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ORIGINAL PAPER

Effects of Silicon and Organic Manure on Growth, Fruit Yield, and Quality of Grape Tomato Under Water-Deficit Stress

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Abstract

Mitigation of deleterious effects of drought stress on the growth and productivity of agronomic and horticultural crops warrants urgent and sustainable actions. Soil application of silicon (Si) and organic manure (OM) could play a promising role in alleviating drought-induced adverse effects on crops. A factorial experiment was conducted to evaluate the effects of Si and OM on growth, physiological traits, fruit yield, and quality of grape tomato under water-deficit stress. The experiment consisted of seven different fertilizer doses in which Si and/or OM were applied with or without nitrogen (N) and phosphorus (P) [control (100% NP), 100% NP + 100% OM, 100% NP + 100% Si, 100% NP + 100% OM + 100% Si, 75% NP + 25% OM + 100% Si, 50% NP + 50% OM + 100% Si, and 100% OM + 100% Si] and three soil moisture regimes [100%, 75%, and 50% field capacity (FC)]. Decreasing soil moisture was equally detrimental for all fertilizer doses, which caused an 86–94% reduction in fruit yield and a 79–92% decrease in irrigation water productivity at 50% FC compared with 100% FC. However, the same soil moisture level (50% FC) increased fruit color index by 129% and total soluble solids content by 19% compared with that at 100% FC. Nevertheless, OM application along with the recommended doses of N and P (100% NP + 100% OM) resulted in a better response of grape tomato with 38% higher root dry matter, 21% higher individual fruit weight, 98% higher fruit number plant^{-1}, 145% higher fruit yield, 159% higher irrigation water productivity, and 31% lower proline content compared with the control. This response was at large similar with 100% NP + 100% OM + 100% Si and 50% NP + 50% OM + 100% Si at 100% and 75% FC, especially for fruit yield and irrigation water productivity. Hence, supplementing OM along with the recommended or even half of the recommended doses of N and P as well as supplementation of Si could be a feasible option for grape tomato cultivation under moderate water-deficit stress of up to 75% FC. Growth and yield reduction at 50% FC could not be compensated for the application of OM or Si.

Keywords Beneficial element · Drought stress · Irrigation water productivity · Plant nutrition · *Solanum lycopersicum* L. var. cerasiforme

1 Introduction

The incessant increase in greenhouse gas emissions in the atmosphere and a concomitant mean ambient temperature rise are considered as one of the most influencing factors for global climate change [1]. Consequently, episodes of more extreme climatic events, such as storms, floods, phases of droughts, and heatwaves, are predicted to be more frequent in the coming future [2]. Drought is one of the most devastating abiotic stresses identified as a major hazard limiting the growth, production, and yields of major crops across the world [3]. Plants exposed to drought stress produce reactive oxygen species, which are a major cause of oxidative damage to plants hampering many key metabolic processes, such as photosynthesis, water and nutrient acquisition, and respiration [4]. The excess reactive oxygen species are needed to be neutralized for which plants accumulate osmolytes by upregulating the antioxidant defense systems. The antioxidants include enzymatic and non-enzymatic components present in almost all cellular components, which stabilize the cell by eliminating reactive oxygen species [4]. Besides

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internal defense mechanisms in plants against drought stress, various agronomic management options, such as proper nutrient management, use of organic manure (OM), application of stress-relieving inorganic nutrients (especially potassium [K] and silicon [Si]), and optimum irrigation management, are also critical in maintaining crop productivity. The beneficial role of inorganic nutrients in improving plant tolerance against various biotic and abiotic stresses is well documented [5, 6].

Silicon plays multifaceted beneficial roles in plant growth and development under stressful environments [7–9], which include, but are not limited to, improving growth, crop yield and quality, photosynthesis, fixation of nitrogen (N), and enhancing plant tolerance/resistance against different biotic and abiotic stresses including drought, extreme heat, salinity, ultraviolet radiation, metallic toxicity, nutrients inadequacy, pathogen infection and fungus attack [10, 11]. Silicon exerts beneficial effects on both agronomic and horticultural crops [12, 13]. Silicon-induced improvement in growth and productivity of crops under drought stress has been attributed to better seed germination, greater biomass production, and enhanced photosynthetic rate through various mechanisms, such as osmotic adjustment, modification of traits in gas exchange, increased minerals uptake, and improved antioxidant defense systems [14, 15]. In addition, the exogenous application of Si in soil minimizes the negative impacts of drought stress by (i) increasing roots' hydraulic conductance and water use efficiency, nutrient uptake, and osmotic adjustment [16], and (ii) decreasing stomatal conductance [17]. Silicon significantly enhances the water retention capacity of the soil to ensure adequate soil water availability for plants, which helps maintain better plant water uptake and photosynthetic carbon assimilation stimulating drought stress tolerance in plants [18]. The exogenous application of Si has been reported to substantially improve drought tolerance in a variety of crops, such as rice (*Oryza sativa* L.) [11, 12], maize (*Zea mays* L.) [19], sorghum [*Sorghum bicolor* (L.) Moench] [20], wheat (*Triticum aestivum* L.) [21], soybean [*Glycine max.* (L.) Merr.] [22], grape tomato (*Solanum lycopersicum* L. var. cerasiforme) [10], strawberry (*Fragaria ananassa* Duch.) [23], cantaloupe (*Cucumis melo* L.) [8], and tomato (*Solanum lycopersicum* L.) [24].

The application of OM in combination with synthetic fertilizers has been regarded as a useful approach in maintaining soil health and optimizing fertilizer use efficiency [25]. In addition, OM application and reduced use of synthetic fertilizers positively regulate biogeochemical cycles driven by soil microbes [26]. The application of OM is critically important for soil health maintenance and environmental protection as it improves the buffering capacity of soil and soil porosity, while reducing soil bulk density, thereby facilitating better aggregation of soil particles [25]. Soil organic matter plays a vital role in conserving soil moisture, and as such the application of organic fertilizers has been regarded as a valuable strategy under the changing climate scenarios. In addition to improving soil's water retention capacity and water use efficiency, OM application in the soil significantly improves soil fertility, crop growth, and productivity [27]. Due to better soil moisture retention capacity, water use efficiency, and availability of plant nutrients, OM application could be an affordable option in the production of agronomic and horticultural crops in drought-prone areas, especially when it is synchronously applied along with other drought-mitigating inorganic nutrients, such as Si.

