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Subsurface Water Retention Technology Promotes Drought Stress Tolerance in Field-Grown Tomato

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Abstract: Agricultural activities depend heavily on irrigation in arid and semi-arid climates, which are one of the most water-limited areas, reducing agricultural productivity. As the climate changes, the lack of precipitation is expected to aggravate in these areas, requiring careful management of water use. Subsurface water retention technology (SWRT) may hold promise as a management tool to save water use and improve crop drought resistance. In this context, the effect of SWRT on tomato yield, growth, physiology, and biochemical characteristics, as well as soil characteristics under two regimes of water (100% field capacity (FC) and 50% FC) in open field conditions, was investigated. The results here suggest that drought affected tomato performance. Nevertheless, SWRT application significantly increased tomato yield (38%), chlorophyll fluorescence (3%), gas exchange (39%), and chlorophyll total content (49%), as well as soil fertility characteristics, with significant increases in organic matter (23%) and assimilable phosphorus contents (25%) compared with the control. Furthermore, it resulted in a significant reduction in enzymatic antioxidant activities and polyphenol and significant improvement in fruit quality by increasing protein content. This technique should be used as a valuable strategy to save irrigation water and mitigate the negative effects of water deficiency on tomato plants in arid and semi-arid regions.

Keywords: biochemical responses; climate change; physiological responses; yield

1. Introduction

Water scarcity due to climate change and increasing population is one of the extreme challenges facing the world [1]. Food and water sectors are closely linked, as irrigated cropland contributes to 40% of global agricultural production [2]. Around the world, water used in the sector of agriculture for irrigation accounts for approximately 70% of the total freshwater [3]. Water scarcity is most acute in Mediterranean regions such as Morocco, requiring a re-evaluation of current water use practices in agriculture [4,5]. In order to mitigate future climate change and assure security of food, several initiatives are being undertaken through research to improve water efficiency [6]. In this context, subsurface water retention technology (SWRT) can be used as a novel practice to economize irrigation water [7].

This technology relies on the installation of a U-shaped impermeable polyethylene membrane under the root zone to retain water and avoid water loss through percolation [8]. This membrane application also conserves more nutrients and prevents leaching nutrients into groundwater [9,10], thus increasing plant production with reduced fertilizer use [11]. Numerous studies have demonstrated that SWRT can boost plant performance and nutrient absorption, enhance the control of the stomatal opening to achieve better water use effectiveness by plants, increase the water supply by keeping water close to the root zone, and reduce oxidative damage under stressful conditions, especially during drought [7,10,12].

The tomato is one of the main cultivated and consumed vegetable crops in the world, with a production of 186 million tons on 5,051,983 hectares in 2020 [11], and a total surface of cultivation of 4.8 million hectares, which is followed by onions, which cover 5.2 million hectares [13]. In Morocco, the tomato is considered as the second most important vegetable crop after potatoes, with a production of over 1.4 million tons in 2020 cultivated on an area of 14,861 ha [14,15]. Tomato fruits have several human health benefits for consumers due to the presence of nutrients, β-carotene, ascorbic acid (vitamin C), lycopene, phenolic compounds, and essential minerals [15]; they are also a revenue source for many rural and suburban farms [16]. Nevertheless, tomato cultivation is severely affected by abiotic constraints such as drought, as it is widely cultivated in the Mediterranean regions where the arid and semi-arid climate lead to a reduction in tomato yield as well as fruit quality; this affects its growth and physiological and biochemical parameters [17,18].

To our own knowledge, this is the first work to describe the role of SWRT on the physiological and biochemical mechanisms of tomato plants subjected to drought stress under field conditions. Therefore, in this work, we examined the ability of SWRT to boost drought stress tolerance in tomatoes and to determine the mechanisms by which SWRT mitigates the negative impact of drought in tomatoes grown under field conditions in Morocco.

The results obtained here will contribute to offer the theoretical bases for the application of SWRT as a sustainable and novel technology to cope with drought stress and climate change. Thus, we hypothesized that the water-stress-induced reduction in tomato plants will be mitigated by the application of SWRT. Furthermore, we predict that SWRT could improve tomato growth and stress tolerance through the enhancement of photosynthetic machinery, the attenuation of oxidative stress, and the improvement of ROS trapping by activating antioxidant enzymes systems under conditions of water stress.

2. Materials and Methods

2.1. Experimental Site, Crop Material, and Treatments Applied

A field experiment was carried out at a private agricultural field that has not been previously treated with any chemicals or any other organic fertilizers. This farm is located in the SAADA district of Marrakesh, Morocco, (31°37′39.9′′ N and 08°07′46.7′′ W). The climate of this location is semi-arid, typically Mediterranean, with an estimated average temperature of 19.6 °C and an average annual precipitation of about 250 mm. The mean annual value for reference evapotranspiration (ET_0), which was calculated according to the FAO-PM equation, is almost 1600 mm [19,20]. Characteristics of the soil are as follows: sand 52.00%, clay 24.00%, loam 24.00%, and bulk density 1.4 g/cm.

