane <n->	2.79			3.93		
Pentadecane <n->	2.21					10.60
Tetradec-1-ene	1.67			3.56		1.90
Heneicosane <n->	2.60					
Octadecane <n->	2.22			2.11		
Butanoic acid, 2-methyl-4-methylpentyl ester		2.64		2.40		
Heptadecane <n->				2.60		
Hexanoate <hexyl->		6.21		2.59		
Eicosane <n->		1.94		5.05		7.58
Octadecyl chloride				6.23		
Nonadecane <n->		8.53		3.05		
Furan <2-pentyl->		2.10	2.94		2.18	
Hexanoate <butyl->		2.13				
Dodecane <n->		2.43				
Nonanoic acid		2.69				
Isophytol			1.58		2.25	
Bergamotene <alpha-, cis->					5.44	
Ionone <(E)-, beta->					2.20	
Hexanoate <methyl->			1.67			
Tetradecane <n->			2.30			
Undecylenic acid methyl ester			4.33			
Hexadecanoate <methyl->			6.59			
Deca-(2E,4Z)-dienoate <ethyl->						3.31
Curcumene <alpha->						2.81
Bisabolene <beta->						1.72
Sesquisabinene						2.23
Khusimene						1.71

MW: municipal water; WW1: physical treatments; WW2: physical + biological treatment.

discoloration (Beuning *et al.*, 2010). Our study identified limonene in the Aydın black variety (Aydın Siyahı), and a decrease in purification levels reduced limonene content (Table 5 and Figure 3).

Exposure to aromatic hydrocarbons, such as benzene, poses significant health risks because of its carcinogenic effects. Benzene exposure may lead to conditions, such as leukemia, aplastic anemia, immune system disorders,

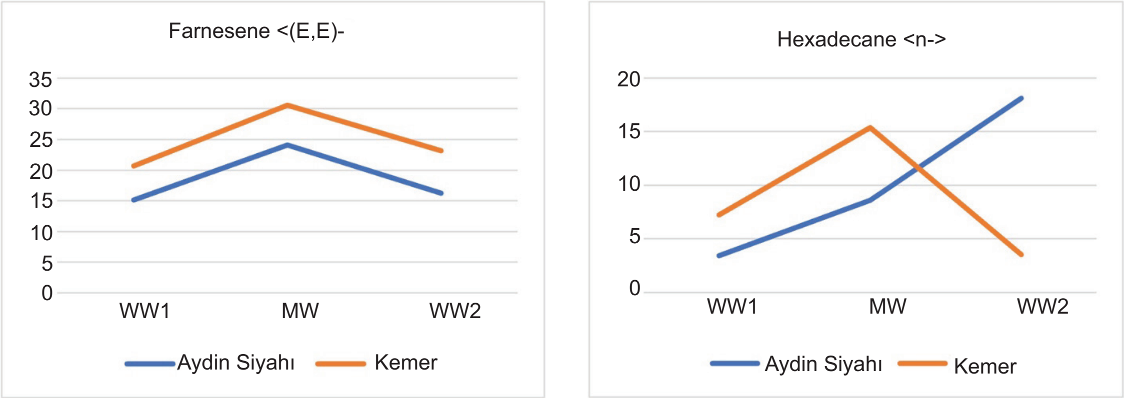

Figure 2. The amount of farnesene <(E,E)-> and hexadecane <n->in eggplant varieties irrigated with different wastewater methods. MW: municipal water; WW1: physical treatments; WW2: physical + biological treatment.