Grape tomato is a rich source of lycopene, various vitamins, and minerals [28]. However, just like other agronomic and horticultural crops, its production at a large scale in the field and protected cultivation systems is threatened by various soil and environmental constraints where drought is a major challenge necessitating environmentally friendly and sustainable solutions. Drought is one of the most significant natural disasters that can severely affect every aspect of human life due to its extensive and prolonged consequences, especially in rural communities depending mostly on agriculture and nature-reliant economies [29]. Over the last several decades, drought has severely impacted the agricultural sector worldwide, threating food security particularly in developing countries [30]. Amongst all environmental stresses, drought has a direct effect on crop production, yield, and irrigation water management, which drastically reduces the final crop yield [31]. However, the role of Si amendment in plant resilience to drought stress has been evident in enhancing crop productivity under semi-arid and arid areas [32]. Application of Si along with OM could be a feasible option in alleviating drought stress on crops, which warrants further investigation. We hypothesized that the combined soil application of Si and OM would enhance plant tolerance against drought stress and increase the growth and productivity of grape tomato under limited soil moisture availability. The objective of the present study was to evaluate the effects of Si and OM on growth, fruit yield, and quality of grape tomato under water-deficit stress.

2 Materials and Methods

2.1 Experimental Setup

The experiment was conducted in a polyhouse at the Asian Institute of Technology (latitude 14°04′53" N and longitude 100°36′33" E), Bangkok, Thailand during 2020–2021. The average temperature and relative humidity fluctuated between 25 °C and 34 °C, and 70% and 80%, respectively, throughout the experimental period. Black plastic pots, 30 cm in height with 36 cm top diameter and 28 cm bottom diameter, were filled with 15 kg soil (air-dried, crushed, and sieved). The soil is classified as Bangkok clay soil containing 62% clay, 28% silt, 10% sand, 2.4% organic matter, and 54 mg kg^{-1} inherent Si content with a slightly acidic pH of 5.4. Seeds of grape tomato (cultivar T309, a hybrid variety) were sown for germination in small trays filled with sterilized peat-moss substrate. One healthy and vigorous seedling was transplanted into each pot 21 days after germination (at the two-leaf stage), which was treated as one treatment combination (one replication unit). Plastic strings were used in sufficient numbers for supporting the plants and fruits during the heavy-bearing period.

2.2 Experimental Design and Treatments

The experiment consisted of seven different fertilizer doses in which Si and/or OM were applied with or without nitrogen (N) and phosphorus (P) [control (100% NP), 100% NP + 100% OM, 100% NP + 100% Si, 100% NP + 100% OM + 100% Si, 75% NP + 25% OM + 100% Si, 50% NP + 50% OM + 100% Si, and 100% OM + 100% Si] and three soil moisture regimes (100%, 75%, and 50% field capacity [FC]). Nutrient combinations of 100% NP, 100% OM, and 100% Si represent recommended field application doses of N at 112.5 kg ha^{-1} applied in the form of urea and P_2O_5 at 50 kg ha^{-1} applied in the form of triple superphosphate [10, 33], cow dung manure at 10 t ha^{-1} [25], and monosilicic acid [$Si(OH)_4$ or H_4SiO_4; 20% Si content] at 300 kg ha^{-1} [10], respectively. Other doses of NP (75% and 50%) and OM (50% and 25%) were calculated based on 100% NP and 100% OM, respectively. The soil moisture regimes were selected based on Sirisuntornlak et al. [19], Alam et al. [8], and Chakma et al. [10, 33]. The experiment was laid out in a completely randomized design with four replications of each treatment. Each plastic pot with one plant was treated as one treatment combination (one replication unit).

2.3 Establishment of Soil Moisture Regimes

The gravimetric method was used to determine the FC of soil as suggested by Datta et al. [34] and Chakma et al. [10, 33]. The soil moisture content at 100% FC was determined at 40%, whereas the soil moisture contents at 75% FC (30%) and 50% FC (20%) were calculated based on the soil moisture content at 100% FC. All plastic pots received sufficient irrigation during the first 15 days after seedlings transplanting, and thereafter the respective soil moisture regimes were implemented. The soil moisture contents of all pots were measured daily with a portable soil moisture meter (SM150 Soil Moisture Sensor; SM150, Delta-T Devices Ltd., Cambridge, UK), and pots were irrigated once the soil moisture reached the desired level.

2.4 Data Collection

2.4.1 Growth, Fruit Yield Parameters, and Irrigation Water Productivity

Plant height (cm) was measured from the soil surface to the tip of the topmost leaf one day before harvest using a measuring tape. After harvesting the fruits, shoot and root dry matter (g $plant^{-1}$) were calculated by drying the fresh shoot and root biomass samples in an oven at 72 °C until a constant weight was attained. Data on individual fruit weight (g), fruit number $plant^{-1}$, and fruit yield (g $plant^{-1}$) were determined at the time of harvest. Irrigation water productivity was computed using the following formula as suggested by Ullah et al. [12] and Maneepitak et al. [35]:

$$\text{Irrigation water productivity } \left(\text{kgm}^{-3}\right) = \frac{\text{Total fruit yield (kg)}}{\text{Total irrigation water input } \left(\text{m}^3\right)} \quad (1)$$

2.4.2 Physiological and Biochemical Parameters

Leaf greenness (relative chlorophyll concentration) was determined nondestructively from fully-expanded young leaves using a portable chlorophyll meter (SPAD-502 plus, Minolta Co. Ltd., Osaka, Japan). To determine leaf relative water content (LRWC), an individual leaf was collected from each plant's middle section, kept in plastic bags, and the fresh weight (FW) was immediately measured. The leaves, after cutting into small pieces of 5 cm length, were immersed in distilled water in Petri dishes, preserved for 24 h in dark, and turgor weight (TW) of the samples was recorded. Fully-turgid leaf samples were dried in an oven at 70 °C until a constant weight was attained, and thereafter the dry weight (DW) was determined. In accordance with the following formula delineated by Jones and Turner [36], LRWC was computed:

$$\text{LRWC}(\%) = \frac{(\text{FW} - \text{DW})}{(\text{TW} - \text{DW})} \times 100 \quad (2)$$