Solanum lycopersicum L. campel 33 variety was used in this study. Tomato seeds were germinated in the peat-containing trays during 2 weeks under greenhouse conditions. Then, the seedlings were transferred to the field for planting. Two different treatments based on SWRT application and two water regimes were used in this study: WW: well-watered plants (100% field capacity (FC)) received 8 l/h 5 days per week; DS: drought stress plants (50% FC) received 4 l/h 5 days per week. These conditions were implemented from week 1 until harvest. The SWRT was installed manually at a depth of 40 cm below the seedlings.

The field plots were irrigated through the use of drip irrigation system lines with adequate internal drippers placed on the soil at the surface of the furrows at intervals of five days in order to manage the amount of irrigation water. Consequently, the experiment included ten replicates for each treatment, with each water regime applied for two treatments:

(1) (SWRT−): Plants without SWRT.
(2) (SWRT+): Plants with SWRT.

2.2. Measured Parameters

2.2.1. Growth Parameters

After four months, plants were collected, and the following growth parameters were measured: shoot height (SH), shoot number (SN), root elongation (RE), number and weight of fruits (NF and WF), dry matter of shoot, and roots and fruits obtained after drying the different parts at 80 °C for 48 h.

2.2.2. Physiological Parameters

Stomatal conductance (g_s) was assessed with a portable porometer (Decagon Device, Inc., Washington, DC, USA). Ten recordings for each treatment were taken on the abdominal side of each plant on sunny days between 9:30 and 11:00 a.m.

The photochemical efficiency of photosystem II was estimated by a portable fluorometer (OPTI-SCIENCE, OS30p, Hudson, NY, USA). Clips were applied on the superior side of young leaves of the identical row. After 20 min of dark adaptation, minimum (F0), maximum (Fm), and variable (Fv) fluorescence emissions were measured on leaves. The efficiency of PSII was expressed as the Fv/Fm ratio [21].

Stem water potential (Ψ) was assessed by a Scholander pressure chamber (Model SKPM 1400. Skye Instruments, Powys, UK) at predawn (06:00–08:00 a.m.). The measures were taken on fresh harvested stems on the same days and directly after gas exchange readings.

The concentrations of chlorophyll a, b, and total chlorophyll were measured spectrophotometrically at 645 and 633 nm as described by Arnon (1949) [22]. Acetone (80%) was used to extract the studied pigments from tomato shoots samples, then they were centrifuged at 10,000× g for 10 min.

2.2.3. Biochemical Parameters

Total soluble sugar (TSS) concentration was assessed in shoots, roots, and fruits by following the method of Dubois et al. (1956) [23]. In brief, liquid nitrogen was used to wet-grind fresh materiel (0.1 g) before homogenizing it with 4 mL of ethanol (80%). Thereafter, the extract (0.25 mL) was combined with the phenol (0.25 mL) and concentrated sulfuric acid (1.25 mL). The absorbance was taken at 484 nm.

Total soluble protein content was determined in shoots, roots, and fruits by following the method of Bradford (1976) [24]. Absorbance was read at 595 nm using bovine serum albumin as the protein standard.

Malondialdehyde (MDA) content in shoots and roots was assessed spectrophotometrically at 760 following the method of Rao and Sresty (2000) [25]. The extract was prepared by blending 0.25 g of sample with trichloroacetic acid (TCA). The extraction was centrifuged at 18,000× g for 10 min. The reaction mixture of MDA content evaluation included supernatant extraction (2 mL) and 20% TCA containing 0.5% thiobarbituric acid (2 mL).

Hydrogen peroxide (H_2O_2) in fresh roots and shoots was estimated according to Velikova et al. (2000) [26]. Briefly, fresh samples (0.25 g) were extracted by using 5 mL of 10% (w/v) TCA and then centrifuged at 15,000× g for 10 min. The reaction mixture contained the extract (2 mL), potassium iodide (1 mL, 1 M), and potassium phosphate buffer (0.5 mL, 10 mM, pH 7). After incubating for one hour in the dark, the absorbance was taken at 390.

The antioxidant enzyme activity was evaluated in shoots and roots. The extract of enzymes was prepared by homogenized sample (0.1 g) with 5 mL of a solution including 0.1 g polyvinylpolypyrrolidone, 0.1 M potassium phosphate buffer (pH 7.0), as well as 0.1 mM ethylenediaminetetraacetic acid (EDTA), and then centrifuged at 18,000× g at 4 °C for 15 min.

Superoxide dismutase (SOD) was measured following the absorbance change at 560 nm as described by Beyer and Fridovich (1987) [27]. The method is based on the capacity to inhibit the photochemical reduction in p-nitroblue tetrazolium by the SOD enzyme.

Catalase activity (CAT) was determined following the reduction in H_2O_2 spectrophotometrically at 240 nm for 60 s as described by Aebi (1984) [28]. A measure of 100 µL of extract was mixed with 1 M potassium phosphate buffer (pH 7.0), 0.1 mM EDTA, and 20 mM H_2O_2. The results are expressed as µL H_2O_2 mg^{-1} protein min^{-1}.

