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Magnetized Water and Proline to Boost the Growth, Productivity and Fruit Quality of 'Taifi' Pomegranate Subjected to Deficit Irrigation in Saline Clay Soils of Semi-Arid Egypt

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Abstract: Water scarcity is becoming a global problem. The shift from traditional irrigation systems to deficit irrigation increased soil salinity, particularly in clay soils. The use of magnetized water (MW) and biostimulants can induce plant resistance to drought and salinity stress. To assess the role of MW and proline (P) on 'Taifi' pomegranate shrubs' growth, productivity, and fruit quality under such conditions, a split-plots experiment was conducted for two seasons using three irrigation levels (100%, 75%, and 50%), based on the crop water requirements (CWR), and four treatments including foliar spray of tap water (control) and P, irrigation with MW, and MW + P. The most pronounced effect was referred to MW + P at 75% CWR that improved shrubs' chlorophyll content and nutritional status, reduced endogenous proline content, and enhanced vegetative growth with minimum consumptive water use (CWU), optimum water use efficiency (WUE), maximum water productivity (WP), utmost yield and average fruit weight, lowest percentage of fruit cracking, and fairly good total soluble solids (TSS), vitamin C and anthocyanin contents. Overall, MW + P at 75% CWR improved the resistance mechanism of pomegranate shrubs in saline clay soils, plus improving the growers' net profit. MW generally reduced soil salinity, expressed as reduced pH, EC, Na^+, and Ca^{2+} values.

Keywords: clay soils; deficit irrigation; magnetic water; osmoregulants; salinity; water relationships

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1. Introduction

The pomegranate (*Punica granatum* L.), belonging to the Lythraceae (formerly Punicaceae) family, is a deciduous shrub or small tree that believed to be originated in Persia (i.e., Iran), Afghanistan, Pakistan, and perhaps Northern India nearly 4000 years ago [1]. Due to the rapid increase in the cultivation and production of pomegranates, no current reliable information is available about the global production, but it was estimated to be around 3.8 million tons in 2017. The top world producers are believed to be India, Iran, Turkey, China, United States of America, Palestine, Egypt, Spain, Afghanistan, Tunisia, Azerbaijan, Morocco, Argentina, Brazil, Chile, Peru, South Africa, Australia, and Italy [2].

Pomegranates grow well in mild-temperate to tropical climates; however, the best fruit quality is attained in Mediterranean climate (regions with cool winter and hot dry summer). Cultivars vary in frost tolerance, and some dormant shrubs are severely injured at temperatures down to −11 °C. Shrubs perform well in deep loamy soils, but still grow quite well in sandy and clay soils, and grow best in a soil pH range of 5.5–7.2. They also prefer well-drained soils, and can tolerate short periods of flooding stress. Shrubs are very drought tolerant, and moderately tolerate salinity stress. Drip irrigation is the preferred method, and shrubs can withstand irrigation with saline water up to electric conductivity (EC) = 2 dS·m^{-1} [3,4].

The main obstacle of pomegranate cultivation under arid and semi-arid conditions is the abiotic stresses, particularly heat [2], drought, and salinity [5]. The effects of drought and salinity, in particular, have increased in the last decades due to water scarcity [6]. Drought has an impact on plant morphology, physiology, and biochemistry. Under such conditions, xylem vessels become susceptible to embolism or dysfunction, leading to lower hydraulic conductance and carbon intake, which in turn affect plant growth characteristics and productivity [7]. Drought stress causes a reduction in root and vegetative growth, number of leaves per branch, leaf area, leaf water content, and number of malformed flowers [8]. Salinity, in particular, is one of the major environmental stresses that can develop through irrigation, and is considered as a limiting factor in agricultural systems [9]. High levels of salts, mainly chlorides (Cl^-) and sulfates ($SO_4{}^{2-}$) of calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^+), cannot be tolerated by most of the plants [10]. Salinity induces cell damages and inhibits plant growth [11] through osmotic stress and ionic stress [12]. Salinity causes leaf injury, as well as a reduction in chlorophyll content, carbon assimilation, and nutrient uptake. It also induces the production of reactive oxygen species (ROS) that negatively affect plant metabolism through the oxidative damage of lipids, proteins, and nucleic acids [13]. Moreover, it causes a reduction in plant height and leaf area, and creates bearing problems with reduced fruit yield and quality [14].

Egypt is ranked the seventh among the top worldwide producers of pomegranates [2]. Total cultivated area is about 31,987 hectares with total production of 382,587 tonnes, and the export of almost 82,866 tonnes (21.6% of the total crop) in 2020; accordingly, Egypt is ranked the fifth among the top world exporters [15]. Harvest season starts by mid-September to early November, and the most important cultivars are 'Manfalouty', 'Wonderful', '116', and 'Red Angel' [16]. 'Taifi' cultivar originated in Saudi Arabia, and it is the most popular cultivar there, particularly in the South West region [17]. It was introduced to Egypt in 2016, but it is not so popular or widely cultivated yet due to fruit cracking, poor outside and inside color, low sugar, and high acidity contents under the semi-arid conditions of Egypt (personal communications). Shrubs are generally medium in size. The proportion of male to perfect flowers (sex ratio) is 35%. Flowers are orange-reddish, and fruits are spherical and large in size with green-reddish peel, and large, soft, and red seeds. Average fruit yield is about 200 fruits per shrub with an average weight of 250 g and almost 63.2% juice per fruit. Fruit has a sweet–sour taste with minimum total sugars = 14.30%, total soluble solids (TSS) = 15.77 °Brix, acidity = 0.56%, and vitamin C = 8.34% [18].

Water scarcity is becoming a recent problem in Egypt, and may become a limiting factor of the overall fruit industry in the future, due to limited water resources and scanty rainfall. One of the major problems of drought is soil salinity [19]. Under such conditions, there is a need to reduce agricultural water demand and increase the economic productivity of water, particularly in the North Delta area where soil salinity is high. Improving on-farm management of agricultural water through the utilization of advanced irrigation technology (e.g., deficit irrigation) and improved irrigation scheduling, offering the prospect of a significant increase in water productivity [20]. Deficit irrigation is a strategy where the amount of applied water is less than the full water requirements of a crop, and the resulting stress has minimal effects on crop yield. It effectively reduced water requirements, and improved plant's water use efficiency (WUE) [21] and fruit quality of various deciduous fruit trees, including pomegranate, depending on the phenological stage when water shortage was applied [22]. However, in salt-affected clay soils, the shift from traditional flood irrigation systems to the modern techniques such as deficit irrigation resulted in increased soil salinity [23,24]. Therefore, the use of magnetized water (MW) under the deficit irrigation system [25], as well as foliar application of some biostimulants can play an important role in inducing plant resistance to drought and salinity stresses [26,27].

Biostimulants are known to improve plant growth, yield, and fruit quality. They include diverse substances like humic substances, compost tea, seaweed extracts, free amino acids (e.g., proline), and plant extracts, as well as microorganisms like free-living bacteria, fungi, and *Arbuscular mycorrhizal* fungi [28].

The flow of water through a magnetic field changes its physiochemical characteristics, and results in what so called "magnetized water". The change or disintegrate of the hydrogen bonds results in a decrease in the angle between hydrogen (H) and oxygen (O), and hence the formation of a hexagonal configuration with reduced surface tension making the water more bioavailable and easily absorbed into root cells. In addition, magnetic field also increases water pH, resulting in a more alkaline water [29] with lower viscosity, EC and contents of Na^+ and Cl^-, but higher permeability and ability to dissolve slight-soluble salts and leach the excess. The application of magnetic field on water decreases the hydration of salt ions and colloids, having a positive effect on salt solubility, accelerated coagulation, and salt crystallization [30]. Under magnetic field, the hydration number of Cl^- ions increases, and hence their mobility decreases, while the mean size of water clusters decreases and their mobility increases [31]. Similarly, Na^+ level under MW irrigation was also lower than that under non-MW irrigation conditions [32]. Therefore, MW can be used as an effective method for soil desalinization [33]. These effects of MW remained for up to 200 h after the magnetic field was ceased. This is called "the memory effect of water" [34]. Water subjected to a magnetic field has shown a modification in its properties, as it became more energetic and able to flow, which can be considered as the birth of a new science called 'magneto biology'. In addition, MW prevents the uptake of harmful metals such as lead (Pb) and nickel (Ni) by roots, and hence prevents them from reaching the fruit [35].

The effect of MW technology on fruit trees is rarely documented and merits further investigations to evaluate its impacts on the yield and fruit quality, particularly under drought and salinity stress conditions. Few studies on different fruit species have shown that MW enhanced soil nutrient availability and salt leaching [36], and therefore improved leaf mineral contents, plant growth characteristics, fruit set, yield, and quality of 'Valencia' orange [37]. Furthermore, there is a relationship between irrigation with MW and photolyase-like blue light receptors, "cryptochromes" (CRY1 and CRY2), which have various roles in plants such as guard cell development, stomata opening, photosynthesis, root development, vegetative growth, and fruit development [38].

As a proteinogenic amino acid, proline ($C_5H_9NO_2$, 115.13 g.mol^{-1} mw) is the most widely distributed osmoprotectant in higher plants that plays an essential role in the defense mechanism of stressed plants through changes in key anatomical features of roots and leaves, the osmotic regulation of the cell sap, membrane and protein stability, enzyme activity, and scavenging the free radicals [39,40]. Enhanced endogenous proline level improved leaf chlorophyll content, yield, and fruit weight, diameter and TSS of non-stressed pomegranate [41] and orange [42], as well as salt-stressed mango [43] and tomato plants [44].