Electrolyte leakage was calculated using the conductivity method as outlined by Lafuente et al. [37] and Camejo et al. [38]. Each sample of uniformly-matured leaves from the middle section of each plant was cut into six discs and cleansed thrice with deionized water to remove any unwanted materials. The discs were immersed in 20 mL of deionized water in test tubes and kept at room temperature for 20 h. Electrical conductivity (EC_1) of the solution was then recorded with a conductivity meter (Model Eutech CON 150, Thermo Scientific, Eutech Instruments, Singapore). Thereafter, electrical conductivity of the solution of dead tissues (EC_2) was recorded after boiling the samples (discs-filled test tubes) in a digital water bath for 15 min and cooling them at room temperature. Electrolyte leakage was calculated using the following formula:

$$\text{Electrolyte leakage (\%)} = \frac{EC_1}{EC_2} \times 100 \quad (3)$$

In accordance with Bates et al. [39], free proline content was determined from the fully-expanded leaves from the middle section of the plant. The samples of fresh leaves were cut into small pieces, grinded in a mortar with liquid N, and 0.05 g powder was homogenized in 1 mL of 3% aqueous sulfosalicylic acid, and thereafter centrifuged at 10,000 rpm for 10 min. Afterward, 200 µL of the extract was added to a test tube filled with 200 µL acid ninhydrin and 200 µL glacial acetic acid, which was then heated for 1 h in boiling water and finally cooled down in an ice bath. After cooling, 200 µL of the solution mixture was extricated and vigorously mixed with 400 µL toluene at 6,000 rpm for 5 min, kept for complete precipitation, and the upper layer was separated to measure the absorbance value at 520 nm. Finally, free proline content in fresh leaves was measured from a standard curve with absorbance values of different concentrations of standard proline solutions.

2.4.3 Fruit Quality Parameters

Fruit diameter (cm) and fruit length (cm) were measured with a vernier scale at the time of harvest. Total soluble solids (TSS) content was measured from fruit juice using a refractometer (Model HI96801, Hanna Instruments, Woonsocket, RI, USA) after homogenizing the fruits in a blender. Color of fruit surface was recorded with a Colorimeter (ColorFlex, Model 45/0, HunterLab, Reston, VA, USA) and color space coordinates *L* (lightness), *a* (coloration intensity of – greenness to + redness), and *b* (coloration intensity of – blueness to + yellowness) were recorded as per the Commission Internationale de l'Eclairage (CIE). Fruit color index was computed using the following formula as described by Hobson et al. [40]:

$$Color\ index = \frac{2000a}{L\sqrt{(a^2 + b^2)}} \quad (4)$$

2.4.4 Statistical Analysis

The data were subjected to a two-way analysis of variance (ANOVA) and were statistically analyzed using the Statistix 8 software (Analytical Software, Tallahassee, FL, USA). Treatment means were separated by conducting post-hoc analyses using the least significant difference test at $P < 0.05$. The data for all the response variables are presented as means of four replications ± standard errors.

3 Results

3.1 Effects of Fertilizer Dose and Soil Moisture Regime on Growth Traits

Fertilizer dose and soil moisture regime had a highly significant individual effect on plant height and root dry matter, while shoot dry matter was affected by the interactive effect between fertilizer dose and soil moisture regime (Table 1). Plants fertilized with 100% NP + 100% OM + 100% Si were the tallest (with a respective increase of 21% and 55% compared with that of the control plants and plants fertilized with 100% OM + 100% Si) (Table 2). Root dry matter largely remained similar among fertilizer treatments, except for 100% NP + 100% OM dose, which

Table 1 Significant levels in two-way ANOVA of the effects of fertilizer dose and soil moisture regime on growth parameters, physiological and biochemical traits, yield parameters, irrigation water productivity, and fruit quality of grape tomato

Items	Fertilizer dose (F)	Soil moisture regime (M)	F×M
Growth parameters			
Plant height (cm)	**	**	ns
Shoot dry matter (g plant^{-1})	**	**	**
Root dry matter (g plant^{-1})	**	**	ns
Physiological and biochemical traits			
Leaf greenness (SPAD value)	**	**	ns
Leaf relative water content (%)	**	**	ns
Electrolyte leakage (%)	ns	**	ns
Free proline content (µg g^{-1} fresh weight)	**	**	**
Yield parameters and water productivity			
Individual fruit weight (g)	**	**	**
Fruit number plant^{-1}	**	**	**
Fruit yield (g plant^{-1})	**	**	**
Irrigation water productivity (kg m^{-3})	**	**	**
Fruit quality			
Fruit diameter (cm)	**	**	**
Fruit length (cm)	*	**	**
Color index	ns	**	*
Total soluble solids (ºBrix)	ns	**	ns

**, *, and ns indicate $P < 0.01$, $P < 0.05$, and not significant, respectively

Table 2 Effects of fertilizer dose and soil moisture regime on growth parameters of grape tomato