Ascorbate peroxidase activity (POX) was evaluated as described by Nakano and Asada (1981) [29]. A mixture of 50 mM potassium phosphate buffer (pH 7.0), 100 µL extract sample, and 0.5 mM H_2O_2, as well as 0.1 mM ascorbate, was prepared. The absorbance was measured at 290 nm for 1 min.

Total phenolic content (TPC) was measured by spectrophotometric method at 760 nm in shoot, root, and fruit extracts using the Folin–Ciocalteu method [30] with slight modifications. An aliquot of 250 µL of extract solution was combined with 2.5 mL of 1 N Folin–Ciocalteu reagent solution. After incubation for 3 min at room temperature, 250 µL of 10% sodium carbonate solution was then added and kept in a dark place for 90 min.

2.2.4. Physico-Chemical Analysis of Soil

In order to assess SWRT's effect on soil quality, soil physico-chemical analysis was evaluated after the experiment. Soil samples were taken close to the root system and then air-dried and sieved (2 mm). The following parameters were then determined: pH and EC were determined in aqueous solution, and total organic carbon as well as organic matter (OM) were assessed as mentioned by Aubert (1978) [29]. Finally, assimilable phosphorus (AP) was quantified by following the Olsen and Sommers' protocol [30].

2.3. Statistical Analysis

The data presented here are the mean values of three replicates ± standard error (S.E). The significance of the difference between each treatment was examined through analysis of variance (one-way ANOVA) using factorial ANOVA in SPSS version 23.0 (IBM, Armonk, NY, USA) for windows. To compare means, Tukey's tests at $p \leq 0.05$ were performed.

3. Results

Plant growth and yield of tomato were significantly influenced by the interaction of drought and SWRT treatments (Table 1). Under WW, no significant difference was observed between SWRT and control plants. However, the application of this technique promotes plant growth and yield under DS. Indeed, SWRT application resulted in a significant increase in SN (31%), shoot dry weight (24%), RE (42%), root dry weight (93%), NF (38%), and WF (76%) compared with the control plants.

Table 1. Effect of subsurface water retention technology (SWRT) on growth parameters of tomatoes subjected to different water regimes (DS: drought stress or WW: well-watered) after 4 months of cultivation.

Treatments	Water Regime	Shoot Height	Shoot Number	Shoot Dry Weight	Root Elongation	Root Dry Weight	Fruits Number	Fruits Weight
SWRT+	WW	96.67 ± 14.01 [a]	9.33 ± 1.53 [a]	168.44 ± 5.80 [a]	23.94 ± 2.14 [a]	16.58 ± 1.47 [a]	27.33 ± 2.52 [a]	691.33 ± 54.01 [a]
	DS	67.67 ± 3.51 [b]	7.00 ± 1.00 [ab]	92.50 ± 3.37 [c]	18.23± 1.90 [b]	11.15 ± 1.29 [b]	17.00 ± 2.52 [b]	442.33 ± 30.01 [b]
SWRT−	WW	96.33 ± 9.07 [ab]	9.00 ± 2.00 [ab]	139.66 ± 8.65 [b]	20.54 ± 2.18 [ab]	16.58 ± 1.47 [a]	28.00 ± 4.36 [a]	635.00 ± 35.34 [a]
	DS	87.00 ± 14.11 [ab]	5.33 ± 1.15 [b]	74.33 ± 5.69 [d]	12.82 ± 1.52 [c]	5.79 ± 0.99 [c]	12.33 ± 4.36 [b]	252.00 ± 52.74 [c]

SWRT−: without SWRT; SWRT+: with SWRT. Data represented are mean of three replicates ± standard error (SE) (n = 3). Different letters in the same column show significant difference at $p < 0.05$.

3.1. Physiological Changes

Table 2 represents the effect of the SWRT technique in regulating physiological parameters in the absence and presence of drought stress. Under DS field conditions, tomato plants showed a significant reduction in physiological parameters. However, SWRT application significantly enhanced g_s, Fv/Fm, ΨLeaf, chlorophyll a, b, and total chlorophyll, as well as carotenoids levels by 39, 3, 22, 59, 37, 49, and 68%, respectively, compared with the control plants.

Table 2. Effect of subsurface water retention technology (SWRT) on stomatal conductance, photosynthetic efficiency, leaf water potential, chlorophyll, and carotenoid content of tomatoes subjected to different water regimes (DS: drought stress or WW; well-watered) after 4 months of cultivation.

Treatments	Water Regime	Stomatal Conductance (mmol m^{-2} s^{-1})	Chl Fluorescence	Leaf Water Potential (bar)	Chl a (mg g^{-1} DW)	Chl b (mg g^{-1} DW)	Total Chl (mg g^{-1} DW)	Carotenoids (mg g^{-1} DW)
SWRT+	WW	53.37 ± 3.49 ^{b}	0.72 ± 0.01 ^{b}	−1.80 ± 0.10 ^{c}	13.54 ± 0.40 ^{a}	9.74 ± 0.68 ^{a}	17.57 ± 0.84 ^{a}	38.78 ± 1.28 ^{a}
	DS	37.23 ± 2.94 ^{c}	0.71 ± 0.01 ^{bc}	−2.22 ± 0.13 ^{b}	9.90 ± 1.03 ^{b}	5.09 ± 0.28 ^{c}	11.01 ± 0.71 ^{c}	26.23 ± 1.34 ^{b}
SWRT−	WW	68.47 ± 2.66 ^{a}	0.76 ± 0.01 ^{a}	−1.58 ± 0.08 ^{c}	11.57 ± 0.64 ^{ab}	8.33 ± 0.34 ^{b}	14.97 ± 0.70 ^{b}	33.23 ± 2.49 ^{a}
	DS	26.70 ± 2.96 ^{d}	0.69 ± 0.0 ^{c}	−2.83 ± 0.15 ^{a}	6.24 ± 0.84 ^{c}	3.72 ± 0.59 ^{d}	7.39 ± 0.99 ^{d}	15.58 ± 3.24 ^{a}

