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Article

Effect of Regulated Deficit Irrigation on Quality and Key Aroma-Active Compounds of Tomato (*Solanum lycopersicum* L.) Fruit

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Abstract: To investigate the effects of regulated deficit irrigation (RDI) on tomato fruit quality and flavor, a study was conducted using the tomato cultivar 'Gaotang No. 1' under three irrigation treatments: CK (conventional irrigation, 16 m³/mu per session), T1 (50% reduction, 8 m³/mu), and T2 (25% reduction, 12 m³/mu). The impact on plant growth, yield, fruit quality, and volatile organic compounds (VOCs) was evaluated. Results showed that the T2 treatment significantly reduced yield (−26.55%) but enhanced fruit firmness (35.57% increase in shoulder hardness), soluble solids (14.56%), vitamin C content (44.19%), and the sugar-to-acid ratio (2.25%). Volatile analysis revealed that T2 markedly increased the concentration of key aroma compounds with odor activity values (OAV) >10, including 2-pentyl furan (24.71%), (Z)-3,7-dimethyl-1,3,6-octadecatriene (128.49%) contributing to floral aroma, 2-ethyl-5-methylpyrazine (204.10%) associated with fruity aroma, and 4-isopropyltoluene (125.79%) contributing to citrus aroma. These compounds significantly shaped the overall aroma profile, resulting in a richer flavor. The findings confirm that moderate RDI (25% reduction) effectively balances yield and fruit quality by improving texture, nutritional value, and aroma complexity, offering a promising strategy for water-efficient, quality-focused tomato production.

Keywords: tomato; *Solanum lycopersicum*; regulated deficit irrigation; fruit quality; aroma-active compounds

1. Introduction

Tomato (*Solanum lycopersicum* L.), a globally cultivated and economically important crop, is highly valued for its nutritional richness—including amino acids, vitamins, and minerals—and is widely consumed both fresh and cooked. Due to evolving consumer preferences, there is increasing demand for tomatoes with improved nutritional value and flavor, surpassing traditional breeding priorities such as disease resistance, yield, and storability (Wang et al., 2016; Li et al., 2023).

Tomato flavor is a complex combination of aroma, taste, and texture. Sugars, organic acids, and bitter compounds primarily determine taste (Klee & Tieman, 2018), while volatile organic compounds (VOCs) are essential for aroma (Yury et al., 2020). As secondary metabolites, VOCs impart distinctive floral, fruity, grassy, fatty, malty, roasted, sweet, and pungent notes that significantly influence sensory perception (Hadi et al., 2013; Amal et al., 2020). Together with sugars and acids, VOCs play a crucial role in consumer preference and product classification (Ning et al., 2023).

Tomato quality is influenced by genetic background, cultivation practices, and harvest maturity (Cheng et al., 2020; Li et al., 2024; Liu et al., 2024). Adjusting cultivation conditions can greatly improve fruit quality. Strategies such as soilless cultivation (Jinghua et al., 2022), grafting (Rivelli et al., 2024), compost leachate application (Li et al., 2024), and the use of plant growth regulators (Ruirui

et al., 2023) have shown beneficial effects. Recently, regulated deficit irrigation (RDI) has gained interest as an effective water-saving technique (Silvia et al., 2024). Studies indicate that RDI reduces water and fertilizer input while improving fruit quality, though it may reduce fruit weight and yield (Costa et al., 2007; Kumar et al., 2015; Lahoz et al., 2016; Nangare et al., 2016; Ning et al., 2023; Zegbe-Domínguez et al., 2003). Despite concerns about yield, some studies have shown that a 50% reduction in irrigation during flowering and fruit set reduced yield by only 13%, while maintaining a high percentage of marketable fruit (Cui et al., 2020; Lahoz et al., 2016). Thus, moderate yield trade-offs may be acceptable to growers when fruit quality improves.

Interestingly, soluble sugar content is often inversely related to fruit size, whereas VOC levels are generally independent of fruit weight (Klee & Tieman, 2018). Furthermore, VOCs influence the perceived sweetness and acidity of fruit, contributing to flavor independently of sugar concentration (Tieman et al., 2012; L et al., 2014). This suggests that flavor can be enhanced without compromising yield or drastically altering sugar levels.

In this study, we applied two levels of regulated deficit irrigation during the first fruit-setting stage of tomatoes and evaluated plant growth, fruit yield, nutrient content, and VOC profiles. The goal was to determine whether tomato fruit quality and flavor could be improved under RDI with minimal yield loss, providing a scientific basis for flavor-oriented, water-efficient cultivation practices.

2. Materials and Methods

2.1. Experimental Basics

The study was conducted from January to June 2022 in a greenhouse (6 m wide, 30 m long, and 3 m high) located at the Hebei Modern Agricultural Experimental Park, Shijiazhuang City, Hebei Province, China. The experimental plots measured 2 m × 10 m and were arranged in a randomized design with three replications.

Tomatoes were cultivated on north–south-oriented ridges. A drip irrigation line was installed in the center of each row, with emitters spaced 30 cm apart and a flow rate of 3 L/h. After laying the drip irrigation lines, a transparent polyethylene mulch film was applied. Planting holes were created through the film, and seedlings were transplanted accordingly.