Factor	Plant height (cm)	Shoot dry matter (g plant^{-1})	Root dry matter (g plant^{-1})
Fertilizer dose (T)			
T_1 = 100% NP (control)	60.5 ± 6.9b	9.3 ± 1.8bc	0.8 ± 0.1b
T_2 = 100% NP + 100% OM	70.4 ± 7.5a	18.4 ± 3.2a	1.1 ± 0.1a
T_3 = 100% NP + 100% Si	62.9 ± 8.2b	8.5 ± 1.6c	0.7 ± 0.1b
T_4 = 100% NP + 100% OM + 100% Si	73.5 ± 7.2a	12.2 ± 1.9b	0.9 ± 0.1ab
T_5 = 75% NP + 25% OM + 100% Si	59.4 ± 6.2b	10.2 ± 2.5bc	0.8 ± 0.1b
T_6 = 50% NP + 50% OM + 100% Si	70.3 ± 7.2a	11.9 ± 3b	0.8 ± 0.1b
T_7 = 100% OM + 100% Si	47.3 ± 5.1c	3.7 ± 0.6d	0.7 ± 0.0b
Soil moisture regime (M)			
M_{50} = 50% field capacity	37.2 ± 1.6c	3.3 ± 0.4c	0.5 ± 0.0c
M_{75} = 75% field capacity	71.5 ± 2.2b	13.1 ± 1.3b	0.9 ± 0.0b
M_{100} = 100% field capacity	81.8 ± 2.6a	15.43 ± 1.6a	1.1 ± 0.1a
Fertilizer dose × Soil moisture regime (T × M)			
$T_1 \times M_{50}$	34.3 ± 1.5	2.8 ± 0.4c	0.5 ± 0.0
$T_1 \times M_{75}$	70.0 ± 4.2	11.8 ± 1.8b	0.7 ± 0.2
$T_1 \times M_{100}$	77.3 ± 5.4	13.3 ± 2.0b	1.1 ± 0.1
$T_2 \times M_{50}$	41.4 ± 2.2	5.7 ± 0.6c	0.8 ± 0.1
$T_2 \times M_{75}$	80.6 ± 2.3	24.5 ± 1.2a	1.1 ± 0.0
$T_2 \times M_{100}$	89.3 ± 3.8	25.2 ± 1.3a	1.3 ± 0.2
$T_3 \times M_{50}$	31.8 ± 1.5	2.3 ± 0.3c	0.5 ± 0.1
$T_3 \times M_{75}$	70.4 ± 2.4	11.3 ± 0.6b	0.8 ± 0.2
$T_3 \times M_{100}$	86.5 ± 1.3	11.8 ± 1.1b	0.8 ± 0.1
$T_4 \times M_{50}$	47.8 ± 4.4	5.5 ± 0.4c	0.5 ± 0.1
$T_4 \times M_{75}$	78.1 ± 4.7	15.2 ± 1.7b	1.0 ± 0.1
$T_4 \times M_{100}$	94.7 ± 3.8	15.8 ± 2.0b	1.2 ± 0.2
$T_5 \times M_{50}$	35.2 ± 1.5	2.8 ± 0.7c	0.5 ± 0.1
$T_5 \times M_{75}$	68.8 ± 3.9	12.2 ± 1.1b	0.9 ± 0.1
$T_5 \times M_{100}$	74.2 ± 1.9	15.6 ± 5.7b	1.0 ± 0.2
$T_6 \times M_{50}$	42.2 ± 1.7	2.6 ± 0.3c	0.4 ± 0.0
$T_6 \times M_{75}$	79.6 ± 1.3	11.8 ± 0.8b	0.8 ± 0.0
$T_6 \times M_{100}$	89.3 ± 2.3	21.2 ± 4.3a	1.0 ± 0.2
$T_7 \times M_{50}$	27.6 ± 0.8	1.4 ± 0.2c	0.2 ± 0.1
$T_7 \times M_{75}$	53.2 ± 0.4	4.8 ± 0.3c	0.7 ± 0.2
$T_7 \times M_{100}$	61.1 ± 3.8	5.1 ± 0.9c	1.1 ± 0.1

Means within a column followed by the same letter are not significantly different by the least significant difference test at $P < 0.05$; data are means of four replications ± standard errors

had 38% higher root dry matter than that of the control plants. A drastic reduction of 55% in plant height and root dry matter was recorded when soil moisture was reduced from 100% FC to 50% FC. There was largely no effect of fertilizer dose on shoot dry matter within a soil moisture regime, except for plants fertilized with 100% NP + 100% OM where shoot dry matter was 108% and 89% higher than the control plants at 75% and 100% FC, respectively. A significant increase in shoot dry matter (187–715% at 100% FC compared with 50% FC) was evident with increasing soil moisture regime irrespective of fertilizer doses.

3.2 Effects of Fertilizer Dose and Soil Moisture Regime on Physiological and Biochemical Traits

There was no significant interaction effect between fertilizer dose and soil moisture regime on SPAD value, LRWC, and electrolyte leakage; however, the interaction between fertilizer dose and soil moisture regime had a significant effect on free proline content (Table 1). SPAD value of plants fertilized with 100% NP + 100% OM was the highest, while plants grown without NP fertilizer (100% OM + 100% Si) exhibited the lowest SPAD value (31% lower than the plants fertilized with 100%

Table 3 Effects of fertilizer dose and soil moisture regime on physiological and biochemical traits of grape tomato

Factor	SPAD value	Leaf relative water content (%)	Electrolyte leakage (%)	Free proline content (μg g^{-1} fresh weight)
Fertilizer dose (T)				
T_1 = 100% NP (control)	54.5 ± 2.5b	47.3 ± 2.2c	28.7 ± 2.2	104.0 ± 6.6a
T_2 = 100% NP + 100% OM	61.3 ± 1.2a	53.0 ± 2.3ab	24.8 ± 1.7	72.0 ± 3.4c
T_3 = 100% NP + 100% Si	48.7 ± 1.7c	50.5 ± 2.8b	27.3 ± 2.2	77.3 ± 2.5bc
T_4 = 100% NP + 100% OM + 100% Si	58.0 ± 1.0ab	55.5 ± 2.7a	25.9 ± 1.6	75.9 ± 3.0bc
T_5 = 75% NP + 25% OM + 100% Si	54.3 ± 1.4b	50.4 ± 2.4b	28.5 ± 1.7	81.7 ± 3.6b
T_6 = 50% NP + 50% OM + 100% Si	57.7 ± 1.7ab	52.7 ± 2.1ab	26.8 ± 2.4	73.0 ± 1.1c
T_7 = 100% OM + 100% Si	42.4 ± 1.4d	51.5 ± 3.2b	26.5 ± 1.9	78.0 ± 2.7bc
Soil moisture regime (M)				
M_{50} = 50% field capacity	50.8 ± 1.5b	42.2 ± 0.7c	33.1 ± 1.0a	87.1 ± 4.1a
M_{75} = 75% field capacity	54.3 ± 1.7a	55.2 ± 0.9b	25.1 ± 0.6b	80.7 ± 2.6b
M_{100} = 100% field capacity	56.4 ± 1.4a	57.4 ± 0.9a	22.6 ± 0.7c	73.0 ± 1.6c
Fertilizer dose × Soil moisture regime (T × M)				
$T_1 \times M_{50}$	46.3 ± 4.6	39.6 ± 0.4	36.1 ± 3.2	125.0 ± 3.8a
$T_1 \times M_{75}$	58.4 ± 0.2	50.7 ± 1.9	25.2 ± 2.3	105.7 ± 3.5b
$T_1 \times M_{100}$	58.8 ± 2.9	51.7 ± 2.5	24.9 ± 1.1	81.3 ± 4.7 cd
$T_2 \times M_{50}$	58.3 ± 2.1	44.4 ± 1.1	30.3 ± 1.9	77.3 ± 4.4de
$T_2 \times M_{75}$	61.9 ± 2.4	56.9 ± 1.1	24.4 ± 1.8	74.3 ± 4.3de
$T_2 \times M_{100}$	63.7 ± 0.5	57.7 ± 2.8	19.7 ± 0.6	66.0 ± 7.9e
$T_3 \times M_{50}$	46.7 ± 3.1	39.9 ± 2.3	32.9 ± 4.0	80.7 ± 5.8 cd
$T_3 \times M_{75}$	48.4 ± 4.1	55.3 ± 1.4	25.3 ± 2.0	77.7 ± 3.3de
$T_3 \times M_{100}$	51.1 ± 2.0	56.5 ± 0.2	23.7 ± 4.0	73.7 ± 4.6de
$T_4 \times M_{50}$	56.5 ± 3.0	45.5 ± 1.1	30.8 ± 2.0	81.7 ± 8.7 cd
$T_4 \times M_{75}$	57.0 ± 0.6	60.3 ± 1.2	25.0 ± 0.3	74.0 ± 2.6de
$T_4 \times M_{100}$	60.6 ± 0.6	60.9 ± 3.0	21.7 ± 1.9	72.0 ± 1.0de
$T_5 \times M_{50}$	51.0 ± 2.8	42.2 ± 1.0	33.6 ± 2.5	92.0 ± 8.2c
$T_5 \times M_{75}$	56.1 ± 2.2	51.9 ± 3.0	27.6 ± 2.6	78.0 ± 2.0de
$T_5 \times M_{100}$	55.9 ± 1.3	57.2 ± 0.9	24.3 ± 0.4	75.0 ± 2.5de
$T_6 \times M_{50}$	56.0 ± 2.4	44.2 ± 2.1	35.4 ± 2.5	74.0 ± 1.8de
$T_6 \times M_{75}$	56.2 ± 3.7	56.5 ± 0.8	24.1 ± 1.7	73.0 ± 2.7de
$T_6 \times M_{100}$	59.8 ± 3.0	57.5 ± 0.7	20.9 ± 1.6	71.0 ± 1.0de
$T_7 \times M_{50}$	40.9 ± 1.8	39.4 ± 0.7	32.5 ± 3.6	78.3 ± 6.4de
$T_7 \times M_{75}$	41.2 ± 3.4	55.2 ± 2.2	24.1 ± 1.5	81.0 ± 6.1 cd
$T_7 \times M_{100}$	45.1 ± 1.8	60.0 ± 0.6	23.0 ± 0.2	75.0 ± 0.5de