Chl: chlorophyll; SWRT−: without SWRT; SWRT+: with SWRT. Data represented are mean of three replicates ± standard error (SE) (n = 3). Different letters in the same column show significant difference at $p < 0.05$.

3.2. Osmolytes Accumulation

Data presented in Figure 1 reveals that TSS and protein content in shoots, roots, and fruits was affected by SWRT application under DS conditions. Indeed, plants with SWRT showed a decrease in TSS content of 16, 8, and 19% in shoots, roots, and fruits, respectively, compared with the control. Conversely, SWRT application under DS showed a significant positive increase in protein content of shoots (31%), roots (54%), and fruits (72%) compared with the control plants.

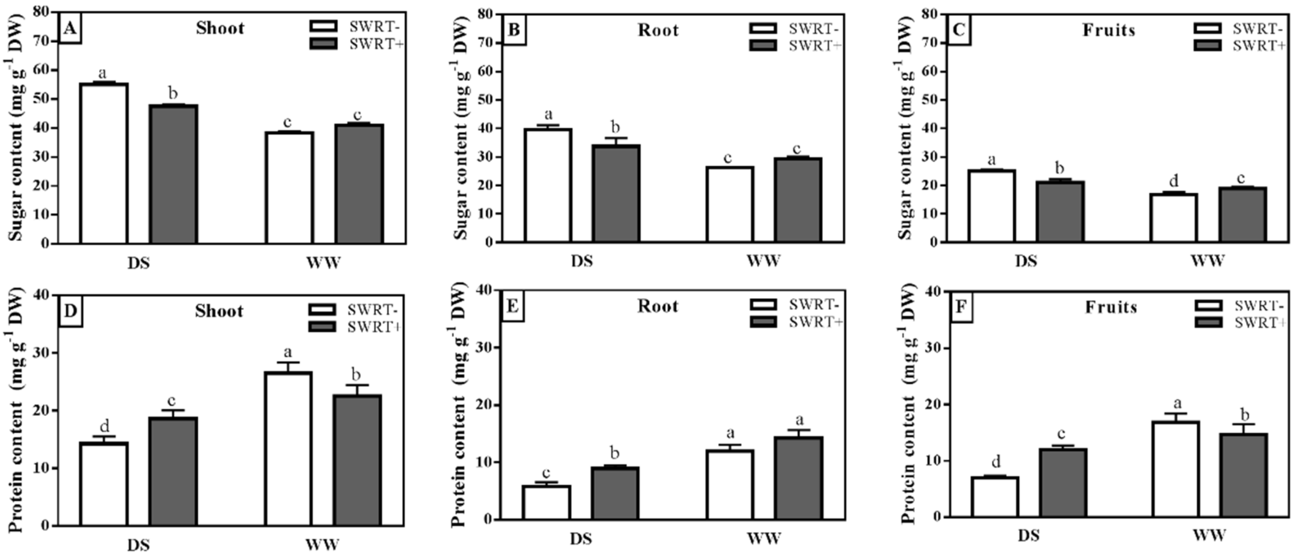

Figure 1. Effects of water regimes (DS: drought stress or WW: well-watered) on shoot, root, and fruit (**A**–**C**) total soluble sugar content, and (**D**–**F**) protein content subjected to treatments. SWRT−: without subsurface water retention technology (SWRT); SWRT+: with SWRT. Data represented are mean of three replicates ± standard error (SE) (n = 3). Different letters in the same column show significant difference at $p < 0.05$.

Under WW conditions, differences were not significant for protein content in roots and TSS content in shoots and roots, while SWRT application increased fruit TSS and decreased protein content in shoots and roots.

3.3. MDA and H_2O_2

Figure 2 shows the impact of several applied water regimes with and without SWRT on the contents of MDA and H_2O_2. Without SWRT, the levels of MDA and H_2O_2 found in tomato leaves and roots were enhanced under drought stress. In contrast, SWRT application led to a significant decrease in MDA and H_2O_2 values with a reduction of 30 and 39% in leaves and 34 and 35% in roots compared with the DS control plants.