Each plot was equipped with an independent irrigation system, consisting of a main water supply pipe with an installed water meter. Water from the main pipe flowed into sub-pipes connected to individual drip lines. A separate valve per plot allowed precise control over irrigation volume.

The tomato cultivar ‘**Gaotang No. 1**’ was used. Seeds were sown in 72-cell seedling trays under greenhouse conditions on January 3, 2022. Uniform seedlings were transplanted on March 8 at a spacing of 1.0 m between rows and 0.33 m between plants. Single-stem pruning was applied throughout the growing season. The plants were terminated on June 22.

The soil at the site was classified as calcareous cinnamon soil. Before planting, the soil was amended with **2,400 kg·mu⁻¹ of cattle manure**, **800 kg·mu⁻¹ of poultry manure**, and **20 kg·mu⁻¹ of compound fertilizer** (N–P₂O₅–K₂O: 18–12–20). During the reproductive stage, fertigation was performed at each fruit-setting stage using a high-potassium fertilizer (N–P₂O₅–K₂O: 18–6–39).

2.2. Irrigation Treatments

Initial irrigation (18 m³·mu⁻¹) and seedling recovery irrigation (12 m³·mu⁻¹) were applied on March 8 and March 15, respectively. The main irrigation treatments began on April 25, 2022, after the first fruit cluster had set. Three irrigation regimes were applied:

- **CK (control):** Conventional irrigation, 16 m³·mu⁻¹ per application
- **T1:** 50% reduction, 8 m³·mu⁻¹ per application
- **T2:** 25% reduction, 12 m³·mu⁻¹ per application

Each treatment was irrigated 10 times throughout the growing period.

2.3. Measurement Indexes and Methods

2.3.1. Plant Growth and Yield

Plant height and stem diameter were measured on March 31, May 6, and June 7, 2022. Ten plants were randomly selected from each plot. Plant height was measured using a telescopic ruler, while stem diameter (1 cm below the first, second, and third fruit clusters) was measured using a digital caliper.

Harvesting began on June 24 and continued until plant termination. Total yield was calculated as grams per square meter (g/m²). The fruit cracking rate (%) was also recorded.

2.3.2. Fruit Quality Analysis

Fifteen fruits at uniform maturity were harvested from the second fruit cluster on May 14 for quality evaluation:

- **Single fruit weight:** Measured using a precision balance (±0.01 g).
- **Fruit firmness:** Measured at the shoulder, equator, and blossom end using a GY-4 digital fruit firmness tester.
- **Moisture and dry weight:** Five fruits per replicate were weighed fresh, oven-dried at 120 °C for 20 minutes (enzyme inactivation), then further dried at 80 °C to a constant weight. Moisture content (%) was calculated as:

$$\frac{(Fresh\ weight\ (g) - Dry\ weight\ (g)) \times 100}{Fresh\ weight\ (g)}$$

- **Nutritional quality** (based on Hesheng, 2004):
 - Soluble solids: TD-45 refractometer
 - Titratable acidity: Standard titration method
 - Vitamin C: 2,6-dichlorophenolindophenol titration
 - Soluble sugars: Anthrone colorimetry
 - Lycopene: Spectrophotometry

The sugar-to-acid ratio was calculated using soluble sugar and titratable acidity values.

2.3.4. VOCs Analysis

Fruits were frozen at -80 °C, ground in liquid nitrogen, and homogenized. A 500 mg sample was transferred to a headspace vial containing saturated NaCl solution and 10 µL of internal standard solution (50 µg·mL⁻¹). Volatile organic compounds (VOCs) were extracted using automated headspace solid-phase microextraction (HS-SPME) and analyzed by gas chromatography–mass spectrometry (GC-MS) using the NIST17 spectral library.

- **Qualitative analysis:** Conducted using the GC-MS workstation with the following parameters: initial area cut-off = 10,000; initial peak width = 0.1; shoulder peak detection = OFF; initial threshold = 5.0. Identification was based on matches from the NIST17S library.
- **Quantitative analysis:** n-Hexane was used as an internal standard. VOC concentrations (µg·kg⁻¹) were calculated as:

$$\frac{[(\frac{peak\ area\ of\ each\ component}{peak\ area\ of\ internal\ standard}) \times concentration\ of\ internal\ standard\ (\mu g - ml^{-1}) \times volume\ of\ internal\ standard\ (\mu L)]}{volume\ of\ sample\ (g)}$$

2.4. Data Analysis

Orthogonal Partial Least Squares Discriminant Analysis (OPLS-DA) was performed using **Origin 2024** to differentiate VOC profiles. Variables with **VIP ≥ 1** and **p < 0.05** were considered

significant. Aroma classifications were referenced from the **Flavor Extract Manufacturers Association (FEMA)** Flavor Ingredient Library (1999). Odor activity values (OAVs) were calculated using the following formula:

$$OAV = \frac{\text{compound concentration}}{\text{odor threshold in water}}$$

Odor thresholds were obtained from Zeist (2011).