The aim of this research work was to improve the growth, productivity, and fruit quality of 'Taifi' pomegranate shrubs, grown in saline clay soils and subjected to deficit irrigation, with the utilization of MW and proline to mitigate the stress effects. To date, few reports have used MW to alleviate salinity stress of fruit trees [36], and pomegranate in particular [45]. In addition, most research on deficit irrigation has been performed in sandy soils [26,27,43,45], but this is considered the first report using deficit irrigation with MW to improve the growth and productivity of pomegranate grown in saline clay soils, which require a lot of water for salt leaching.

2. Materials and Methods

2.1. Experimental Site

This research was performed on 9-year-old 'Taifi' pomegranate (*Punica granatum* L.) grown in a private orchard located at Al-Riadh, Kafr Elsheikh, Egypt (31°23′68″ N, 30°94′54″ E) for two consecutive seasons (2019 and 2020). The climatic conditions of the experimental site are semi-arid without summer rains [46], as shown in Table 1. Soil and water analysis were carried out according to Chapman and Pratt [47] and are displayed in Table 2. All used chemicals in this experiment were imported from Sigma Aldrich, St. Louis, MO, USA.

Table 1. Weather data of Al-Riadh, kafr Elsheikh, Egypt during the 2019 and 2020 seasons.

Season		Temperature (°C)	Humidity (%)	Rainfall (mm·month^{-1})	Wind Speed (km·h^{-1})	Cloud (%)	Sun (days·month^{-1})	UV Index
Winter	2019	16.0	61.7	23.0	13.8	19.3	30.0	4.3
	2020	16.0	68.0	26.8	13.2	31.7	28.7	4.0
Spring	2019	23.0	57.3	15.7	14.0	13.3	30.0	6.0
	2020	23.0	59.3	5.3	14.6	16.7	30.3	6.3
Summer	2019	30.7	63.0	1.2	13.0	4.7	30.7	8.0
	2020	30.7	62.7	0.07	13.9	5.0	30.7	7.7
Fall	2019	26.7	63.7	6.03	11.9	10.0	30.0	6.3
	2020	26.7	64.3	11.7	11.6	15.7	29.3	6.3

Table 2. Soil and water analysis of the experimental site.

	Soil Analysis			Water Analysis
Depth (cm)	**0–30**	**30–60**	**60–90**	
Sand (%)	25.2	22.7	25.5	
Silt (%)	27.1	28.1	39.3	
Clay (%)	47.7	49.2	35.1	
Texture	Clay	Clay	Loamy clay	
Density (g·cm^{-3})	1.29	1.36	1.42	
Field capacity (%)	42.2	39.7	38.9	
Permineant wilting point (%)	22.7	21.6	21.2	
Available water (%)	73.6	76.6	78.1	
Depth (cm)		**0–60**		
EC (ds·m^{-1})		1.69		
pH		8.2		7.3
Total dissolved salts (ppm)				400
$CaCO_3$ (%)		8.54		
HCO^{3-} (meq·L^{-1})		0.90		2.1
CO^{3-} (meq·L^{-1})		0.00		
$So_4{}^{2-}$ (meq·L^{-1})		0.26		4.1
Cl^- (meq·L^{-1})		0.50		2.3
Na^+ (meq·L^{-1})		0.45		2.7
K^+ (meq·L^{-1})		0.21		0.2
Ca^{2+} (meq·L^{-1})		0.80		3.1
Mg^{2+} (meq·L^{-1})		0.20		2.5

2.2. Treatments

Seventy-two shrubs, planted at 5 × 5 m in clay soil, similar in size and vigor with no symptoms of nutrient deficiency, were selected for this experiment. Shrubs were subjected to drip irrigation and the same cultural practices as the entire orchard. They were distributed in a randomized complete block design (RCBD) as a split-plot experiment, to minimize variations among the shrubs [48], of twelve treatments with three replicates each. Two shrubs represented each replicate. Three irrigation levels were randomly assigned as the main plots by varying the number drippers per shrub with each dripper delivering 4.0 L.h^{-1}, i.e., 100%, 75%, and 50% crop water requirements (CWR) were achieved with 16 (I_1, the control shrubs, based on the regular irrigation program used in the area), 12 (I_2), and 8 (I_3) drippers, respectively. Total amount of water per shrub throughout the season is presented in Table 3.

Table 3. Quantity of the irrigation water applied during the 2019 and 2020 seasons.

Month	Irrigation Frequency Per Month	Irrigation Period (h)	Dripper Discharge Amount ($L \cdot h^{-1}$)	Irrigation Levels ($L \cdot Tree^{-1} \cdot Season^{-1}$)		
				I_1 = 16 Drippers/Shrub (Control = 100% CWR *)	I_2 = 12 Drippers/Shrub (25% Less = 75% CWR)	I_3 = 8 Drippers/Shrub (50% Less = 50% CWR)
January	3	1	4	192	144	96
Febreuary	8	1	4	512	384	256
March	8	2	4	1024	768	512
April	14	2	4	1792	1344	896
May	14	2	4	1792	1344	896
June	15	2	4	1920	1440	960
July	15	3	4	2880	2160	1440
August	15	3	4	2880	2160	1440
September	10	2	4	1280	960	640
October	8	1.30	4	768	576	384
November	8	1	4	512	384	256
December	4	1	4	256	192	128
Total water ($m^3.tree^{-1}.season^{-1}$)				15.81	11.86	7.90

* CWR: crop water requirements.

Each main plot was divided into four sub-plots that randomly received four different treatments each. The first and second sub-plots were subjected to foliar sprays of tap water, the control shrubs (C), and proline (P) (200 $mg.L^{-1}$) twice at full bloom (19 and 22 March of 2019 and 2020 seasons, respectively) and 4 weeks after. Shrubs in the third sub-plot were irrigated with water subjected to a magnetic field, "magnetized water" (MW), throughout the season using a magnetic field device (strength = 14,500 Gauss and diameter = 2 inch) (Thread connection, Delta Water Inc., Alexandria, Egypt) that was installed on the main irrigation pipe after the water pump and before the fertilizers tank. The fourth sub-plot was representing a combined application of MW and P (MW + P). Treatments were separated by two rows of buffer (border) trees. The layout of one block of the experiment is displayed in Figure 1.

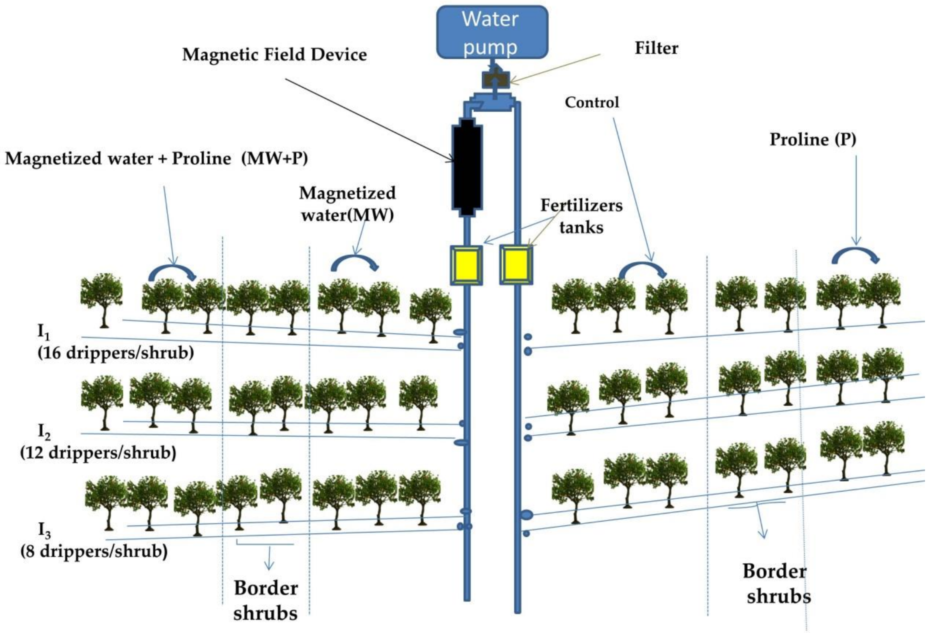

Figure 1. Layout of one block of the experiment.

2.3. Leaf Analysis

Leaf samples were randomly collected from the four sides (N, E, S, W) of the shrub, by mid-June of each season, to evaluate total chlorophyll content (green color intensity, as a SPAD value) in different sections at the middle of the leaf blade [49] using a portable Minolta chlorophyll meter Model SPAD-501 (Spectrum Technologies, Inc., Aurora, IL, USA).

Leaf proline concentration (mg.100 g^{-1} fw) was determined by homogenizing fresh leaf sample (0.2 g) with 3 mL sulphosalicylic acid (3% *w*/*v*) using a porcelain mortar and pestle set (Fisher Scientific, Waltham, MA, USA), and then the mixture was centrifuged at 18,000× *g* for 15 min using a benchtop general purpose centrifuge Model Allegra V-15R (Beckman Coilter Life Sciences, Indianapolis, IN, USA). Afterwards, the supernatant (1 mL) was mixed with 2 mL glacial acetic acid and 2 mL freshly made acid ninhydrin reagent (1.25 g ninhydrin dissolved in 30 mL glacial acetic acid and 20 mL orthophosphate (6 M)) in a test tube. The tubes were incubated in a 'Precision™ General Purpose' water bath (Thermo Fisher Scientific, Waltham, MA, USA) at 100 °C for 1 h, and then left to cool at room temperature (≈22–23 °C) for 24 h. Subsequently, the solution was mixed with toluene (4 mL) using a Vortex-Genie 1 mixer (Scientific Industries, Inc., Bohemia, NY, USA) for 20 s. To allow the toluene and the aqueous phase to separate, the tubes were left in upright position for at least 10 min, and then the toluene phase was carefully pipetted out into a cuvette, and the absorbance was measured at 520 nm using a spectrophotometer Model UV-120-20 (Shimadzu Corp., Kyoto, Japan). Eventually, a proline standard curve was used to calculate the proline concentration [50].