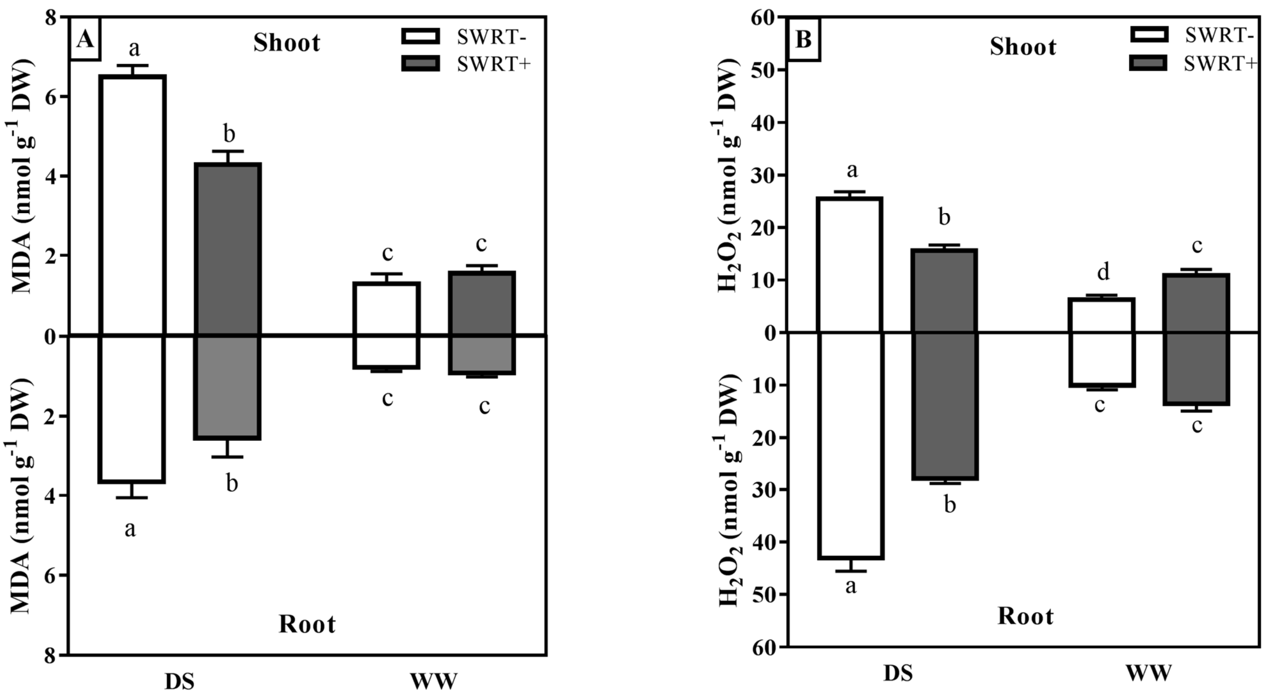

Figure 2. Effects of water regimes (DS: drought stress or WW: well-watered) on shoot and root (**A**) malondialdehyde (MDA) and (**B**) hydrogen peroxide (H_2O_2) content subjected to treatments. SWRT−: without subsurface water retention technology (SWRT); SWRT+: with SWRT. Data represented are mean of three replicates ± standard error (SE) (n = 3). Different letters in the same column show significant difference at $p < 0.05$.

3.4. Oxidative Stress Attributes

Data of the antioxidant enzyme activities in tomato plants are given in Figure 3. The results indicate that these activities increased under DS conditions without SWRT application. In the same conditions, SOD, CAT, and POX levels were greater in the root part than in the shoot one, with an enhancement of 248, 46, and 66%, respectively. However, the opposite was recorded for TPC by comparing the two parts of the plant. Under WW, any significant difference was not noted between plants with and without SWRT. Nevertheless, SWRT application in tomatoes under drought conditions was accompanied by a reduction in SOD, CAT, POX, and TPC activities in leaves by 67, 113, 41, and 18%, respectively, and in roots by 75, 130, 85, and 17%, respectively, compared with the control plants.

3.5. Soil Characteristics

Data presented in Table 3 show the field soil characteristics before and after the experiment. Findings showed that all soil characteristics were improved after harvesting whatever the conditions applied, as compared with the initial state. In addition, compared with the WW conditions, soil quality was affected by DS conditions, which caused a decrease in TOC, OM, and AP by 45, 81, and 45%, respectively. Under the same conditions (DS conditions), SWRT application caused a significant enhancement in all studied parameters EC, TOC, OM, and AP by 9, 8, 23, and 25%, respectively, when compared with the plants without SWRT.