Means within a column followed by the same letter are not significantly different by the least significant difference test at $P < 0.05$; data are means of four replications ± standard errors

NP + 100% OM) (Table 3). There was no difference in SPAD values at 100% and 75% FC; however, plants at 50% FC had significantly lower SPAD values. Application of 100% NP + 100% OM + 100% Si resulted in the highest LRWC, which was 17% higher than that of the control (Table 3). Among three soil moisture regimes, plants at 100% FC had 4% and 36% higher LRWC than that at 75% and 50% FC, respectively. Electrolyte leakage was increased by 11% and 46% when soil moisture was reduced from 100% FC to 75% and 50% FC, respectively (Table 3). Plants not supplemented with OM or Si had higher free proline content across soil moisture regimes (Table 3). Free proline content of plants fertilized with 100% NP was largely similar to other fertilizer doses at 100% FC, but at 50% FC and 75% FC an increase in the range of 36–69% and 30–45%, respectively, was evident in free proline content of the control plants compared with other fertilizer doses. The effect of decreasing soil moisture regime on free proline content was largely not evident for all fertilizer doses, except for the control plants where an increase of 54% in free proline content was observed at 50% FC compared with that of 100% FC.

3.3 Effects of Fertilizer Dose and Soil Moisture Regime on Fruit Yield Parameters and Irrigation Water Productivity

The individual and two-way interaction effects of fertilizer dose and soil moisture regime on fruit yield parameters and irrigation water productivity were highly significant (Table 1). Individual fruit weight remained significantly lower at 50% FC across fertilizer doses, while 100% NP + 100% OM, 100% NP + 100% OM + 100% Si, and 50% NP + 50% OM + 100% Si fertilizer doses had the highest individual fruit weight at 75% FC (Table 4). At 100% FC, plants fertilized with 75% NP + 25% OM + 100% Si had 29% lower individual fruit weight than plants fertilized with 100% NP + 100% OM and 100% NP + 100% OM + 100% Si fertilizer doses. Fruit number plant^{-1} remained significantly lower for plants fertilized with 100% OM + 100% Si irrespective of soil moisture regimes, which was 74%, 79%, and 81% lower than plants fertilized with 100% NP + 100% OM at 50%, 75%, and 100% FC, respectively (Table 4). Plants subjected to 50% FC exhibited a drastic reduction in

Table 4 Effects of fertilizer dose and soil moisture regime on yield parameters and irrigation water productivity of grape tomato