To determine the content of macro and micronutrients, leaf samples were collected and dried at 65 °C for 72 h until reaching a constant weight using a bench-top Heratherm GP oven (Thermo Fisher Scientific, Waltham, MA, USA). Dried leaves were then pulverized using the mortal and pistil set, and the powder was digested with concentrated sulphuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) [51]. The produced solution was used to determine total nitrogen (N) and phosphorus (P) colorimetrically using the spectrophotometer [52,53]. Potassium (K) concentration was determined using a flame photometer Model FP8400 (Kruss Optronic, Hamburg, Germany) [54]. The contents of Ca, Mg [55], iron (Fe), zinc (Zn), and manganese (Mn) [56] were also determined using atomic absorption spectrometer Model AA990 (PG Scientific, Inc., Auburn, CA, USA). All values of macro and micronutrients were expressed as a percentage and mg·L^{-1} per dry weight of leaves, respectively.

2.4. Vegetative Growth

By mid-August of each season, one shoot on four sides (N, E, S, W) of each shrub per replicate was randomly selected and tagged to measure shoot length (cm). Twelve mature mid-branch leaves were collected from each branch to determine leaf area (cm^2) using a leaf area meter Model Li 3100 (LI-COR, Inc., Lincoln, NE, USA), as described [57].

2.5. Yield

Harvest season started by mid-September (≈173–176 days from full bloom) with the harvest window extended for almost 12–15 days in both seasons. Fruit yield (kg·$shrub^{-1}$) was recorded using a regular digital scale (200 kg capacity) (VEVOR Equipment and Tools, Rancho Cucamonga, CA, USA), and then total yield (kg.ha^{-1}) was calculated.

2.6. Consumptive Water Use (CWU), WUE, and Water Productivity (WP)

Soil samples were collected at different depths (i.e., every 15 cm up to 60 cm) before and after each irrigation time, and then weighted to determine CWU (cm) in the root growth zone (≈50–60 cm), using the following equation [58]:

$$\text{CWU} = \sum_{i=1}^{i=4} (\theta 2 - \theta 1/100) \times \text{Dbl} \times \text{Di} \quad (1)$$

where i = number of soil layers (4 layers); θ1 and θ2 = soil moisture (%) before irrigation and 48 h after, respectively; Dbl = soil bulk density (g·cm^{-2}); and Di = soil layer depth (15 cm).

Calculated CWU (cm) was used to calculate total CWU per total area (m^3·ha^{-1}). Accordingly, WUE and WP were calculated [59]:

$$\text{WUE } (\text{kg}\cdot\text{m}^{-3}) = \text{Yield}/\text{CWU} \quad (2)$$

$$WP\ (kg \cdot m^{-3}) = Yield/AIW \tag{3}$$

where, Yield = $kg \cdot ha^{-1}$; CWU = $m^3 \cdot ha^{-1}$; and AIW = applied irrigation water ($m^3 \cdot ha^{-1}$).

2.7. Fruit Physiochemical Characteristics

A sample of 15 ripe fruits was randomly selected from the four directions (N, E, S, and W) and three levels (top, medium, and bottom) of each shrub to calculate average fruit weight and volume, in addition to fruit length and diameter. Fruit weight (g) was measured using a bench-top digital scale Model PC-500 (Doran scales, Inc., Batavia, IL, USA). Average fruit volume (cm^3) was determined using the water displacement method in a one-liter gradual cylinder (Fisher Scientific, Waltham, MA, USA). Fruit length (without calyx) (L) and diameter (the maximum width in the middle of the fruit) (D) (cm) were measured using a digital caliper with 0.01 mm accuracy (Grizzly Industrial, Chicago, IL, USA), and then fruit shape index (L/D), as an indicator of sphericity (roundness shape), was calculated [60].

Total soluble solids (TSS) percentage was estimated at room temperature (≈22–23 °C) using a hand-held refractometer, Model RA-130 (KEM Kyoto Electronics Manufacturing Co., Ltd., Tokyo, Japan). Total acidity as a percentage (g citric acid$\cdot$100 mL^{-1} juice) was determined by the titration method of sodium hydroxide (NaOH) [0.1 N] with phenolphthalein, as an indicator, and then TSS/acid ratio was calculated. Fruit ascorbic acid (vitamin C) content (mg$\cdot$100 mL^{-1} juice) was determined by titrating 5 mL of juice with 2,6-Dichlorophenol indophenol, according to AOAC protocol [61]. Anthocyanins were extracted and determined using the spectrophotometer at wavelength of 535 nm, and values were expressed as mg$\cdot$100 g^{-1} fw [62].

2.8. Fruit Physiological Disorders

The numbers of cracked and sunburned fruit per replicate were counted at harvest, and then their percentages out of the total yield were calculated. The pattern of cracks on fruit can be vertical cracks along the length of the fruit, horizontal cracks along the diameter of the fruit, and splitting fruit into different parts, including the stem end cracks at the point where fruit is attached to the branch [63]. The sunburn (sunscald) appears on the sun-exposed side of the fruit as brown or bronze discoloration [64].

2.9. Soil Chemical Characteristics after the Experiment

By the end of the two seasons, soil samples were randomly collected at a depth of 0–60 cm under the drippers to determine some soil chemical characteristics. A 2 mm stainless-steel test sieve (Fisher Scientific, Waltham, MA, USA) was used to filter the soil samples, which were subsequently saturated with distilled water, and a saturated extract was then obtained using a vacuum pump (12 cfm) (VEVOR Equipment and Tools, Rancho Cucamonga, CA, USA). The EC and pH of the saturated extract were measured using a portable EC meter Model DDB-11A (Anhui Haochuang Instrument Co., Ltd., Wuhu, China) and a benchtop pH meter Model STAR A111 (Thermo Fisher Scientific, Waltham, MA, USA), respectively. Both Ca and Mg were evaluated in the saturated extract using a complexometric titration analysis in the presence of Ethylenediaminetetraacetic acid (EDTA), but the flame photometer was used to assess Na and K concentrations [32].

2.10. Feasibility Study

This study was performed to evaluate the economic value of the applied treatments (i.e., MW, P and MW + P) during both seasons using the following inputs;

(1) Treatment cost ($500.31, $59.54, and $559.85, respectively) taking into account that irrigation water is free.
(2) Cost of the regular agricultural practices: electricity for irrigation = 298\cdot ha^{-1}$; fertilizers (N, P, K, Ca and micronutrients) = 745\cdot ha^{-1}$; pesticides = 447\cdot ha^{-1}$; and labor = 296.12\cdot ha^{-1}$.

(3) Average fruit price (USD·kg^{-1}) was determined per fruit weight; 200–299 g = $0.25, 300–399 g = $0.31, and ≥400 g = $0.34.

2.11. Statistical Analysis

Data were first analyzed for numerical normality and homogeneity of variance using Shapiro–Wilk's and Levene's tests, respectively. Data were then statistically analyzed, and the analysis of variance (ANOVA) was performed using CoStat software package (version 6.303, Monterey, CA, USA). Means were compared using Duncan's multiple rage test (DMRT) and the least significant difference (LSD) at $p \leq 0.05$ [48].

3. Results

3.1. Leaf Chlorophyll and Proline Contents

Chlorophyll concentration (expressed as a SPAD value) was generally related to the level of soil moisture. The highest values were recorded in shrubs subjected to 100% CWR during both seasons (Figure 2). The application of MW, P, and MW + P effectively improved chlorophyll content compared to the stressed, non-treated shrubs at both deficit irrigation levels (the control at 75% and 50% CWR), but the difference was insignificant. The difference was also insignificant in comparison to the non-stressed non-treated shrubs (the control at 100% CWR) during both seasons. The application of MW + P significantly improved chlorophyll content of the non-stressed plants compared with the sole application of each treatment and the control in both seasons.