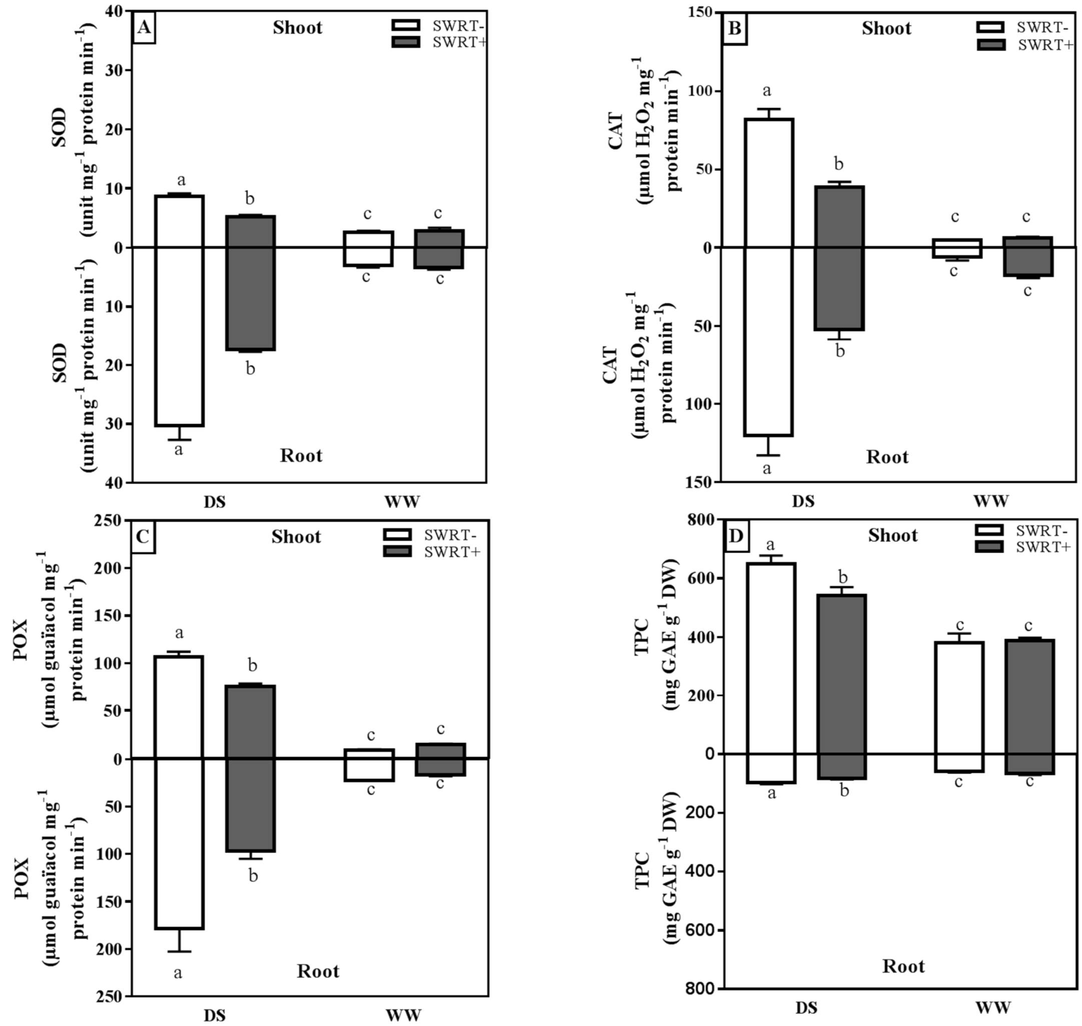

Figure 3. Effects of water regimes (DS: drought stress or WW: well-watered) on shoot and root (**A**) superoxide dismutase (SOD), (**B**) catalase (CAT), (**C**) ascorbate peroxidase (POX) activities, and (**D**) total phenolic content (TPC) subjected to treatments. SWRT−: without subsurface water retention technology (SWRT); SWRT+: with SWRT. Data represented are mean of three replicates ± standard error (SE) (n = 3). Different letters in the same column show significant difference at $p < 0.05$.

Table 3. Effect of subsurface water retention technology (SWRT) on main characteristics of different treatments on agricultural soil physicochemical parameters before and after experiment.

Treatments	Before Experiment	After Experiment			
		SWRT+		SWRT−	
		WW	DS	WW	DS
pH	7.84 ± 0.07 [a]	7.42± 0.05 [c]	7.53 ± 0.23 [b]	7.48 ± 0.24 [b]	7.50 ± 0.45 [b]
EC (mS cm^{-1})	1.76 ± 0.22 [a]	1.38 ± 0.16 [d]	1.57 ± 0.14 [c]	1.46 ± 0.22 [c]	1.66 ± 0.23 [b]
TOC (%)	0.83 ± 0.02 [d]	1.25 ± 0.15 [b]	1.05 ± 0.23 [c]	1.54 ± 0.13 [a]	0.85 ± 0.14 [d]
OM (%)	1.27 ± 0.22 [e]	2.14 ± 0.23 [b]	1.80 ± 0.11 [c]	2.65 ± 0.16 [a]	1.46 ± 0.22 [de]
AP (%)	26.32 ± 2.32 [e]	37.45 ± 3.11 [b]	34.45 ± 1.23 [c]	40.21 ± 1.33 [a]	27.66 ± 1.32 [de]

EC: electrical conductivity; TOC: total organic carbon; OM: organic matter; AP: assimilable phosphorus; SWRT−: without SWRT; SWRT+: with SWRT. Data represented are mean of three replicates ± standard error (SE) (n = 3). Different letters in the same column show significant difference at $p < 0.05$.

3.6. Principal Component Analysis (PCA)

The principal component analysis highlighted the relationship between SWRT technique, drought, and measured parameters. The PCA1 (variability; 81.22%) vs. PCA2 (variability; 13.7%) dispersion plot is shown in Figure 4. The data showed that all treatments applied were separated from each other. Under WW conditions, the application of SWRT was positively linked with yield and growth parameters (SH, RH, NL, FW, and SDW) as well as soil physico-chemical traits (TOC and OM). Moreover, a positive correlation was found between SWRT and sugar content, pH, and EC in DS conditions.