3. Results and Analysis

3.1. Plant Height and Stem Diameter

Both T1 and T2 treatments significantly reduced plant height compared to the control (CK) (Figure 1). On May 6, T1 and T2 decreased plant height by 8.24% and 9.22%, respectively. By June 7, the reductions reached 13.10% (T1) and 10.83% (T2). However, no significant difference in plant height was observed between T1 and T2 at either time point. Regarding stem diameter, T2 showed a significant increase of 13.71% ($p < 0.05$) on May 6, whereas T1 did not differ significantly from CK. By June 7, T2 maintained the largest stem diameter, although the difference from CK was not statistically significant, while T1 exhibited a significant reduction of 16.48% ($p < 0.05$).

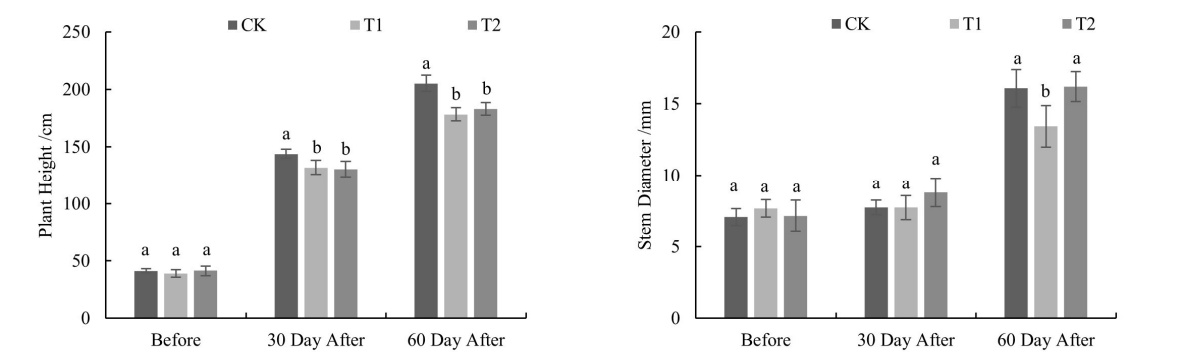


Figure 1. Plant height and stem thickness of tomatoes at different times under regulated deficit irrigation (RDI).

3.2. Fruiting Characteristics, Yield, and Fruit Cracking Rate of Tomatoes

As shown in Table 1, compared with the control (CK), the number of fruiting ears per plant under the T1 treatment was significantly reduced by 13.11% ($p < 0.05$), while no significant reduction was observed under T2. The number of fruits per plant was significantly decreased by 19.16% and 13.76% under T1 and T2, respectively, with no significant difference between the two treatments. Tomato yield was significantly reduced by 37.03% under T1 and 26.55% under T2, with T2 showing a significantly higher yield than T1 ($p < 0.05$). Notably, the fruit cracking rate was significantly reduced by 57.05% in T2 ($p < 0.05$), whereas T1 had no significant effect on cracking compared to CK.

Table 1. Fruiting characteristics, yield, and cracking rate of tomato under regulated deficit irrigation (RDI).

Treatment	Number of fruiting ears	Number of fruits	Yield	Split
		pcs	g m-2	%
CK	6.33±2.16a	26.67±0.67a	5074.68±207.18a	17.86±3.00a
T1	5.50±3.98b	21.56±0.71b	3195.41±210.86c	14.74±1.50a
T2	6.00±2.98ab	23.00±0.50b	3727.26±121.59b	7.67±1.50b

3.3. Fruit Weight, Moisture, and Dry Weight of Tomato Fruits

As illustrated in Figure 2, compared with the control (CK), the single fruit weight was significantly reduced by 16.14% under the T1 treatment ($p < 0.05$), while T2 showed a non-significant reduction of 5.45%. No significant differences were observed among treatments in fruit moisture content. However, dry weight was significantly reduced by 16.56% under T1, whereas T2 showed no significant change compared to CK.

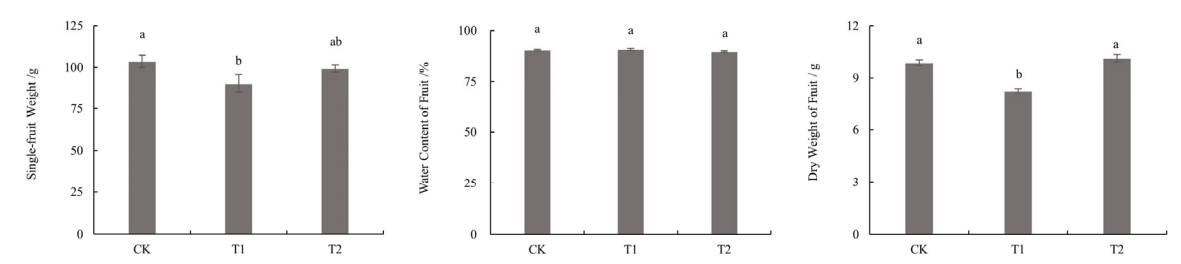


Figure 2. Single-fruit weight, moisture, and dry weight of tomato fruits under regulated deficit irrigation (RDI).