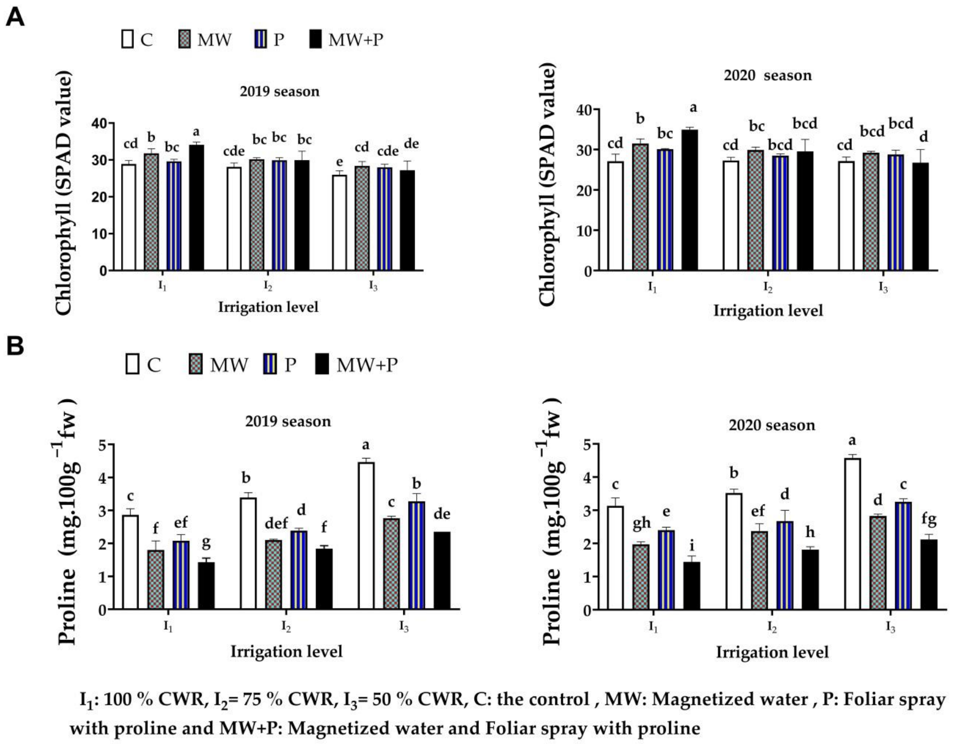

Figure 2. Effect of magnetized water (MW), foliarly sprayed proline (P), and their combination (MW + P) on leaf chlorophyll (**A**) and proline (**B**) contents of "Taifi" pomegranate shrubs grown under different irrigation regimes (I_1, I_2, and I_3), based on cop water requirements (CWR) during the 2019 and 2020 seasons. Values are the means ± standard deviation (SD). Duncan's multiple range test (DMRT) was used for mean comparisons at $p \leq 0.05$.

Figure 2 also shows that the higher the irrigation level, the lower the endogenous proline content in 'Taifi' pomegranate leaves during both seasons. The application of MW, P, and MW + P significantly reduced proline content compared with the control at all irrigation levels. The application of MW + P effectively mitigated the stress effect, expressed as reduced proline content at both 75% and 50% CWR, but the most pronounced effect was recorded at 75% CWR in both seasons.

3.2. Leaf Macro and Micronutrient Contents

The concentrations of macro and micronutrients showed a positive response to the level of soil moisture content with the highest values recorded at 100% CWR, as indicated in Tables 4 and 5, respectively. However, there were no significant differences between concentrations at 100% and 75% CWR, except for the difference in phosphorus (P) concentration during both seasons (Table 4). On the other hand, the applied treatments to mitigate salinity effects were also effective improving nutrient levels in stressed plants, with the most pronounced effect recorded for MW + P, followed by MW, and then P in both seasons, which confirm the effective role of MW.

Table 4. Effect of MW, P, and MW + P on leaf macronutrient contents (%) of "Taifi" pomegranate shrubs grown under different irrigation regimes (I_1, I_2, and I_3), based on CWR, during the 2019 and 2020 seasons.

Treatment	N		P		K		Ca		Mg	
	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
Irrigation levels										
I_1: 100% CWR (control)	1.86	1.84	0.23	0.23	0.98	0.95	0.13	0.13	1.25	1.29
I_2: 75% CWR	1.82	1.81	0.21	0.21	0.94	0.94	0.13	0.13	1.26	1.22
I_3: 50% CWR	1.74	1.72	0.19	0.19	0.82	0.82	0.13	0.13	0.82	0.87
LSD ($p \leq 0.05$)	0.062	0.066	0.014	0.008	0.072	0.032	ns	ns	0.126	0.123
Salinity-mitigating treatments										
C: tap water (control)	1.68	1.64	0.18	0.18	0.78	0.80	0.05	0.05	0.86	0.88
MW: magnitized water	1.83	1.83	0.22	0.22	0.95	0.96	0.14	0.15	1.20	1.21
P: proline	1.75	1.72	0.20	0.20	0.90	0.86	0.11	0.11	1.02	1.07
MW + P	1.97	1.96	0.23	0.23	1.02	1.00	0.17	0.18	1.36	1.34
LSD ($p \leq 0.05$)	0.037	0.043	0.007	0.005	0.035	0.032	0.011	0.014	0.091	0.080
Interaction										
I_1 + C (control)	1.75	1.72	0.20	0.19	0.78	0.87	0.09	0.09	0.95	0.99
I_1 + MW	1.86	1.94	0.23	0.24	1.04	1.01	0.14	0.14	1.32	1.41
I_1 + P	1.82	1.75	0.22	0.22	1.00	0.86	0.10	0.11	1.19	1.22
I_1 + MW + P	2.01	1.95	0.26	0.25	1.08	1.06	0.18	0.19	1.54	1.54
I_2 + C (75% CWR)	1.72	1.64	0.18	0.18	0.85	0.81	0.08	0.08	0.95	0.91
I_2 + MW	1.82	1.85	0.22	0.22	0.96	1.01	0.15	0.15	1.43	1.33
I_2 + P	1.77	1.73	0.21	0.20	0.89	0.91	0.11	0.12	1.09	1.15
I_2 + MW + P	1.98	2.01	0.24	0.24	1.04	1.02	0.18	0.18	1.57	1.48
I_3 + C (50% CWR)	1.56	1.55	0.17	0.17	0.71	0.71	0.11	0.11	0.67	0.73
I_3 + MW	1.82	1.72	0.20	0.20	0.84	0.84	0.13	0.16	0.84	0.90
I_3 + P	1.67	1.68	0.18	0.18	0.80	0.81	0.13	0.11	0.77	0.84
I_3 + MW + P	1.92	1.91	0.21	0.21	0.93	0.90	0.15	0.16	0.98	0.99
LSD ($p \leq 0.05$)	0.064	0.075	ns	0.009	0.061	0.055	0.018	0.024	0.158	0.139

LSD: Least significant difference used for mean comparisons, ns: non significant.

Accordingly, the best interaction values were recorded for MW + P at 100% CWR, followed by those at 75% CWR, and the lowest nutrient concentrations were recorded at 50% CWR during both seasons. Interestingly, the effect of MW + P on macro and micronutrients was insignificant between the stressed plants (75% CWR) and the non-stressed ones (100% CWR), except for phosphorus (P) (Table 4), and Zn (Table 5) during the 2020 and 2019 seasons, respectively.

Table 5. Effect of MW, P, and MW + P on leaf micronutrient contents (mg·L^{-1} dw) of "Taifi" pomegranate shrubs grown under different irrigation regimes (I_1, I_2, and I_3), based on CWR, during the 2019 and 2020 seasons.

Treatment	Fe		Zn		Mn	
	2019	2020	2019	2020	2019	2020
Irrigation levels						
I_1: 100% CWR (control)	126.1	123.2	115.7	104.4	114.5	115.9
I_2: 75% CWR	125.4	124.1	101.1	103.2	111.3	111.1
I_3: 50% CWR	101.2	102.0	75.1	71.6	85.8	84.6
LSD ($p \leq 0.05$)	9.75	12.87	9.65	19.11	5.79	9.02
Salinity-mitigating treatements						
C: tap water (control)	99.0	99.1	74.6	74.4	80.5	83.9
MW: magnitized water	123.8	122.7	103.8	98.6	113.8	109.2
P: proline	110.6	110.8	97.7	8.3	96.2	98.4
MW + P	136.7	133.1	113.1	111.0	124.9	124.0
LSD ($p \leq 0.05$)	8.63	5.25	6.43	8.27	8.00	6.45
Interaction						
I_1 + C (control)	102.0	104.2	89.5	89.6	91.4	92.8
I_1 + MW	133.8	129.2	123.7	109.0	122.8	122.5
I_1 + P	120.4	120.8	113.2	90.4	106.7	108.0
I_1 + MW + P	148.1	138.7	136.4	128.7	136.9	140.5
I_2 + C (75% CWR)	102.6	101.2	90.4	90.6	86.7	86.0
I_2 + MW	132.3	131.8	102.5	106.6	124.0	120.4
I_2 + P	115.5	116.4	98.6	100.1	101.3	103.6
I_2 + MW + P	151.3	147.0	112.9	115.6	133.0	134.3
I_3 + C (50% CWR)	92.5	91.9	43.9	43.1	63.4	72.8
I_3 + MW	105.4	107.0	85.2	80.2	94.6	85.0
I_3 + P	96.2	95.3	81.1	74.5	80.9	83.6
I_3 + MW + P	110.8	113.7	90.0	88.6	104.7	97.1
LSD ($p \leq 0.05$)	ns	9.09	11.14	14.33	ns	11.16

3.3. Shoot Length and Leaf Area

Results indicated that the lower the soil moisture content, the smaller the shoot length and leaf area, but the application of MW, P, or MW + P significantly improved both parameters in comparison with the control at all three irrigation levels, except for shoot length during the first season (Figure 3). The most pronounced effect was recorded with MW + P, followed by MW, and then P, which confirms the role of MW, at 100% or 75% CWR. All three treatments at 75% CWR significantly improved the shoot length (second season only) and leaf area (both seasons) compared with the non-stressed non-treated shrubs (the control at 100% CWR), with the most pronounced effect recorded for MW + P.

3.4. Plant/Water Relationships

The CWU of pomegranate shrubs was the highest at 100% CWR compared with other deficit irrigation treatments during both seasons (Figure 4A). The foliar applications of MW or MW + P were the most effective treatments reducing the CWU compared with the stressed non-treated shrubs (the control at 75% and 50% CWR), as well as the non-stressed non-treated shrubs (the control at 100% CWR) during both seasons. Although MW + P obtained lower CWU values, the difference was insignificant compared to MW during both seasons.