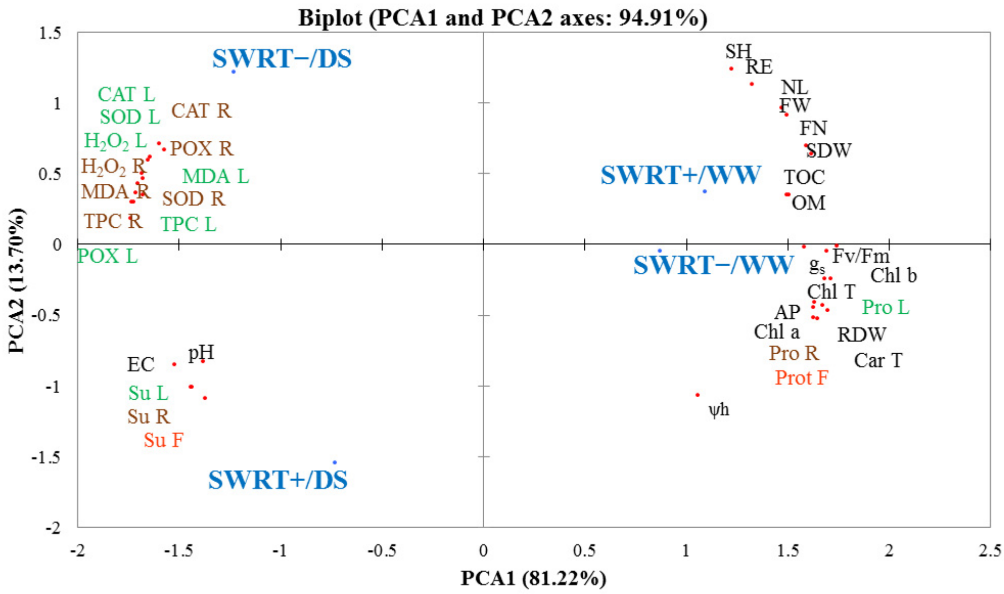

Figure 4. Principal component analysis (PCA) of tomatoes exposed to different treatments. SWRT−: without subsurface water retention technology (SWRT); SWRT+: with SWRT under two water regimes (DS: drought stress or WW: well-watered). SH: shoot height; NL: number of leaves; SDW: shoot dry weight; RE: root elongation; RDW: root dry weight; FN: fruit number; FW: fruit weight; g_s: stomatal conductance; Fv/Fm: chlorophyll fluorescence; ψh: Stem water potential; Chl a: chlorophyll a content; Chl b: chlorophyll b content; Chl T: chlorophyll total content; Car T: carotenoid content; Su L: sugar content in leaves; Su R: sugar content in roots; Su F: sugar content in fruits; Pro L: protein content in leaves; Pro R: protein content in roots; Prot F: protein content in fruits; MDA L: malondialdehyde content in leaves; MDA R: malondialdehyde content in roots; H_2O_2 L: hydrogen peroxide content of the leaves; H_2O_2 R: hydrogen peroxide level of the roots; SOD L: superoxide dismutase activity of the leaves; SOD R: superoxide dismutase activity of the roots; CAT L: catalase activity of the leaves; CAT R: catalase activity of the roots; POX L: peroxidase activity of the leaves; POX R: peroxidase activity of the roots; Phe L: phenolic content of the leaves; Phe R: phenolic content of the roots; pH: potential of hydrogen; EC: electrical conductivity; TOC: total organic carbon; OM: organic matter; AP: phosphorus assimilable.

4. Discussion

Tomatoes are considered one of the most drought-sensitive plants, making irrigation the main source of water for them in semi-arid regions, which makes them one of the key determinants to affect yield and fruit quality. The current investigation is the first to quantify the SWRT impact on drought resistance in tomatoes based on morphological, physiological, and biochemical traits. We also tested whether the application of this technique can improve soil parameters.

According to the obtained results, it appears that the crop biomass was significantly decreased by drought. Many previous studies have shown the negative impacts of drought on tomatoes [31,32]. The reduction in leaf growth parameters under DS conditions can be attributed to decreased cell division and elongation due to loss of turgidity, reduced photosynthesis, and decreased energy input [33,34]. However, SWRT application enhanced the growth parameters investigated, namely SH, RE, and shoot and root weight, especially under DS. This can be attributed to the reduction in water and mineral loss through percolation [11,35] and the improvement of soil fertility and structure, as showed in this study, which creates a better conditions for plant establishment [8]. In terms of productivity, our data showed that the application of SWRT improved tomato and yield under DS, especially fruit number and weight. Improved growth and better nutrition was accompanied by higher productivity in terms of quality and quantity [36]. These findings are in harmony with what has been published by Aoda et al. (2021) and Hommadi and Almasraf (2018) [7,37], who showed that the application of SWRT improved the yield of tomatoes and chili peppers, respectively, grown in the field.