3.4. Hardness of Tomato Fruit

As shown in Table 2, compared with CK, fruit shoulder hardness significantly increased by 23.71% under T1 and by 35.57% under T2 ($p < 0.05$). Similarly, fruit equatorial hardness was significantly enhanced by 25.85% in T1 and 19.39% in T2. In contrast, fruit umbilical hardness was significantly reduced by 20.36% under T2, while no significant difference was observed in T1 compared to CK.

Table 2. Determination of hardness of various parts of tomato fruits under different water consumption.

Treatment	Fruit shoulder hardness	Equatorial surface hardness	Navel hardness
-----N-----			
CK	10.40±0.37b	8.77±0.24b	9.17±0.56a
T1	12.87±0.73a	11.03±0.40a	8.43±0.26a
T2	12.98±0.73a	10.47±0.29a	7.20±0.29b

3.5. Nutritional Quality of Tomato Fruits

As shown in Table 3, compared with CK, lycopene content decreased by 23.45% in T1 ($p < 0.05$), while it increased by 6.70% in T2 ($p < 0.05$). Vitamin C content increased by 9.24% in T1 and by 44.19% in T2 ($p < 0.05$). Soluble solids content rose by 4.43% and 14.56% in T1 and T2, respectively ($p < 0.05$). Soluble sugar content significantly increased by 8.12% in T2 ($p < 0.05$), with no significant change in T1. Titratable acid increased by 8.82% in T1 and 5.88% in T2 ($p < 0.05$). The sugar-to-acid ratio significantly decreased by 9.71% in T1 and increased by 2.25% in T2 ($p < 0.05$).

Table 3. Determination of nutrient quality of tomato fruits under different water use levels.

Treatment	Lycopene content	Vitamin C content	Soluble Solids content	Soluble Sugar content	Titratable Acid content	Sugar-acid Ratio
-----mg/100g/FW----- %/FW-----						
CK	3.88±0.23b	15.69±0.04c	7.90±0.04c	6.65±0.01b	0.68±0.02c	9.77±0.05b
T1	2.97±0.07 c	17.14±0.12b	8.25±0.04b	6.56±0.12b	0.74±0.01a	8.85±0.03c
T2	4.14±0.01 a	22.62±0.08a	9.05±0.01a	7.19±0.06a	0.72±0.01a	9.99±0.10a

3.6. Volatile Organic Compounds

3.6.1. Composition and Abundance of VOCs

GC-MS detected a total of 526 volatile organic compounds (VOCs) in both CK and T2 treatments. Data analysis using Orthogonal Partial Least Squares Discriminant Analysis (OPLS-DA) revealed a significant separation between the groups, as shown in the score plot (Figure 3A) (A et al., 2015). The OPLS-DA model ($Q^2 > 0.5$, $p < 0.05$) identified 131 differential metabolites with Variable Importance in the Projection (VIP) scores ≥ 1 and p -values ≤ 0.05 . These metabolites were classified into nine groups: alcohols, aromatics, phenols, aldehydes, terpenes, hydrocarbons, ketones, esters, and heterocyclic compounds. As illustrated in Figure 3B, terpenes were the dominant class in CK (23.25%), followed by heterocyclics (16.04%) and aromatics (13.39%). In T2, terpenes remained predominant (21.24%), but heterocyclics (17.69%) and phenols (13.96%) increased. T2 showed a reduction in the proportions of terpenes, ketones, and heterocyclics, while alcohols, aromatics, phenols, aldehydes, hydrocarbons, and esters were elevated, indicating a reconfiguration of the VOC profile without a change in overall diversity.