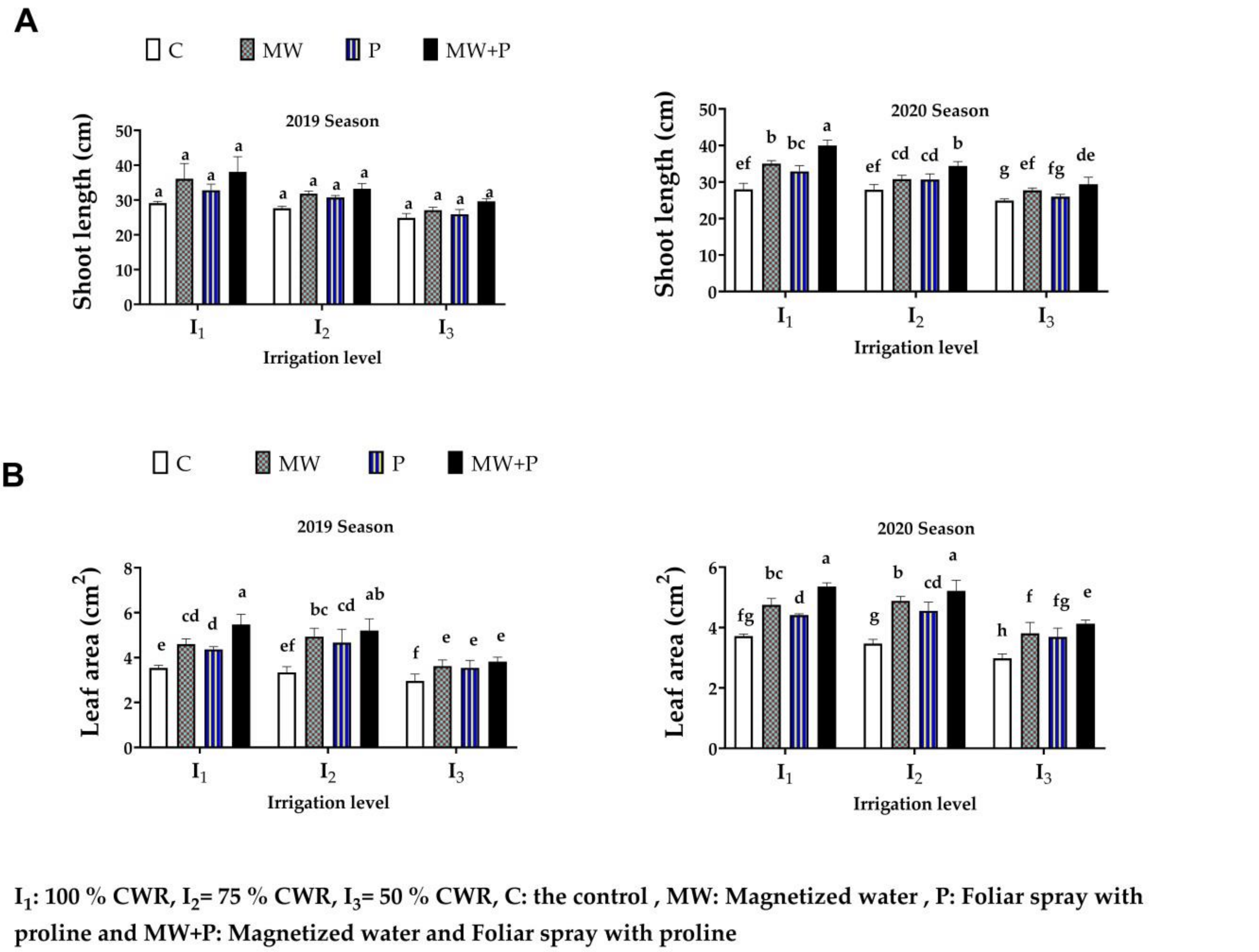

Figure 3. Effect of MW, P, and MW + P on shoot length (**A**) and leaf area (**B**) of "Taifi" pomegranate shrubs grown under different irrigation regimes (I_1, I_2, and I_3), based on CWR, during the 2019 and 2020 seasons. Values are the means ± SD. DMRT was used for mean comparisons at $p \leq 0.05$.

Accordingly, the shrubs' WUE was the lowest at 100% CWR compared with deficit irrigation treatments (75% or 50% CWR); however, the difference was only significant in the 2020 season (Figure 4B). At both deficit irrigation levels, the applications of MW, P, or MW + P significantly improved WUE compared with the control of the stressed and non-stressed shrubs, and the most pronounced effect was recorded with MW + P, followed by MW, and then P, which confirms the vital role of MW.

Likewise, Shrubs' WP was the lowest at 100% CWR, and significantly improved with the reduction in soil moisture content (Figure 4C). Overall, the salinity-mitigating treatments positively improved WP compared with the control at all three levels of CWR, but the most pronounced effect was noticed with the application of MW + P at 75% CWR, which was insignificantly different from MW + P and MW at 50% CWR during both seasons.

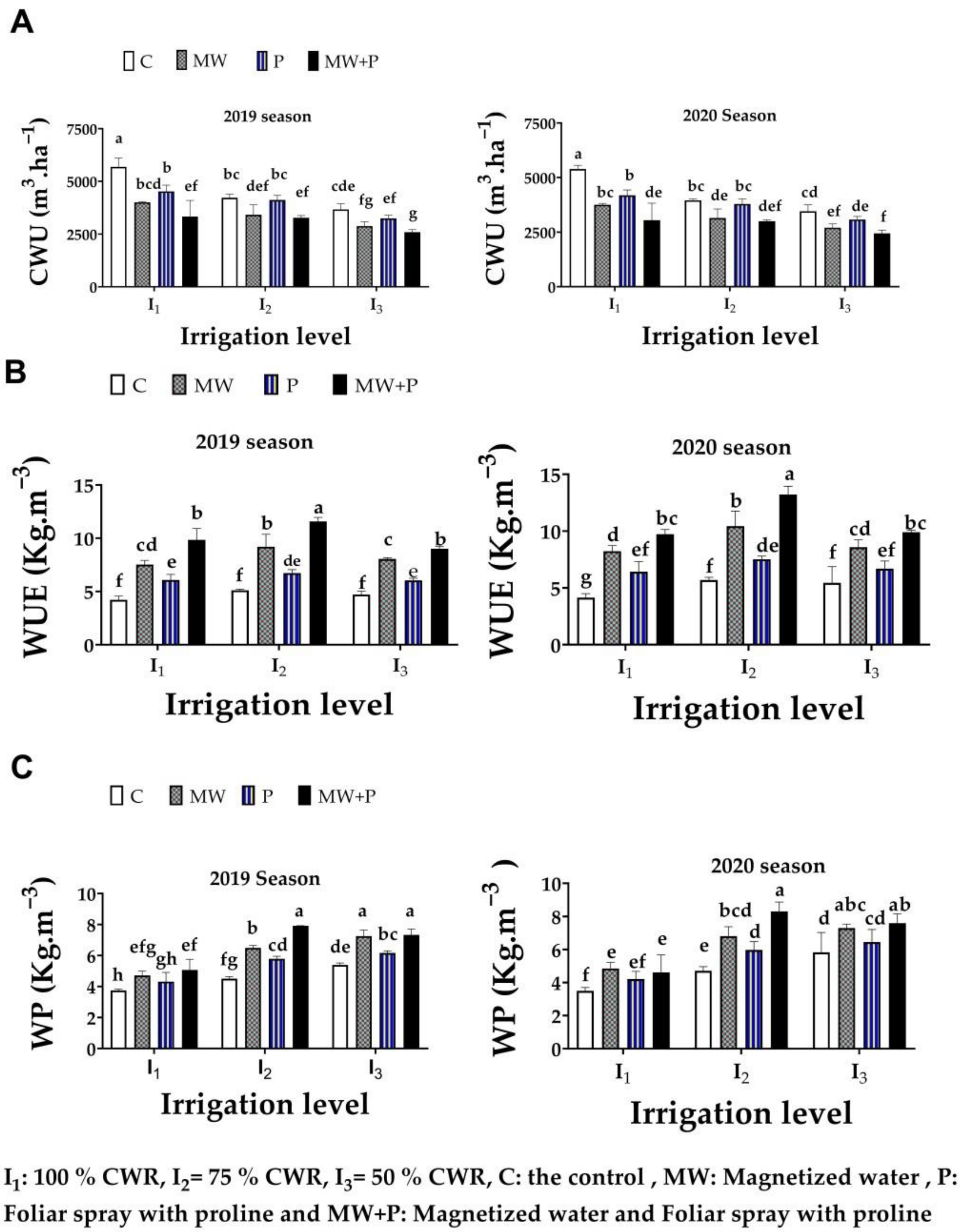

Figure 4. Effect of MW, P, and MW + P on consumptive water use (CWU) (**A**), water use efficiency (WUE) (**B**), and water productivity (WP) (**C**) of "Taifi" pomegranate shrubs grown under different irrigation regimes (I_1, I_2, and I_3), based on CWR, during the 2019 and 2020 seasons. Values are the means ± SD. DMRT was used for mean comparisons at $p \leq 0.05$.

3.5. Yield and Fruit Physiochemical Characteristics

Results in Table 6 revealed that deficit irrigation at 75% CWR was the best at improving total yield, but the application of 50% CWR resulted in the lowest yield during both seasons. Meanwhile, all three salinity-mitigating treatments positively improved the total yield, compared with the control shrubs, with the highest yield recorded for MW + P, followed by MW, and then P. However, the difference between MW + P and MW was insignificant during the second season. Overall, the best yield was recorded with the application of MW + P at 75% CWR.

Table 6. Effect of MW, P, and MW + P on yield and fruit physical characteristics of "Taifi" pomegranate shrubs grown under different irrigation regimes (I_1, I_2, and I_3), based on CWR, during the 2019 and 2020 seasons.