The results from our investigations show that drought application led to a decrease in the photosynthetic parameters of tomato plants due to the depletion of soil water content, this is a typical response of plants to water shortage in soil [38,39]. Many studies have reported a reduction in photosynthesis mainly due to the reduction in g_s, which limits the supply of CO_2 to the intercellular space [40–42]. Drought can also interrupt the carbon and nitrogen exchange in the soil [43], which might lead to reduced photosynthetic metabolism in plants [44,45]. Under the same conditions, SWRT application allowed for a continuous supply of the plants' available moisture through increasing the soil's ability to store water [8,9], thereby increasing g_s and Fv/Fm and reducing chlorophyll and carotenoid degradation [46,47]. Enhancement in physiological characteristics suggests boosted performance of the photosynthetic machinery, which leads to enhanced CO_2 uptake for photosynthesis [48].

Limited water availability significantly increased the level of MDA and H_2O_2 in tomato leaves and roots as compared with the control plants. Malondialdehyde is produced in plant cell membranes by the breakdown of polyunsaturated fatty acids as a result of dehydration conditions [49], therefore lipid oxidative damage in cell membranes, is detected by high MDA concentrations in plants [50]. Consequently, increased lipid peroxidation and H_2O_2 levels increase oxidative stress due to a significant accumulation of reactive oxygen species (ROS) and of the disruption of the enzymatic defense in plants growing under drought [51]. Our findings are in agreement with the results of previous research, they reported that MDA and H_2O_2 considerably elevated under drought stress in cactus [52] tomato [32], quinoa [53], and alfalfa [54] plants. Our results show that the application of SWRT on tomatoes mitigated the damaging effects of drought by eliminating damage caused by oxidative stress and protecting the cell membranes through their ability to upgrade soil water holding ability in plant root zones and by enhancing native soil quality through increased carbon, OM, and PA [8,9].

Under DS, plants produce and accumulate a functional antioxidant system, which is either enzymatic (SOD, CAT, and POX) or non-enzymatic (polyphenol), to maintain ROS balance [55]. These primary cellular antioxidants protect the cell by directly scavenging superoxide radicals (O^{2-}) and hydrogen peroxide (H_2O_2) and converting intracellular ROS into less reactive species [56]. Total phenolic content also plays a role as a non-enzymatic free radical scavenger by neutralizing singlet oxygen or quenching metal ions or supplying a substrate for POX enzymes to protect the membrane from oxidative stress [57,58]. Our results reveal an increase in the level of antioxidant indices (SOD, CAT, POX, and TPC) in leaves and roots of tomatoes exposed to drought in order to hinder their detrimental effects. These findings are quite close to those of Tahiri et al. (2022) and Lahbouki et al. (2022), who reported an increase in SOD, CAT, POX, and TPC with increasing levels of MDA and H_2O_2 in drought-exposed tomatoes and cactuses, respectively [32,59]. In contrast, applying the SWRT technique led to a decrease in the accumulation of antioxidants (SOD, CAT, POX, and TPC) and MDA and H_2O_2 contents. These findings can be explained by the contribution of SWRT to water and nutrient preservation in the root zone, hence a decrease in the oxidative stress of plant cells [8,60].

Water stress effects not only plant performance but also soil physic-chemical properties, as shown above. Our data are in line with the results of Benaffari et al. (2022) [53]. The decrease can be explained by the adverse effects of drought soil structure, aggregates, and glomalin soil [61,62]. In addition, drought directly affects the activity and composition of soil microbial communities [63], especially those involved in making soil enzymes important for soil fertility, such as urease (N cycle), β-glucosidase (C cycle), and phosphatase (P cycle) [64]. However, SWRT application improved soil chemical and nutrient quality through various mechanisms, one of them being the contribution to the maintenance of soil moisture, which in turn helped to increase microbial communities and organic acids [8,65]. These contribute to the low pH of the soil [66]. The increase in organic matter and nutrients in the soil can also be explained by the contribution of the impermeable membrane applied in increasing the content of organic matter and nutritional elements retained [9,67].

To visualize the differences between the treatments regarding the measured parameters, a PCA analysis was performed. Global outcomes of this analysis indicated the effectiveness of SWRT in plant growth under non-stressful conditions, as well as its close link to osmolyte accumulation under drought stress conditions, which may promote a more complete understanding of the protective effects of SWRT in tomatoes under stressful conditions.

5. Conclusions

The current investigation proved that drought stress severely affects tomato plants' growth traits, physiological responses, and biochemical reactions. However, the application of SWRT has shown their capacity to overcome the negative impacts of water deficit through the enhancement of chlorophyll fluorescence and stomatal conductance, as well as osmotic adjustment and enzymatic antioxidant systems. Additionally, the application of this technique under drought reduced soil pH and increased the percentage of OM and available phosphorus in the soil. The mechanisms for the action of SWRT's application in improving plant performance under drought are probably related to its ability to improve soil mineral and water retention and to avoid their loss by percolation into the soil. According to our research, SWRT could be a practical option for promoting plant performance in arid and semi- arid climates and as an important tool for agriculture system sustainability in the face of climate change.

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