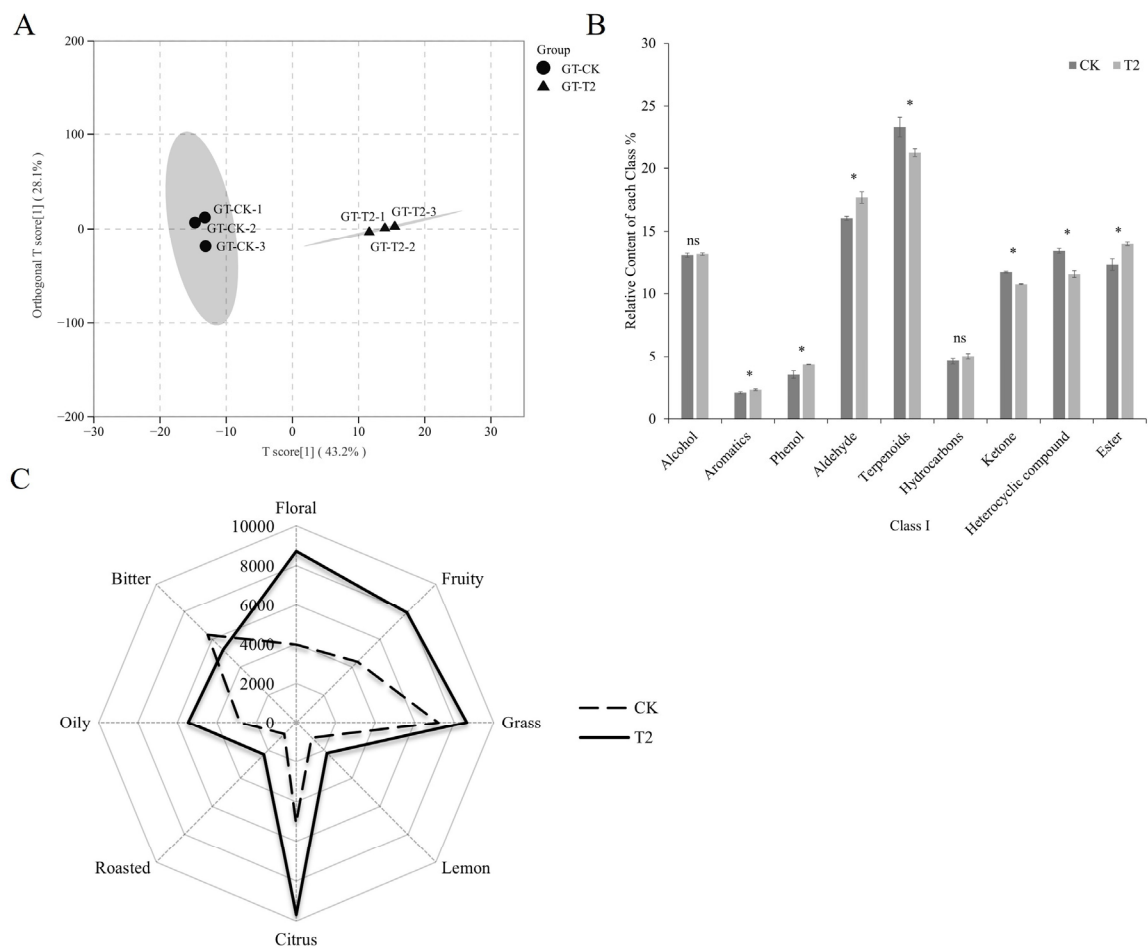


Figure 3. Effect of RDI on volatile substances in tomato fruits. A: OPLS-DA score plot; B: Percentage of each volatile substance; C: Radar plot of aroma composition; * denotes significant at $p < 0.05$ for T-test; NS denotes not significant.

3.6.2. Key Aroma-Active Compounds

Among the 44 flavor-impacting VOCs listed in Table 4, T2 significantly reduced the levels of 3-methyl-2-cyclohexen-1-one (−4.85%), 2-acetylpyrrole (−6.15%), benzaldehyde (−20.36%), eugenol (−29.73%), 2-isobutylthiazole (−29.90%), benzyl benzoate (−36.12%), and trans- β -farnesene (−37.83%).

Conversely, T2 markedly increased compounds such as 4-propylphenol (+275.37%), 2-ethyl-5-methylpyrazine (+204.10%), undecanol (+188.72%), nerol acetate (+178.50%), 2-undecenal (+178.45%), (E)-2-undecenal (+173.52%), 4-hydroxybenzaldehyde (+162.06%), ocimene (+142.67%), phellandrene (+135.07%), (Z)-3,7-dimethyl-1,3,6-octadecatriene (+128.49%), 4-isopropyltoluene (+125.79%), and trans-2-decenal (+103.63%), with other compounds increasing by 11.88–97.53%. Overall, the total content of aroma-active compounds was higher in T2 than in CK.

The contribution of volatile compounds to aroma depends not only on their concentration but also on their odor thresholds. Odor Activity Value (OAV) analysis, a widely accepted approach for identifying key aroma-active compounds in foods, accurately evaluates the individual impact of volatiles on the overall aroma profile (L et al., 2014; Shewmaker et al., 2000). Generally, compounds with OAV > 1 are considered aroma contributors, while those with OAV > 10 play critical roles in defining the aroma profile (Gong et al., 2024). As shown in Table 5, CK and T2 contained 22 and 23 compounds with OAV > 10, respectively. Additionally, five compounds in both treatments exhibited OAVs between 1 and 10, indicating moderate aroma contributions.

Aroma-active compounds (OAV > 1) were grouped into eight categories (Table 5): floral, fruity, green, citrus, oily, baked, lemony, and bitter. Radar plots (Figure 3C) revealed distinct aroma profiles: CK was characterized by dominant green, citrus, and bitter notes, whereas T2 emphasized floral, fruity, green, and citrus attributes with reduced bitterness. This shift suggests that water reduction reconfigured the aroma signature, enhancing desirable sensory characteristics while diminishing off-flavors.

Table 4. Types of volatile substances, aroma description and content of tomato fruits.