Treatment	Yield (Kg·shrub^{-1})		Fruit Weight (g)		Fruit Volume (cm^3)		Fruit Shape Index (Sphericity) (length·diameter^{-1})	
	2019	2020	2019	2020	2019	2020	2019	2020
Irrigation levels								
I_1: 100% CWR (control)	71.2	68.1	416.7	416.6	454.6	447.1	0.88	0.91
I_2: 75% CWR	73.8	76.6	408.2	406.7	417.4	427.2	0.86	0.88
I_3: 50% CWR	52.1	54.3	266.5	266.05	245.4	239.5	0.86	0.91
LSD ($p \leq 0.05$)	1.51	3.34	8.53	16.83	62.15	32.47	ns	ns
Salinity-mitigating treatments								
C: tap water (control)	52.3	52.9	316.7	317.8	288.7	292.3	0.80	0.94
MW: magnitized water	70.2	71.6	383.2	365.3	405.1	404.8	0.84	0.87
P: proline	62.4	63.6	346.9	357.0	344.7	339.2	0.90	0.93
MW + P	77.9	77.3	408.4	412.4	451.3	448.7	0.88	0.87
LSD ($p \leq 0.05$)	5.27	7.10	14.90	17.53	29.07	30.54	0.020	0.030
Interaction								
I_1 + C (control)	59.8	55.9	379.9	358.0	359.7	356.7	0.77	1.02
I_1 + MW	75.3	75.8	434.4	433.8	523.3	484.3	0.83	0.80
I_1 + P	68.9	67.9	393.3	398.0	398.0	401.0	0.86	0.98
I_1 + MW + P	80.7	73.0	459.3	476.5	537.3	546.3	0.87	0.87
I_2 + C (75% CWR)	53.9	56.3	340.9	366.2	325.3	327.7	0.78	0.91
I_2 + MW	77.6	80.1	429.3	384.0	421.2	464.4	0.83	0.91
I_2 + P	69.7	71.5	392.6	408.3	394.3	389.0	0.96	0.90
I_2 + MW + P	94.7	98.4	470.2	468.3	528.9	527.7	0.89	0.81
I_3 + C (50% CWR)	43.0	46.5	229.3	229.2	181.2	192.6	0.85	0.89
I_3 + MW	57.8	58.9	285.8	278.0	270.7	265.7	0.85	0.90
I_3 + P	49.1	51.3	254.8	264.7	241.8	227.7	0.89	0.90
I_3 + MW + P	58.4	60.6	295.8	292.3	287.7	272.2	0.86	0.95
LSD ($p \leq 0.05$)	9.14	12.29	25.81	30.36	50.35	52.89	0.042	0.051

The highest fruit weight and volume was recorded at 100% CWR, but the difference was insignificant compared to 75% CWR. In addition, MW, P, and MW + P significantly improved both fruit weight and volume with the most conspicuous effect with the application of MW + P in both seasons. In regards to fruit shape, there were no significant differences among all three levels of soil moisture, but the lowest values were recorded with 75% CWR during both seasons. Moreover, the application of salinity-mitigating treatments increased, but decreased the fruit shape index compared with the control during the 2019 and 2020 seasons, respectively. The interaction effect has shown the best values of fruit weight and volume with the application of MW + P at 100% CWR, followed by MW + P at 75% CWR; however, the difference between both treatments was insignificant during both seasons.

Fruit TSS significantly increased with the reduction in CWR during both seasons, but the best effect on juice acidity was recorded with 75% CWR, compared with the control during the second season only. Accordingly, TSS/acid ratio differed from one season to another (Table 7). The effect of soil moisture was not noticeable on vitamin C, but the highest anthocyanin values were recorded with 75% and 50% CWR in the 2019 and 2020 seasons, respectively, although the difference was insignificant between 50% and 75% CWR during the 2020 season. The application of MW, P, or MW + P has significantly improved all parameters of fruit chemical characteristics with the most prominent effect recorded for MW + P during both seasons. However, the difference between MW + P and MW was insignificant on TSS during both seasons, as well as on anthocyanins during the second season only.

Table 7. Effect of MW, P, and MW + P on fruit chemical characteristics of "Taifi" pomegranate shrubs grown under different irrigation regimes (I_1, I_2, and I_3), based on CWR, during the 2019 and 2020 seasons.

Treatment	TSS (%)		Acidity (%)		Tss/Acid Ratio		Vitamin C (mg·100 mL^{-1})		Anthocyanins (mg·100 g^{-1})	
	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
Irrigation levels										
I_1: 100% CWR (control)	12.5	12.2	1.3	2.4	9.3	5.2	8.0	8.1	14.2	13.7
I_2: 75% CWR	13.1	12.9	1.5	1.9	8.9	6.8	9.8	8.7	15.1	14.5
I_3: 50% CWR	13.5	13.4	1.5	2.1	9.2	6.5	7.7	9.4	14.5	14.9
LSD ($p \leq 0.05$)	0.51	0.32	ns	0.32	0.31	0.70	ns	ns	0.53	0.86
Salinity-mitigating treatments										
C: tap water (control)	11.9	11.4	1.5	3.2	7.9	3.6	5.9	5.4	11.9	11.4
MW: magnitized water	13.6	13.5	1.2	2.1	11.0	6.3	8.2	9.6	15.3	15.3
P: proline	12.9	12.9	2.0	1.9	6.4	6.8	8.8	9.4	14.9	14.7
MW + P	13.6	13.6	0.9	1.2	14.5	11.2	11.0	10.6	16.3	16.0
LSD ($p \leq 0.05$)	0.31	0.30	0.50	0.21	1.79	0.67	0.76	0.94	0.68	0.76
Interaction										
I_1 + C (control)	11.3	10.3	2.3	3.1	4.8	3.4	4.1	3.5	11.0	8.9
I_1 + MW	13.3	13.3	1.1	2.2	11.6	6.1	8.2	9.0	15.1	15.2
I_1 + P	12.5	12.5	1.1	3.1	10.8	4.0	9.1	9.0	14.1	14.5
I_1 + MW + P	12.9	12.7	0.7	1.0	16.8	12.2	10.5	11.0	16.6	16.2
I_2 + C (75% CWR)	11.8	11.5	1.1	2.8	10.3	4.1	7.7	5.6	12.7	12.3
I_2 + MW	13.5	13.30	1.9	2.4	7.0	5.4	9.0	9.4	16.0	15.2
I_2 + P	12.8	12.7	1.9	1.2	6.7	11.0	9.7	9.0	15.4	14.9
I_2 + MW + P	14.1	13.9	0.9	1.2	15.7	11.9	12.6	10.9	16.3	15.6
I_3 + C (50% CWR)	12.6	12.5	1.0	3.7	12.3	3.4	5.9	7.1	11.9	13.1
I_3 + MW	14.1	14.0	0.6	1.8	22.0	7.8	7.3	10.3	14.9	15.6
I_3 + P	13.5	13.3	3.03	1.4	4.4	9.4	7.7	10.1	15.2	14.8
I_3 + MW + P	13.8	14.0	1.15	1.4	12.0	9.9	9.8	10.0	16.0	16.3
LSD ($p \leq 0.05$)	ns	0.52	0.87	0.36	3.10	1.16	1.32	1.62	ns	1.31

The interaction effect of the irrigation levels and salinity-mitigating treatments was significant on fruit acidity, TSS/Acid ratio, and vitamin C during both seasons, whereas this effect on TSS and anthocyanins was only significant during the second season (Table 7). Overall, it can be mentioned that the application of MW + P at 75% CWR was the most effective treatment on fruit chemical characteristics, but the difference was insignificant on TSS and anthocyanins when compared to MW + P at 50% CWR. Similarly, insignificant differences were noticed between MW + P at 75% CWR and MW + P at 100% CWR on acidity, TSS/Acid ratio, and anthocyanins.

3.6. Fruit Physiological Disorders

It is obvious that higher irrigation levels positively increased fruit cracking, whereas they decreased fruit sunburn percentages (Figure 5). However, the lowest percentage of fruit sunburn was recorded for 75% CWR in 2020 season. The application of MW + P showed the lowest percentages of fruit cracking at 75% CWR compared with the stressed non-treated shrubs (the control at 75% CWR) and the non-stressed non-treated shrubs (the control at 100% CWR) during the second season, although the difference was insignificant compared to MW and P treatments at 75% CWR, and MW, MW + P and the control at 50% CWR (Figure 5A).

Meanwhile, all three treatments showed a reduction in fruit sunburn percentage compared with the non-treated plants at all soil moisture levels. The most distinct effect was noticed with the application of MW + P at 100% CWR, followed by MW + P at 75%

CWR, compared with the non-stressed non-treated shrubs (the control at 100% CWR) in both seasons (Figure 5B).