Factor	Individual fruit weight (g)	Fruit number plant^{-1}	Fruit yield (g plant^{-1})	Irrigation water productivity (kg m^{-3})
Fertilizer dose (T)				
T_1 = 100% NP (control)	2.9 ± 0.2bc	19.0 ± 3.5c	60.0 ± 12.8c	0.17 ± 0.0c
T_2 = 100% NP + 100% OM	3.5 ± 0.3a	37.6 ± 8.7a	146.9 ± 31.0a	0.44 ± 0.1a
T_3 = 100% NP + 100% Si	3.1 ± 0.3b	34.7 ± 8.7b	140.3 ± 32.0b	0.42 ± 0.1b
T_4 = 100% NP + 100% OM + 100% Si	3.5 ± 0.3a	36.0 ± 8.8ab	143.6 ± 31.8ab	0.43 ± 0.1ab
T_5 = 75% NP + 25% OM + 100% Si	2.7 ± 0.2c	17.0 ± 3.4c	48.6 ± 10.7 d	0.15 ± 0.0d
T_6 = 50% NP + 50% OM + 100% Si	3.4 ± 0.3a	35.9 ± 9.2ab	142.1 ± 32.4ab	0.43 ± 0.1ab
T_7 = 100% OM + 100% Si	2.9 ± 0.3bc	7.8 ± 1.4d	25.9 ± 5.5e	0.10 ± 0.0e
Soil moisture regime (M)				
M_{50} = 50% field capacity	2.2 ± 0.1c	6.2 ± 0.7c	13.7 ± 1.4c	0.06 ± 0.0c
M_{75} = 75% field capacity	3.6 ± 0.1b	33.8 ± 1.6b	129.2 ± 14.8b	0.34 ± 0.0b
M_{100} = 100% field capacity	3.8 ± 0.1a	40.3 ± 5.3a	160.3 ± 17.5a	0.51 ± 0.1a
Fertilizer dose × Soil moisture regime (T × M)				
$T_1 \times M_{50}$	2.2 ± 0.2ef	5.3 ± 0.3gh	11.4 ± 0.1ij	0.05 ± 0.0ij
$T_1 \times M_{75}$	3.3 ± 0.0 cd	22.0 ± 0.6d	72.4 ± 1.4e	0.22 ± 0.0f
$T_1 \times M_{100}$	3.2 ± 0.2 cd	29.7 ± 2.4c	96.3 ± 8.0c	0.25 ± 0.0e
$T_2 \times M_{50}$	2.2 ± 0.1ef	11.7 ± 1.9e	24.9 ± 2.9 h	0.06 ± 0.0i
$T_2 \times M_{75}$	4.0 ± 0.1ab	47.0 ± 0.3b	187.8 ± 2.0b	0.50 ± 0.0c
$T_2 \times M_{100}$	4.2 ± 0.1a	54.0 ± 4.7a	228.2 ± 0.7a	0.76 ± 0.0a
$T_3 \times M_{50}$	2.1 ± 0.1ef	5.7 ± 0.3gh	12.4 ± 0.5ij	0.11 ± 0.0 h
$T_3 \times M_{75}$	3.6 ± 0.2bc	45.3 ± 0.9b	183.0 ± 2.0b	0.46 ± 0.2d
$T_3 \times M_{100}$	3.7 ± 0.2abc	53.0 ± 0.9a	225.4 ± 1.3a	0.70 ± 0.0b
$T_4 \times M_{50}$	2.3 ± 0.3e	8.0 ± 1.0efg	18.5 ± 1.7hi	0.06 ± 0.0i
$T_4 \times M_{75}$	4.0 ± 0.1ab	46.7 ± 0.7b	186.2 ± 1.4b	0.50 ± 0.0c
$T_4 \times M_{100}$	4.2 ± 0.1a	53.3 ± 0.9a	226.0 ± 1.8a	0.74 ± 0.0a
$T_5 \times M_{50}$	2.1 ± 0.4ef	4.7 ± 0.9gh	9.2 ± 0.1j	0.05 ± 0.0ij
$T_5 \times M_{75}$	3.0 ± 0.3d	18.7 ± 1.2d	55.2 ± 4.8f	0.16 ± 0.0 g
$T_5 \times M_{100}$	3.0 ± 0.2d	27.7 ± 2.4c	81.5 ± 4.4d	0.24 ± 0.0ef
$T_6 \times M_{50}$	2.2 ± 0.2ef	5.7 ± 0.9fgh	14.0 ± 1.5ij	0.09 ± 0.0 h
$T_6 \times M_{75}$	4.0 ± 0.0ab	46.7 ± 0.9b	186.2 ± 2.9b	0.45 ± 0.0d
$T_6 \times M_{100}$	4.1 ± 0.2a	54.3 ± 1.8a	226.0 ± 2.1a	0.74 ± 0.0a
$T_7 \times M_{50}$	1.8 ± 0.1f	3.0 ± 0.0 h	5.4 ± 0.2j	0.03 ± 0.0j
$T_7 \times M_{75}$	3.0 ± 0.2d	10.0 ± 1.0ef	33.9 ± 1.5 g	0.14 ± 0.0 g
$T_7 \times M_{100}$	3.8 ± 0.1ab	10.3 ± 1.5ef	38.5 ± 6.3 g	0.14 ± 0.0 g

Means within a column followed by the same letter are not significantly different by the least significant difference test at $P < 0.05$; data are means of four replications ± standard errors fruit number plant^{-1} at all fertilizer doses. Decreasing soil moisture level caused a drastic reduction in fruit yield at all fertilizer doses ranging from 86–94% at 50% FC compared with that at 100% FC (Table 4). Plants fertilized with 100% NP + 100% OM had the highest fruit yield across soil moisture regimes with a respective reduction of 54% and 78%, 61% and 82%, and 58% and 83% for the control plants and plants fertilized with 100% OM + 100% Si at 50%, 75%, and 100% FC, respectively. A highly significant interaction between fertilizer dose and soil moisture regime indicated that irrigation water productivity drastically reduced (ranging from 79–92%) with decreasing soil moisture regimes across fertilizer doses (Table 4). Among applied fertilizer doses, irrigation water productivity was the highest for plants fertilized with 100% NP + 100% OM at 100% FC, which was significantly greater than that of the control (67% reduction), 100% NP + 100% Si (8% reduction), 75% NP + 25% OM + 100% Si (68% reduction), and 100% OM + 100 Si (82% reduction).

Table 5 Effects of fertilizer dose and soil moisture regime on fruit quality parameters of grape tomato