No.	CAS	Class I	Compounds	Aroma Description	Threshold	OAV ^a		relative content, µg kg ⁻¹	
					in water, mg kg ⁻¹	CK	T2	CK	T2
1	20125-84-2	Alcohol	3-Octen-1-ol, (Z)-	Dust, Toasted Nut	– ^b	–	–	1125.83±48.95	1618.46±57.71
2	18409-18-2	Alcohol	2-Decen-1-ol, (E)-	Fruit	–	–	–	765.87±41.57	1559.51±211.56
3	112-42-5	Alcohol	1-Undecanol	Mandarin	0.700000	1.10	3.18	771.46±44.72	2227.38±86.01
4	104-54-1	Alcohol	2-Propen-1-ol, 3-phenyl-	Floral, Honey, Oil	0.077000	10.82	14.23	832.92±33.67	1095.9±10.03
5	628-99-9	Alcohol	2-Nonanol	Cucumber	0.058000	15.78	24.21	915.07±128.51	1403.9±27.54
6	100-51-6	Alcohol	Benzyl Alcohol	Boiled Cherries, Moss, Roasted Bread, Rose	2.546210	0.55	0.73	1393.78±166.62	1859.25±151.17
7	98-00-0	Alcohol	2-Furanmethanol	Burnt, Caramel, Cooked	4.500500	0.33	0.38	1472.23±49.58	1690.18±50.74
8	1195-32-0	Aromatics	Benzene, 1-methyl-4-(1-methylethenyl)-	Citrus, Pine	0.085000	14.28	16.43	1213.74±38.85	1396.21±13.36
9	99-87-6	Aromatics	p-Cymene	Citrus, Fresh, Solvent	0.005010	184.81	417.29	925.9±44.9	2090.6±168.78
10	645-56-7	Phenol	Phenol, 4-propyl-	Additives for fruit ices, jams, chewing gum	0.107000	5.30	20.00	567.21±117.23	2139.79±104.12
11	97-53-0	Phenol	Eugenol	Burnt, Clove, Spice	0.002500	1625.74	1142.38	4064.35±265.06	2855.95±134.19
12	123-08-0	Aldehyde	BenzAldehyde, 4-hydroxy-	Roast	–	–	–	878.27±35.94	2301.59±137.88
13	53448-07-0	Aldehyde	2-Undecenal, E-	Bakery, Dairy, Meat, Seasoning Pickle Additives	0.001400	601.17	1644.30	841.64±65.59	2302.03±161.4
14	2463-77-6	Aldehyde	2-Undecenal	Bakery, Dairy, Meat, Seasoning Pickle Additives	–	–	–	810.23±30.02	2256.06±122.44
15	5910-87-2	Aldehyde	2,4-Nonadienal, (E,E)-	Cereal, Deep Fried, Fat, Watermelon, Wet Wool	0.000100	10266.53	18183.86	1026.65±133.63	1818.39±139.21
16	100-52-7	Aldehyde	BenzAldehyde	Bitter Almond, Burnt Sugar, Cherry, Malt, Roasted Pepper	0.750890	1.48	1.18	1108.55±21.31	882.83±20.73
17	111-71-7	Aldehyde	Heptanal	Citrus, Fat, Green, Nut	0.002800	381.74	537.24	1068.87±30.31	1504.28±45.59
18	66-25-1	Aldehyde	Hexanal	Apple, Fat, Fresh, Green, Oil	0.061500	10.85	17.19	667.37±45.32	1057.05±27.89
19	3913-81-3	Aldehyde	(E)-2-Decenal	Fat, Fish, Orange	0.002700	206.48	775.05	557.48±99.61	2092.64±65.66
20	25152-84-5	Aldehyde	2,4-Decadienal, (E,E)-	Coriander, Deep Fried, Fat, Oil, Oxidized	0.000077	16250.31	20052.04	1251.27±61.5	1544.01±51.11
21	35158-25-9	Aldehyde	2-Isopropyl-5-methylhex-2-enal	Floral	–	–	–	822.05±75.88	1384.37±128.68
22	13877-91-3	Terpenoids	.beta.-Ocimene	Floral	–	–	–	1309.88±400.45	3178.73±583.19
23	18794-84-8	Terpenoids	(E)-.beta.-Farnesene	Spice, herb, fresh green, sweet	–	–	–	1751.63±115.65	1088.94±61.17
24	99-85-4	Terpenoids	.gamma.-Terpinene	Bitter, Citrus	1.000000	1.14	1.50	1139.89±16.62	1495.44±42.78
25	3338-55-4	Terpenoids	1,3,6-Octatriene, 3,7-dimethyl-, (Z)-	Floral	0.034000	36.65	83.75	1246.21±373.83	2847.45±491.32
26	99-86-5	Terpenoids	1,3-Cyclohexadiene, 1-methyl-4-(1-methylethyl)-	Lemon	0.080000	14.00	27.65	1119.74±347.31	2211.81±382.22