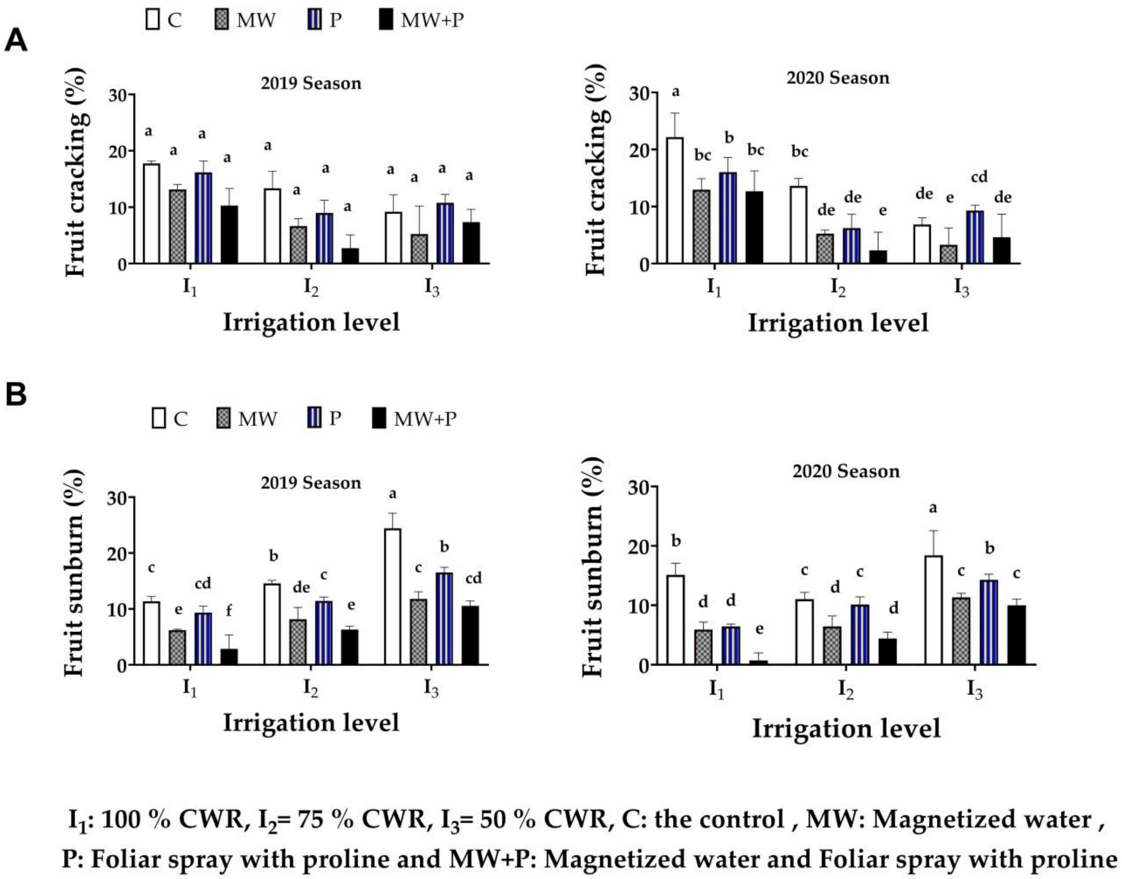

Figure 5. Effect of MW, P, and MW + P on fruit cracking (**A**) and sunburn (**B**) of "Taifi" pomegranate shrubs grown under different irrigation regimes (I_1, I_2, and I_3), based on CWR, during the 2019 and 2020 seasons. Values are the means $\pm$ SD. DMRT was used for mean comparisons at $p \leq 0.05$.

3.7. Soil Chemical Characteristics after the Experiment

It is obvious that soil-applied treatment (i.e., MW) should affect soil chemical characteristics, but foliarly sprayed treatment (i.e., P) has nothing to do with soil characteristics. However, all of the used treatments were statistically analyzed together since it is hard to separate these parameters in such an RCBD experiment. By the end of the second season, soil pH was not significantly affected by the irrigation levels or the interaction with salinity-mitigating treatments, whereas the effect of salinity-mitigating treatments on pH was significant (Table 8). Both MW and MW + P treatments similarly decreased soil pH, but no significant difference was recorded for the P treatment, compared to the control, which confirms the role of MW (but not P) affecting soil characteristics.

Soil EC was not also affected by the interaction of irrigation levels and salinity-mitigating treatments, but each factor was significantly effective by itself (Table 8). It could be noticed that the higher the soil moisture content, the lower the EC value with no significant difference between 100% and 75% CWR. Additionally, the application of MW or MW + P effectively reduced soil EC, which also confirms the role of MW affecting soil EC. In this regard, the difference between MW and MW + P was insignificant.

The irrigation levels significantly affected soil Mg^{+2}, Na^{+}, and Ca^{+2} with the highest values recorded at 50% CWR, but no significant effect was noticed on K^{+} (Table 8). The application of MW or MW + P markedly decreased soil contents of Na^{+} and Ca^{+2}, but no significant effect was recorded for the P treatment, which confirms the role of MW affecting soil nutrient contents. The interaction effect indicated that the best treatment that reduced soil Na^+ and Ca^{+2} was MW + P at 100% CWR. No significant difference was noticed on Ca^{+2} in response to MW + P and MW at 100% CWR, which confirms the role of MW. Both MW and MW + P improved K^+ levels at 100% CWR, albeit the difference was insignificant compared to the control. Interestingly, the interaction effect has also shown that the application of 75% CWR insignificantly increased soil K^+ level compared with the control (0.33 vs. 0.28 meq/L^{-1}); however, this treatment saved 25% of the used water.

Table 8. Effect of MW, P, and MW + P on post-experiment soil chemical characteristics under different irrigation regimes (I_1, I_2, and I_3), based on CWR, during the 2019 and 2020 seasons.

Treatment	pH	EC (dS·m^{-1})	Soluble Cations (meq·L^{-1})			
			K^+	Mg^{2+}	Na^+	Ca^{2+}
Irrigation levels						
I_1: 100% CWR (control)	8.16	1.59	0.33	0.17	0.33	0.52
I_2: 75% CWR	8.17	1.60	0.27	0.32	0.36	0.60
I_3: 50% CWR	8.39	1.67	0.27	0.39	0.43	0.66
LSD ($p \leq 0.05$)	ns	0.039	ns	0.052	0.043	0.035
Salinity-mitigating treatments						
C: tap water (control)	8.36	1.65	0.28	0.27	0.42	0.64
MW: magnitized water	8.18	1.61	0.30	0.28	0.34	0.54
P: proline	8.27	1.67	0.29	0.30	0.39	0.63
MW + P	8.15	1.58	0.29	0.32	0.35	0.56
LSD ($p \leq 0.05$)	0.140	0.034	ns	ns	0.032	0.049
Interaction						
I_1 + C (control)	8.24	1.58	0.28	0.14	0.36	0.57
I_1 + MW	8.13	1.60	0.34	0.16	0.32	0.46
I_1 + P	8.16	1.65	0.35	0.19	0.40	0.58
I_1 + MW + P	8.12	1.65	0.34	0.20	0.26	0.46
I_2 + C (75% CWR)	8.26	1.65	0.33	0.28	0.39	0.59
I_2 + MW	8.15	1.59	0.29	0.30	0.31	0.50
I_2 + P	8.16	1.64	0.24	0.32	0.36	0.66
I_2 + MW + P	8.12	1.52	0.23	0.38	0.39	0.63
I_3 + C (50% CWR)	8.59	1.71	0.21	0.39	0.50	0.76
I_3 + MW	8.26	1.63	0.28	0.39	0.40	0.66
I_3 + P	8.50	1.71	0.28	0.38	0.41	0.65
I_3 + MW + P	8.23	1.66	0.31	0.38	0.39	0.58
LSD ($p \leq 0.05$)	ns	ns	0.060	ns	0.050	0.080

3.8. Feasiability Study

The above-mentioned results showed the positive role of MW + P application at 75% CWR on plant growth and productivity. Therefore, the highest yield was recorded for this treatment, compared with other treatments and the control during both seasons, and hence this was the most profitable treatment for the growers (Table 9).

Table 9. The feasibility study of the applied treatments.

Treatment	(1) Treat-mentCost (USD·ha^{-1})	(2) Fixed Cost (USD·ha^{-1})	(3 = 1 + 2) Total Cost (USD·ha^{-1})	(4) Total Yield (t·ha^{-1})		(5 = 4 × Ⓟ) Total Return (USD·ha^{-1})		(6 = 5 − 3) Net Profit (USD·ha^{-1})	
				2019	2020	2019	2020	2019	2020
I_1 (100% CWR) + C (tap water) [control]	-	1786.12	1786.12	23.91	22.29	7476.22	6970.82	5690.10	5184.7
I_1 + MW (magnitized water)	500.31	1786.12	2286.43	30.12	30.94	10,358.88	10,642.28	8072.45	8355.85
I_1 + P (proline)	59.54	1786.12	1845.66	27.55	26.81	8876.33	8980.20	7030.67	7134.54
I_1 + MW + P	559.85	1786.12	2345.97	32.29	29.43	11,105.75	10,123.81	8759.78	7777.84
I_2 (75% CWR) + C	-	1786.12	1786.12	21.57	22.53	6745.08	7045.24	4958.96	5259.12
I_2 + MW	500.31	1786.12	2286.43	31.04	32.53	10,675.58	10,170.94	8389.15	7884.51

Table 9. *Cont.*

Treatment	(1) Treat-mentCost (USD·ha^{-1})	(2) Fixed Cost (USD·ha^{-1})	(3 = 1 + 2) Total Cost (USD·ha^{-1})	(4) Total Yield (t·ha^{-1})		(5 = 4 × Ⓟ) Total Return (USD·ha^{-1})		(6 = 5 − 3) Net Profit (USD·ha^{-1})	
				2019	2020	2019	2020	2019	2020
I_2 + P	59.54	1786.12	1845.66	27.65	28.56	9222.38	9253.08	7376.72	7407.42
I_2 + MW + P	559.85	1786.12	2345.97	37.86	39.67	13,021.84	13,643.94	10,675.87	11,297.97
I_3 (50% CWR) + C	-	1786.12	1786.12	17.21	18.56	4305.32	4643.90	2519.20	2857.78
I_3 + MW	500.31	1786.12	2286.43	21.37	21.66	5346.90	5346.90	3060.47	3060.47
I_3 + P	59.54	1786.12	1845.66	21.38	22.13	5348.91	5536.96	3503.25	3691.30
I_3 + MW + P	559.85	1786.12	2345.97	23.35	24.2	6299.15	6299.15	3953.18	3953.18

Ⓟ: average fruit price (USD·kg^{-1}) was determined per fruit weight; 200–299 g = $0.25, 300–399 g = $0.31 and ≥400 g = $0.34.