Factor	Fruit diameter (cm)	Fruit length (cm)	Color index	Total soluble solids (°Brix)
Fertilizer dose (T)				
T_1 = 100% NP (control)	1.5 ± 0.1c	2.7 ± 0.1bc	139.8 ± 20.1	9.8 ± 0.5
T_2 = 100% NP + 100% OM	1.7 ± 0.1a	2.9 ± 0.1a	141.8 ± 19.1	10.7 ± 0.4
T_3 = 100% NP + 100% Si	1.5 ± 0.1c	2.7 ± 0.1bc	157.1 ± 15.9	10.1 ± 0.5
T_4 = 100% NP + 100% OM + 100% Si	1.6 ± 0.1bc	2.7 ± 0.1bc	170.4 ± 25.8	10.7 ± 0.5
T_5 = 75% NP + 25% OM + 100% Si	1.5 ± 0.1c	2.7 ± 0.1bc	151.4 ± 19.0	10.2 ± 0.2
T_6 = 50% NP + 50% OM + 100% Si	1.6 ± 0.1bc	2.6 ± 0.2c	169.7 ± 28.7	9.9 ± 0.3
T_7 = 100% OM + 100% Si	1.6 ± 0.1bc	2.6 ± 0.3c	161.3 ± 23.8	9.8 ± 0.2
Soil moisture regime (M)				
M_{50} = 50% field capacity	1.3 ± 0.0c	2.2 ± 0.1c	229.2 ± 8.9a	11.2 ± 0.2a
M_{75} = 75% field capacity	1.6 ± 0.0b	2.9 ± 0.1b	138.5 ± 6.8b	10.1 ± 0.2b
M_{100} = 100% field capacity	1.8 ± 0.0a	3.0 ± 0.0a	100.1 ± 6.5c	9.4 ± 0.2c
Fertilizer dose × Soil moisture regime (T × M)				
$T_1 \times M_{50}$	1.3 ± 0.1ghi	2.2 ± 0.0ij	204.5 ± 3.8bcd	10.8 ± 0.3
$T_1 \times M_{75}$	1.5 ± 0.1 fg	2.7 ± 1.2def	140.6 ± 24.2efghi	10.5 ± 1.1
$T_1 \times M_{100}$	1.8 ± 0.0ab	3.1 ± 0.0a	74.3 ± 0.9j	8.1 ± 0.1
$T_2 \times M_{50}$	1.5 ± 0.0 fg	2.5 ± 0.3ghi	214.3 ± 3.3bcd	12.1 ± 0.1
$T_2 \times M_{75}$	1.7 ± 0.1abc	3.0 ± 0.0ab	116.6 ± 13.7fghi	10.3 ± 0.1
$T_2 \times M_{100}$	1.9 ± 0.1a	3.1 ± 0.1a	94.6 ± 11.8hij	9.6 ± 0.2
$T_3 \times M_{50}$	1.2 ± 0.0i	2.3 ± 0.0hij	189.3 ± 21.6cde	11.6 ± 0.8
$T_3 \times M_{75}$	1.6 ± 0.1def	2.9 ± 0.2abc	143.9 ± 23.4efgh	9.8 ± 0.8
$T_3 \times M_{100}$	1.7 ± 0.0abc	2.9 ± 0.1abc	138.0 ± 35.1gfhi	9.0 ± 0.6
$T_4 \times M_{50}$	1.4 ± 0.1gh	2.5 ± 0.1ghi	254.4 ± 26.7ab	12.2 ± 0.9
$T_4 \times M_{75}$	1.5 ± 0.0 fg	2.8 ± 0.0cde	166.3 ± 22.6def	10.3 ± 0.2
$T_4 \times M_{100}$	1.8 ± 0.1ab	2.9 ± 0.1abc	90.6 ± 4.6ij	9.9 ± 0.5
$T_5 \times M_{50}$	1.3 ± 0.1ghi	2.1 ± 0.0j	222.0 ± 22.7bc	10.2 ± 0.1
$T_5 \times M_{75}$	1.6 ± 0.1def	3.0 ± 0.1ab	116.5 ± 0.8fghi	10.3 ± 0.5
$T_5 \times M_{100}$	1.6 ± 0.0def	2.9 ± 1.3abc	115.6 ± 7.5fghi	9.7 ± 0.3
$T_6 \times M_{50}$	1.3 ± 0.0ghi	2.1 ± 0.1j	277.8 ± 3.6a	10.7 ± 0.6
$T_6 \times M_{75}$	1.7 ± 0.3abc	2.6 ± 0.3efg	147.8 ± 8.1efg	9.5 ± 0.2
$T_6 \times M_{100}$	1.8 ± 0.1ab	3.1 ± 0.1a	83.7 ± 1.3j	9.5 ± 0.2
$T_7 \times M_{50}$	1.2 ± 0.2i	1.5 ± 0.0 k	242.2 ± 32.1ab	9.9 ± 0.1
$T_7 \times M_{75}$	1.7 ± 0.0abc	3.1 ± 0.1a	137.9 ± 20.8fghi	9.8 ± 0.3
$T_7 \times M_{100}$	1.7 ± 0.0abc	3.1 ± 0.1a	103.8 ± 10.5ghij	9.7 ± 0.5

Means within a column followed by the same letter are not significantly different by the least significant difference test at $P < 0.05$; data are means of four replications ± standard errors

3.4 Effects of Fertilizer Dose and Soil Moisture Regime on Fruit Quality

The interaction between fertilizer dose and soil moisture regime had a significant effect on fruit diameter, fruit length, and fruit color index, while TSS content was significantly affected by soil moisture regime (Table 1). Fruit diameter was generally lower for plants subjected to 50% FC across fertilizer doses compared with other soil moisture regimes (Table 5). Plants fertilized with 100% NP + 100% OM at 100% FC had the highest fruit diameter, which was statistically at par with all other fertilizer doses at the same soil moisture regime, except for plants fertilized with 75% NP + 25% OM + 100% Si where fruit diameter at 100% FC was 16% lower. Fruit length was not affected by fertilizer dose at 100% FC and the same was also true for most of the cases at 75% and 50% FC (Table 5). The lowest fruit length was recorded for plants fertilized with 50% NP + 50% OM + 100% Si, and 100% OM + 100% Si at 75% and 50% FC, respectively. The effect of decreasing soil moisture level was evident on fruit length at all fertilizer doses with a significant reduction at 50% FC compared with the other soil moisture regimes. Fruit color index largely remained similar among fertilizer doses at 75% and 100% FC, while plants fertilized with 50% NP + 50% OM + 100% Si had the highest color index at 50% FC, which was 36% higher than that of the control (Table 5). Increasing soil moisture level significantly decreased fruit color index in the range of 27–70% across fertilizer doses. Total soluble solids content decreased by 10% and 16% at 75% FC and 100% FC, respectively, compared with that at 50% FC (Table 5).

4 Discussion

Crop growth and yields are drastically reduced due to critical physiological, morphological, and biochemical damages caused by drought [10, 19, 33, 41]. A substantial reduction in fruit yield parameters and physiological traits of grape tomato was observed in the present study when soil moisture level was reduced from 100% FC, and the impact was markedly visible at 50% FC. Low soil moisture content locks the available soil nutrients making it difficult for the plant to uptake, thereby hampering growth, physiological traits, and ultimately the yield of almost all crops at least up to a certain degree. The reduction in final fruit yield induced by water-deficit stress might be attributed to: (i) a fewer number of trusses and smaller size of fruit plant^{-1} due to an insufficient availability of carbohydrate owing to a decreased photosynthetic rate, and (ii) flower abortion contributing to lesser number of fruit plant^{-1} [42, 43]. In addition, the reduction could be resulted from the declined carbohydrate synthesis and weakened translocation of assimilates toward reproductive organs caused by drought stress [44]. Drought can disrupt a wide range of essential physiological and metabolic processes involved in plant growth and development [45]. The findings are in line with Kuscu et al. [46] who also noted that vegetables including tomato are highly susceptible to drought stress. Nangare et al. [47] observed a significant decrease in plant growth traits (plant height and leaf area index), root parameters (weight and depth), and chlorophyll contents of tomato grown under a regulated low irrigation level of 0.6 × ETc. The deleterious effects of drought stress on growth, physiological traits, and yields of various crops have been well documented in the literature [45, 48, 49]. A decrease in plant growth under water-deficit stress might be a consequence of either reduction in cell turgor, cell growth and elongation, and/or the blocking up of vascular tissue, restricting translocation, or a combination of all these factors [50]. Chakma et al. [10] observed a decreased fruit yield and impaired vegetative growth of grape tomato induced by water-deficit stress, which was mainly caused by a reduced irrigation water productivity and LRWC, whereas electrolyte leakage was higher at lower soil moisture levels. Similarly, Hayat et al. [51] reported an increase in electrolyte leakage and a decrease in LRWC at a lower soil moisture regime. Such a reduction in LRWC could have resulted from an increase in membrane permeability (leaf relative conductivity) and a decrease in water supply [17, 52].