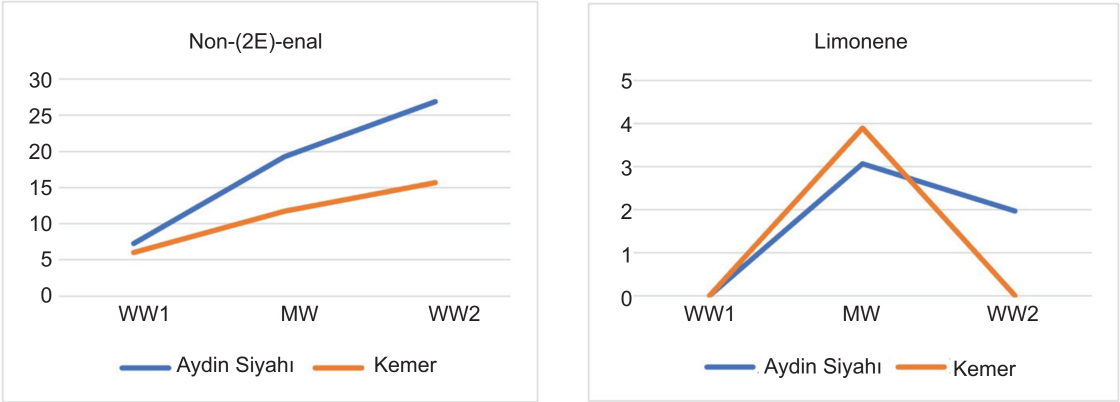

Figure 3. The amount of non-(2E)-enal and limonene in eggplant varieties irrigated with different wastewater methods. MW: municipal water; WW1: physical treatments; WW2: physical + biological treatment.

skin irritation, and an increased likelihood of infection (Xiang *et al*., 2019). The concentration of benzene varies between 2.91% and 22.05%, which is higher in both eggplant varieties irrigated with WW2. Research suggests that the wastewater treatment method significantly affects the quantity of benzene (Thanekar *et al*., 2021). This could be due to the technique used during biological treatment (Table 5 and Figure 4).

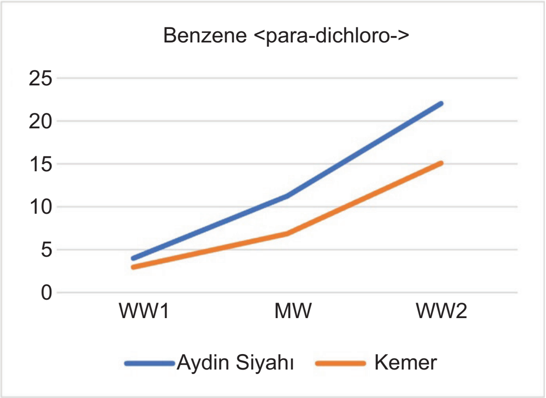

Figure 4. The amount of benzene <para-dichloro-> in eggplant varieties irrigated with different wastewater methods. MW: municipal water; WW1: physical treatments; WW2: physical + biological treatment.

Conclusions

The research demonstrated that irrigation with treated and untreated wastewater significantly influenced eggplant's various characteristics. Eggplant varieties irrigated with wastewater exhibited higher dry matter content, altered pH levels, and increased total phenolic compounds than those irrigated with tap water. These findings suggested that the source of irrigation water influenced the quality and nutritional value of eggplant varieties.

The research identified a notable impact of wastewater treatment on eggplant's aromatic profiles. Specifically, the Kemer eggplant variety exhibited a significant concentration of specific aroma components, notably farnesene, under different wastewater treatment conditions. Additionally, variations in the concentrations of potentially hazardous compounds, such as benzene, were observed in eggplant varieties irrigated with different wastewater treatment methods, highlighting the importance of wastewater treatment methods in agricultural practices.

The findings underscore the importance of sustainable water management practices, particularly in the regions facing water scarcity and climate change challenges. While using treated wastewater in agriculture presents opportunities for water conservation and nutrient recycling, carefully considering potential risks, such as harmful substances and pathogens, is essential to ensure soil quality, environmental health, and food safety. Implementing suitable irrigation strategies and periodic soil analyses, coupled with drip irrigation techniques, can mitigate risks associated with wastewater irrigation and contribute to sustainable agricultural practices.

The future research efforts must focus on further investigating the specific mechanisms underlying the influence of irrigation water quality on eggplant characteristics, including the role of different wastewater treatment methods. Additionally, longitudinal studies assessing the long-term impacts of wastewater irrigation on soil health, crop quality, and human health outcomes would provide valuable insights for policymakers, agricultural stakeholders, and researchers seeking to address the complex challenges at the intersection of water management, agriculture, and food security.

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