4. Discussion

As water scarcity has recently become a global problem [19], water deficit regimes have been used to reduce agricultural water demand and increase economic productivity [21]. However, using deficit irrigation particularly under saline soil conditions is very critical, since it results in increased soil salinity [23,24]. Therefore, the use of some modern techniques such as MW [25], as well as foliar application of plant bio-regulators (i.e., proline) can play an important role in inducing the plant's ability to withstand adverse stress conditions, thereby improving plant growth, productivity, and fruit quality [28,39]. The results of the present study addressed the positive role of MW and proline on the vegetative growth (Figure 3) and nutrient contents (Tables 4 and 5) of stressed (i.e., 75% CWR) and non-stressed (i.e., 100% CWR) 'Taifi' pomegranate shrubs. Improved vegetative growth could be attributed to the increase in leaf chlorophyll content (Figure 2), associated with improved photosynthesis and accumulation of more assimilates [65]. Irrigation with MW, characterized by lower viscosity and surface tension, resulted in reduced soil pH, stimulated carbon deposition, enhanced levels of phosphorus (P) and K in soil solution, and increased activity of soil microbes [32]. It was reported that MW altered the permeability and transport capability of the cellular membrane, and improved nutrient accumulation in plant cells [66,67]. The results of the present study are in accordance with previous findings on the role of MW enhancing the vegetative growth and nutritional status of 'Valencia' orange [37]. Furthermore, proline plays an important role as antioxidant that stimulates the stress responsive genes, adjusts the cytoplasmic osmotic pressure, protects cells against ROS (that negatively affect plant metabolism through the oxidative damage of lipids, protein and nucleic acids), stabilizes the cellular membrane and proteins [68,69], and eventually improves the shoot length and leaf area of 'Manfalouty' and 'Wonderful' pomegranate shrubs [41,70].

The results of the current study are in accordance with the previous findings indicating that the higher the soil moisture levels, the higher the chlorophyll content and the lower the proline accumulation in the plant [71]. The increase in leaf chlorophyll, associated with the decrease in proline contents of MW + P-treated 'Taifi' pomegranate shrubs subjected to 100% and 75% CWR, compared with those received no MW or proline at 50% CWR (Figure 2), suggested a positive role of MW and proline mitigating the deleterious effects of salinity and drought stress. Khoshravesh et al. [72] stated that MW had less hydrophobicity due to the reaction with released ions in soil solution, which increased the binding of water molecules to soil particles. Thereby, soil moisture level was higher in plots irrigated with MW than the control, and led to improved absorption of macro and micronutrients (Tables 4 and 5). The combined application of MW + P resulted in reduced leaf proline content, as previously reported on 'Wonderful' pomegranate [70].

Total fruit yield was also the highest with the application of MW + P at 75% CWR (Table 6). It was reported that MW may alleviate the impacts of salinity stress either by reducing Na^+ absorption through plant roots [73] or improving the capacity of nutrient and water uptakes, and hence improves plant root and vegetative growth, which in turn increases fruit yield [74]. A positive effect of exogenous proline application on orange fruit has been reported [42], particularly when combined with MW under salinity stress conditions [37]. The reduction in fruit yield of non-MW treated shrubs, compared with the MW-treated ones, could be related to the unbalanced effect on the plant's nutritional status and vegetative growth [72].

The application of MW + P resulted in the lowest CWU at 50% CWR, but the highest WUE at 75% CWR, and WP at both 75% and 50% CWR (Figure 4). The improvement in WUE and WP may be attributed to the increase in fruit yield (Table 6), while the reduction in CWU may be due to the lower hydrophobicity of MW. Therefore, soil moisture levels should be higher in MW-irrigated plots compared with the control ones [72]. A previous report on 'Manfalouty' pomegranate stated that the maximum WUE was found in moderate irrigation levels, while it was decreased with higher or lower amounts of water [45]. The improvement in fruit weight and volume (Table 6) with MW + P treatment at 100% or 75% CWR could be owing to the role of MW altering the permeability of the cell membrane, causing changes in cell metabolism with improved water and nutrient uptakes [45]. For instance, K^+ adjusts the osmotic pressure of the cell, and leads to cell enlargement [75]. Proline also plays an important role under stressful conditions by balancing the osmotic pressure of the cytosol and the vacuole with that of the external environment, resulting in improved water and nutrient uptakes [42]. The improvement in nutrient uptake (Tables 4 and 5) confirms the previous findings. Furthermore, the positive effect of irrigation at 75% CWR, compared with 100% CWR (non significant) and 50% CWR (significant), on fruit weight (Table 6) may be due to the balanced effect on vegetative growth, as previously reported [71,72,76].

The positive effect of MW + P treatment on TSS, TSS/acid ratio, vitamin C, and anthocyanins at 75% or 50% CWR, as well as the role of MW on TSS at 50% CWR (Table 7) confirmed the previous findings on orange fruit characteristics [37,76], which could be owing to the role of MW on cryptochromes (CRY1 and CRY2), which are considered as photolyase-like blue light receptors that have various roles on plant growth such as the functional role of guard cells in stomatal opening, photosynthesis, root development, and the subsequent roles on fruit growth, development, and the translocation of assimilates from leaves to fruit (source/sink relationship) that governs overall fruit growth and quality [38]. It could also be mentioned that the survival of 'Taifi' pomegranate shrubs under reduced irrigation levels, particularly with MW application, could be related to the improved biosynthesis rate of anthocyanins under such conditions (Table 7). Anthocyanins are the prominent phenolic compounds, which contribute to the plant antioxidant capacity more than other phenolic compounds [77], in addition to their role in fruit color [78], which was also enhanced at reduced CWR compared with the control during both seasons. The improvement in fruit color, associated with increased TSS and reduced acidity under such conditions (Table 7), is in accordance with the previous reports [79–84]. In addition, the application of MW + P with reduced CWR also effectively reduced the percentage of fruit cracking at 75% or 50% CWR (Figure 5). A previous finding confirmed a reduction in fruit cracking of 'Wonderful' pomegranate under moderate water deficit conditions [70]. It could be noticed that higher fruit weight and volume (both seasons), as indicators of fruit size [85], and lower shape index (second season) were associated with a reduction in fruit cracking percentage, compared with the control, particularly in the second season (Figure 5A). This means that bigger and more spherical fruit are less susceptible to fruit cracking. Small size fruit were reported to be more susceptible to fruit cracking [60]. It was found that fruit shape index ranged between 0.80 and 0.97, meaning closer to a round shape [86], and values could reach up to 1.61, suggesting a slenderer shape of the fruit [87]. The less rounded fruit at harvest indicated a steady decline in sphericity with fruit development [60], and this change in fruit shape with development might coincide with the onset of physical defects that are related to fruit growth stress such as cracking and splitting [88] due to the reduction in epidermal cell density, thus further weakening the skin [87]. However, it was reported that in pomegranate, the relationship between skin thickness or fruit volume and resistance to cracking was not significant [89]. On the other hand, the reduction in fruit sunburn was noticed with increased CWR to be the minimum at 100% CWR (Figure 5). A linear reduction in the incidence and severity of apple fruit sunburn with increased soil water levels was recorded [90].

Soil characteristics after the application of 100% and 75% CWR indicated a significant reduction in soil pH, EC, and the concentration of Mg^{+2}, Na^{+}, and Ca^{+2}, in comparison with 50% CWR, and the lowest values were recorded with MW application. Simultaneously, there was an insignificant increase in K^{+} level (Table 8). The application of MW at 100% CWR might promote salt leaching and lower Na^{+} and Ca^{+2} concentrations in the soil, and consequently reduce soil pH and EC. This could be attributed to the water molecules of MW that are more linked to soil particles than ions, easily penetrate into soil particle micro spaces, and do not go deeper into the soil, and hence become more available for plant absorption [32]. Overall, the use of MW at 100% CWR was very helpful to reduce soil salinity and enhance soil characteristics (Table 8). However, the combined application of MW and proline (MP + P) at 75% CWR was the best treatment, in terms of the total yield (Table 6), fruit quality (Tables 6 and 7), and grower's net profit (Table 9).

5. Conclusions

To improve the growth and productivity of 'Taifi' pomegranate shrubs grown in saline clay soils with reduced amounts of irrigation water, a sustainable, eco-friendly, and easily available approach was used via a combined application of MW and foliarly sprayed proline (200 $mg \cdot L^{-1}$) at 75% CWR (11.86 $m^3 \cdot tree^{-1} \cdot season^{-1}$). This approach effectively compensated for the reduction in normal CWR and mitigated the deleterious effect of drought and salinity stresses with enhanced soil characteristics and improved shrub's growth, WUE, WP, yield, and fruit quality, in addition to grower's profit. Future research could incorporate the long-term effects of using MW on saline soil characteristics, plant productivity, and fruit quality under the semi-arid conditions. Future prospective studies could also include the molecular basis of pomegranate defense mechanism, which currently has no reported findings. In addition, the role of MW on reducing Ca^{+2} in the soil could be a focal point for further research to reduce its level in calcareous soils around the world.

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