The application of a variety of exogenous protectants has been found highly effective in mitigating the harmful effects of drought stress in various crops. Application of mineral nutrients under water-deficit conditions can promote root growth resulting in an accelerated water- and nutrients-acquisition from deeper soil layers, which in turn enhances plant tolerance against abiotic stresses [53]. The beneficial roles of Si and OM in alleviating the harmful effects of water-deficit stress have been well documented. The application of Si has been reported equally effective in mitigating the detrimental impacts of abiotic stresses including drought in agronomic and horticultural crops [8, 12, 19]. Chakma et al. [10] reported that the exogenous application of Si significantly improved growth, fruit yield, and quality of grape tomato under water-deficit stress. The present findings revealed that the application of Si in combination with N, P, and OM markedly improved the growth parameters of grape tomato (Table 2). The results of the current study are in close agreement with Shi et al. [54] and Zhang et al. [55] who mentioned that Si application considerably enhanced tomato seedling's biomass under water-deficit stress. In the present study, the highest root biomass was observed at 100% NP + 100% OM, which was statistically at par with 100% NP + 100% OM + 100% Si, indicating that both Si and OM have a significant beneficial role in improving growth and development of root systems. The expanded length and surface area of roots due to Si and OM application help improve the uptake of water and nutrients from the soil, thereby maintaining better plant-water relations under water-deficit stress [54]. Ullah et al. [56] observed a 36% and 45% increase in shoot and root dry matter, respectively, in tomato plants in response to the application of 50 ppm Si. The most of these beneficial effects induced by the exogenous application of Si under water-deficit stress are credited to a decreased membrane oxidative damage and an enhanced root hydraulic conductance facilitating better plant water uptake [15, 54]. Increased root dry matter and enhanced root hydraulic conductance as a result of Si application might enable the grape tomato plants in enhancing drought tolerance capacity. Other potential stress-alleviating mechanisms stimulated by Si application include a reduced transpirational water loss coupled with an improved root water uptake and enhanced metabolism [18, 57]. A decrease in chlorophyll biosynthesis is a commonly observed trend in plants under drought stress [58]. A reduction in SPAD value was observed in the present study at 50% FC, but it was improved in treatments where Si and OM were applied along with N and P or where OM was applied along with N and P (Table 3). These findings are in close agreement with Bukhari et al. [59] who reported a degradation in chlorophyll in canola (*Brassica napus* L.) cultivars grown under water-deficit stress, whereas a positive effect on SPAD value was noted with the exogenous application of Si. A decrease in leaf chlorophyll content under drought stress is caused by the oxidative damage to chloroplast due to the overproduction of reactive oxygen species [60]. Shi et al. [54] reported that Si-mediated improvement in leaf chlorophyll content under water-deficit stress could be linked with the enhanced antioxidant defense system and reduced oxidative damage as a result of Si application.

In the present study, the overall performance of grape tomato was better when 100% N and P were supplemented with 100% OM, followed by the plants fertilized with 100% N and P along with 100% OM and 100% Si. The beneficial role of OM in improving soil structure, increasing water-holding capacity, and providing essential nutrients to plants is well documented in various crops. Chemura [61] observed an improved growth efficacy of coffee (*Coffea arabica* L.) plants grown under low irrigation water levels and integrated soil fertility management (addition of OM), which has been attributed to the beneficial effects of OM on physical and chemical properties of soil. Ullah et al. [25] reported better growth and yield response of rice plants fertilized with OM along with the recommended doses of N and P compared with the plants grown without the application of OM. The addition of OM significantly improves soil structure, formation, texture, and porosity, which resultantly enhance the water-holding capacity of soil [62]. Organic fertilizer application has been reportedly increased grain yield of winter wheat by 23% and 15%, and water-use efficiency by 25% and 23%, respectively, under water stress and well-watered conditions [63]. The improved water-use efficiency under organic fertilization has been credited to an elevated photosynthesis and a decreased transpiration rate and stomatal conductance. Salehi et al. [64] reported that organic fertilizers, such as vermicompost, can improve a plant's drought tolerance by decreasing soil bulk density, enhancing soil water-holding capacity, and increasing soil microbial abundance. Despite visible benefits associated with OM and Si supplementation, it was observed in the present study that decreasing N and P doses could significantly reduce the growth, physiological response, and fruit yield of grape tomato. Therefore, OM and Si should be applied in synchronization with the recommended doses of N and P.

5 Conclusion

At severe water-deficit stress (50% FC), growth, fruit yield, and irrigation water productivity of grape tomato were drastically reduced across fertilizer doses, although an improvement in fruit quality (fruit color index and TSS) was evident. However, the exogenous application of different fertilizer combinations of OM and Si along with the addition of major nutrients, such as N and P, were found considerably beneficial in moderate (75% FC) and well-watered (100% FC) conditions. At moderate (75% FC) to well-watered condition (100% FC), the fertilizer combinations of 100% NP + 100% OM, 100% NP + 100% OM + 100% Si, and 50% NP + 50% OM + 100% Si resulted in the highest fruit yield and irrigation water productivity together with an enhanced SPAD value and LRWC in grape tomato. Therefore, an application of OM and Si in combination with major nutrients (N and P) is recommended in alleviating the detrimental effects of moderate water-deficit stress and maintaining fruit yield and water productivity of grape tomato.

Authors Contribution All authors contributed to the study's conception and design. RC, JS, and AB acquired the data and performed the statistical analysis with guidance from HU, SKH, and AD. RC and AB drafted the manuscript, and HU, SKH, and AD critically reviewed it for important intellectual content. All authors read and approved the final manuscript.

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Data Availability The datasets used and/or analyzed during the current study are available from the corresponding author on request.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflict of Interest The authors declare no competing interest.

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