27	99-83-2	Terpenoids	.alpha.-Phellandrene 1	Citrus, Fresh, Mint, Pepper, Spice, Wood	0.040000	29.29	68.85	1171.55±437.16	2753.98±478.16
28	1193-18-6	Ketone	2-Cyclohexen-1-one, 3-methyl-	Savory	-	-	-	1027.06±11.1	977.3±9.21
29	2497-21-4	Ketone	4-Hexen-3-one	Fruit	-	-	-	1507.44±74.97	1728.39±26.55
30	30086-02-3	Ketone	3,5-Octadien-2-one, (E,E)-	Green	0.100000	18.45	20.64	1844.87±46.97	2064.1±38.23
31	3796-70-1	Ketone	5,9-Undecadien-2-one, 6,10-dimethyl-, (E)-	Fruit	0.060000	29.87	18.30	1792.31±113.17	1097.75±58.19
32	110-93-0	Ketone	5-Hepten-2-one, 6-methyl-	Citrus, Mushroom, Pepper, Rubber, Strawberry	0.068000	14.86	17.77	1010.69±10.07	1208.68±28.15
33	1072-83-9	Heterocyclic compound	Ethanone, 1-(1H-pyrrol-2-yl)-	Bread, Cocoa, Hazelnut, Licorice, Walnut	58.585250	0.02	0.02	1026.21±6.3	963.10±22.23
34	18640-74-9	Heterocyclic compound	2-Isobutylthiazole	Green, Tomato, Tomato Leaf, Wine	0.029000	17.46	12.24	506.47±8.82	355.03±8.21
35	13360-64-0	Heterocyclic compound	Pyrazine, 2-ethyl-5-methyl-	Fruit, Green	0.016000	63.61	193.43	1017.71±415.87	3094.86±519.07
36	3777-69-3	Heterocyclic compound	Furan, 2-pentyl-	Butter, Floral, Fruit, Green Bean	0.005800	172.68	215.36	1001.55±61.01	1249.09±70.06
37	539-90-2	Ester	Butanoic acid, 2-methylpropyl ester	Fruit	0.009400	106.84	168.83	1004.3±64.62	1587.03±70.14
38	112-32-3	Ester	Formic acid, octyl ester	Floral	-	-	-	894.11±97.05	1350.55±89.24
39	112-06-1	Ester	Acetic acid, heptyl ester	Floral, Fresh	0.420000	2.16	3.23	905.4±70.49	1355.18±79.3
40	122-72-5	Ester	3-Phenyl-1-propanol, acetate	Floral	-	-	-	577.91±184.22	1044.9±121.21
41	659-70-1	Ester	Butanoic acid, 3-methyl-, 3-methylbutyl ester	Green	0.020000	44.41	70.85	888.23±71.54	1416.91±171.11
42	120-51-4	Ester	Benzyl Benzoate	Balsamic, Herb, Oil	0.341000	3.86	2.46	1315.52±140.07	840.36±55.24
43	141-12-8	Ester	2,6-Octadien-1-ol, 3,7-dimethyl-, acetate, (Z)-	Floral, Fruit	2.000000	0.39	1.09	786.34±60.03	2189.92±125.53
44	2311-46-8	Ester	Hexanoic acid, 1-methylethyl ester	Fresh	-	-	-	1031.25±126.21	1592.28±200.12
total content, µg kg ⁻¹								48957.05±2716.49	74772.15±2672.71

^aData sources [Flavor Extract Manufacturers Association \(FEMA\) \(femaflavor.org\)](https://www.femaflavor.org/) (*Flavor Ingredient Library*, 1999) and ODOUR THRESHOLDS (Zeist, 2011). ^b “-” indicates that no odor threshold was found for the compound.

Table 5. Classification of Tomato Fruit Aroma Composition.

Flavor Classification	CAS	Class I	Compounds
floral	3777-69-3	Heterocyclic compound	Furan, 2-pentyl-
	3338-55-4	Terpenoids	1,3,6-Octatriene, 3,7-dimethyl-, (Z)-
	104-54-1	Alcohol	2-Propen-1-ol, 3-phenyl-
	112-06-1	Ester	Acetic acid, heptyl ester
	141-12-8	Ester	2,6-Octadien-1-ol, 3,7-dimethyl-, acetate, (Z)-
fruity	539-90-2	Ester	Butanoic acid, 2-methylpropyl ester
	13360-64-0	Heterocyclic compound	Pyrazine, 2-ethyl-5-methyl-
	3796-70-1	Ketone	5,9-Undecadien-2-one, 6,10-dimethyl-, (E)-
	645-56-7	Phenol	Phenol, 4-propyl-
	111-71-7	Aldehyde	Heptanal
green	659-70-1	Ester	Butanoic acid, 3-methyl-, 3-methylbutyl ester
	30086-02-3	Ketone	3,5-Octadien-2-one, (E,E)-
	18640-74-9	Heterocyclic compound	2-Isobutylthiazole
	628-99-9	Alcohol	2-Nonanol
	66-25-1	Aldehyde	Hexanal
Orange	120-51-4	Ester	Benzyl Benzoate
	99-87-6	Aromatics	p-Cymene
	99-83-2	Terpenoids	.alpha.-Phellandrene 1
	110-93-0	Ketone	5-Hepten-2-one, 6-methyl-
	1195-32-0	Aromatics	Benzene, 1-methyl-4-(1-methylethenyl)-
Oil	112-42-5	Alcohol	1-Undecanol
	25152-84-5	Aldehyde	2,4-Decadienal, (E,E)-
	5910-87-2	Aldehyde	2,4-Nonadienal, (E,E)-
	3913-81-3	Aldehyde	(E)-2-Decenal
	97-53-0	Phenol	Eugenol
Bitter	100-52-7	Aldehyde	BenzAldehyde
	99-85-4	Terpenoids	.gamma.-Terpinene
Lemon	99-86-5	Terpenoids	1,3-Cyclohexadiene, 1-methyl-4-(1-methylethyl)-
bakery	53448-07-0	Aldehyde	2-Undecenal, E-

4. Discussion

Appearance quality of tomato fruits—including fruit size, texture, and color—is closely related to consumer preference (Brashlyanova & Ganeva, 2014). Among these traits, hardness is a key textural characteristic directly linked to fruit storability and shelf life (Zhou et al., 2025). Lycopene, a linear carotenoid responsible for the characteristic red pigmentation in ripe tomatoes, is known to be synthesized and accumulated under controlled water regimes (Wang et al., 2025). In this study, moderate water deficit (T2: 25% water reduction) enhanced shoulder firmness by 35.57% and equatorial firmness by 25.85%, reduced fruit cracking by 57.05%, and increased lycopene content by 6.70%. These improvements in fruit mechanical strength and color align with previous reports by Amal et al. (2020) and Lahoz et al. (2016).

T2 also elevated soluble solids by 14.56%, soluble sugars by 8.12%, titratable acid by 5.88%, and sugar-acid ratio by 2.25%, further enhancing the fruit's sweet-acid balance consistent with consumer flavor preferences (Zhao et al., 2019). Unlike some earlier studies, we observed no significant changes in fruit weight, moisture content, or dry matter under T2, suggesting that the solute accumulation was not simply driven by reduced single-fruit weight (Lahoz et al., 2016) or dilution effects (Nangare et al., 2016). Instead, osmotic regulation mechanisms may prioritize photoassimilate allocation toward sugar and acid accumulation in the fruit (Bertin & Génard, 2018), possibly via upregulated sucrose and organic acid synthesis (Klee & Giovannoni, 2011) or partial suppression of glycolysis (Wu et al., 2024). Further metabolomic and transcriptomic analyses are warranted to elucidate the molecular basis of sugar and acid enhancement.

Enhancing fruit flavor requires understanding the synergistic effects of volatile compound ratios on aroma profiles. In this study, T2 did not alter VOC diversity but significantly increased the relative proportions of floral volatiles such as 2-pentylfuran (+24.71%) and (Z)-3,7-dimethyl-1,3,6-octadecatriene (+128.49%), fruity compounds including 2-ethyl-5-methylpyrazine (+204.10%), and citrus-associated compounds like 4-isopropyltoluene (+125.79%) and undecanol (+188.72%) (Table 6). Concurrently, bitter phenols (eugenol: -29.73%) and aldehydes (benzaldehyde: -20.36%) were reduced, potentially imparting a richer and more desirable flavor profile (Ning et al., 2023; Tieman et al., 2017).

Notably, C9 and C10 volatiles comprised 55.56% of aroma-active compounds (OAV > 1) under T2, likely reflecting upregulated enzymatic activity involved in VOC biosynthesis under water deficit (G et al., 2009). These compounds originate from the lipoxygenase (LOX) and hydroperoxide lyase (HPL) pathways, where 9-LOX and 9-HPL catalyze synthesis of C9 aldehydes with low odor thresholds and significant aroma contribution. LOX-derived aldehydes may be reduced to alcohols by alcohol dehydrogenases (ADHs) or undergo reversible interconversion (L et al., 2014; Jing Zhang et al., 2024; Zhonghui Zhang et al., 2024), followed by esterification mediated by alcohol acyltransferases (AATs) using acyl-CoA, alcohol acceptors, and acid donors (Jing Zhang et al., 2024). Additionally, cinnamaldehyde, derived from phenylalanine, is enzymatically converted to cinnamyl alcohol (C₉H₁₀O) (Tieman et al., 2007), while phenylpropanoid pathway metabolites serve as substrates for eugenol (C₁₀H₁₂O₂) synthesis (L et al., 2014). These findings suggest that water regulation primarily modulates tomato VOC composition through fatty acid and phenylpropanoid metabolic pathways (César et al., 2023), highlighting the need for future enzymatic assays and genetic validation to confirm these mechanisms.

The improvements in flavor and firmness—two pivotal traits for premium tomato quality (Mathilde et al., 2010)—partially offset the yield reduction observed under T2 (-26.55%), despite a decline in fruit number per plant (-13.76%). This trade-off supports a "quality-first" production strategy for growers, as demonstrated by Nangare et al. (2016), where marketable yield was maintained through flavor and texture optimization under regulated deficit irrigation (RDI). However, this study focused solely on the cultivar 'Gaotang No. 1'; thus, future research should validate these effects across diverse cultivars and over multiple growing seasons.

5. Conclusion

Regulated deficit irrigation (RDI) at 25% water reduction (T2) effectively optimized tomato quality by enhancing fruit firmness (35.57% increase at the shoulder), soluble solids (14.56%), vitamin C content (44.19%), and sugar-to-acid ratio (2.25%) while incurring a manageable yield loss (−26.55%). The VOC profile shifted toward floral, fruity, and citrus aroma notes through activation of LOX and phenylpropanoid metabolic pathways, enriching flavor complexity. This study provides a theoretical foundation for synergistically optimizing water-saving cultivation and tomato quality, addressing the typical yield-quality trade-off in tomato production. Future work should incorporate metabolomic and transcriptomic analyses to further clarify sugar-acid metabolic dynamics and validate the effectiveness of RDI across diverse tomato cultivars.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

CK, control check; OAV, odor activity values; RDI, regulated deficit irrigation; T1, treatment 1; T2, treatment 2; T3, treatment 3; VOCs, volatile organic compounds.

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