

Original Research

# The Effect of Magnetized Water on the Growth and Physiological Conditions of *Moringa* Species under Drought Stress

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## Abstract

Magnetic water technology is supposed to be an eco-friendly tool used for alleviating drought stress in the agricultural sector. The present study investigates the role of magnetized water on the two *Moringa* species (*Moringa oleifera* and *Moringa peregrina*) under drought stress. The experiments were conducted in a greenhouse to compare three watering regimes, including, 100% field capacity (FC, as Control), 50% field capacity (FC, as moderate drought stress), and 20% field capacity (FC, as severe drought stress), and two water treatments (normal water and magnetic water). Significant reductions in plant height, leaf area, relative water content (RWC), chlorophyll and ion contents, assimilation rate (A), transpiration (E), stomatal conductance (gs), water use efficiency (WUE), and vapor pressure deficit (VPD) were observed during the drought stress. *M. oleifera* and *M. peregrina* seedlings when treated with MW during SS level, exhibited 13.09%, 21.1%, 22.6%, 23%, and 10.7%, 15.2%, 12.9%, 13.19% decreases in Chl a, Chl b, Chl (a+b) and carotenoids contents respectively, as compared to control seedlings. The *M. oleifera* and *M. peregrina* seedlings exposed to drought stress (MS, SS) showed 1.26%, 3.79%, and 1.2%, 3.7% decreases in  $F_v/F_m$  under MWT. The drought-stressed seedlings treated with magnetic water (MW) recovered from growth inhibition, chlorosis, and ion disruption. Magnetic water (MW) improved the  $Na^+/K^+$  ratio by lowering the accumulation of  $Na^+$  ions. Hence, the application of magnetized water (MW) mitigated the adverse effects of drought in the *Moringa* species.

**Keywords:** magnetic water,  $F_v/F_m$ , ion content, photosynthesis, abiotic stress, leaf gas exchange

## Introduction

As the global population expands, the economic, agricultural, industrial, and energy sectors also grow,

due to which water consumption and demand has vastly increased. Anthropogenic activities are leading toward an increase of greenhouse gases, which are responsible for global climate change. Consequently, drought has become more common and severely occurred due to all of these factors [1-3]. Drought is one of the serious problems that has withheld global crop

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production, considered as a major abiotic stress that has affected plant growth rate and development [3-5]. Due to changing climatic conditions, water shortages have become more apparent not just in arid regions, but humid regions as well [6]. Unequal rainfall patterns have been found to limit plant growth [7]. As water is required for almost all biochemical, physiological, and morphological plant processes, its shortage is harmful for their normal growth and development [8]. Drought stress affects various metabolic activities, including photosynthesis in the plants [9-10]. The leaf gas exchange traits such as assimilation (A), transpiration (E), stomatal conductance (gs), water use efficiency (WUE), vapor pressure deficit (VPD), and maximum quantum efficiency of the photosystem II were known to decrease under drought stress [11-14]. Reduction of the photosynthetic electron chain occurred due to stomatal closure and a decrease in CO<sub>2</sub> fixation under drought stress [15].

In recent years, various approaches have been used to alleviate the drought stress among agricultural crops. These include nutritional management strategies, the application of chemical and biological amendments (including mycorrhizal applications), and the use of robotics and biosensors [15-16]. Some modern technologies have been used for environmental management, including GIS [15] and nanotechnology [17-22]. Magnetic water (MW) technology is one of the environmentally friendly and cost-effective techniques, recently used in agricultural fields to result in better crop growth and yield [23]. MW is generated by treating normal water with a magnetic field, resulting in the rearrangement of water structure into a new hexagonal form in various ways [23]. Many researchers have reported the beneficial effects of MW in the agricultural sector [16, 24-26].

*M. oleifera* and *M. peregrina* are the two common species among the family of the Moringaceae. *M. oleifera* is regarded as a multipurpose tree and shrub species and it is used as a food, fodder, medicine, fencing, gum, and firewood, as well as a coagulant to treat polluted water [27]. *M. peregrina* is also considered a medicinally important plant due to its antioxidant, antifungal, and antibacterial properties [28].

Since MW has been reported to have positive effects on plant growth and physiology, it was hypothesized that this technique may also improve plant physiology and growth characteristics under drought stress. Subsequently, some information is available about the application of MW on plants under drought stress; a broader study, however, is absent regarding the effects of drought stress on the growth and physiology of *Moringa* species under MWT. The present study was carried out to assess the effects of drought stress on the growth and some physiological traits of the *Moringa* species under magnetic water treatment (MWT). The results of this study may provide information for improving the irrigation methods

and management through MWT – especially for the production of *Moringa* species under drought stress.

## Materials and Methods

### Experimental Materials and Setup

The experiment was carried out at a greenhouse in King Abdulaziz University (KAU), Jeddah, Saudi Arabia. The seeds of two *Moringa* species (*M. oleifera* and *M. peregrina*) were collected from the Abha region, Saudi Arabia. Seeds were collected in sealed plastic bags and transferred to the laboratory at KAU. The seeds were sown in the pot under randomized completely block design (RCBD). All seeds were sown on the same day. The soil was sandy loam, which was mixed with peat moss and compost (1:1:1) vigorously. The pots were kept under greenhouse-controlled conditions (light/dark regime about 12/12 h; temp., 25/15±30°C; relative humidity (RH) 30-50%). A magnetic instrument was used (150d magnetic technologies L.L.C) with power of 30 mT for magnetizing the water by following the methods of Selim and El-Nady (2011) [29]. Half of the pots were irrigated with normal tap water and remaining pots were irrigated with the MW.

### Field Capacity Measurements

Water-holding capacity or field capacity of soil was determined according to the gravimetric method with slight modifications [30]. The experiment was done with five replicates. Soil samples were collected from the source of used soil in the experiment. First, soil was air dried and ground to pass through a 5 mm sieve. The bottoms of small cylindrical pots were covered with paper and taped without soil. Each of the pots are loaded with 300 g soil (by compression) and weighed. All pots were settled in the tray and filled with water until saturation. The tray was allowed 3 h for saturation and then all pots were transferred to quartz soil intended for drainage and filtering for 2 h. The pots were cleaned and weighed the saturated soil again. Then all saturated soil was oven dried at 105°C for 24 h and dry weight was calculated by measuring the oven-dried soil. Soil field capacity was measured using the following formula:

Field capacity (FC %) =

$$\frac{\text{Saturated soil weight} - \text{Dry weight of soil}}{\text{Dry weight of soil}} \times 100\%$$

### Drought Stress Treatments

Plants were irrigated daily with normal and magnetic water up to 60 days for the plant establishment. After the plant establishment, *Moringa* species were subjected to drought treatment including 100% FC

(control), 50% FC (moderate stress, MS), and 20% FC (severe stress, SS) for 30 days. The plant sample was collected during harvest time at 90 days.

Growth Conditions

Growth parameters were summarized by the analysis of plant height, leaf number, shoot length, root length, internodes distance, leaf area, and fresh and dry weights. Plant height (cm) and internode distances (cm) were measured from the surface to the top of the plant at 5DAT to 30 DAT. The plant parts (leaf, stem, root) were dried at 70°C for 72 h and dry weight (g) were obtained.

Leaf Area and Relative Water Content

A leaf area meter (LICOR-3000A, USA) was used for measuring leaf area. For calculating the relative water content (RWC), leaf discs were obtained from seedlings and weighed, and fresh weight (FW) was obtained. The leaf discs were taken and floated on distilled water. After 8 h, surface water was removed using paper towels and turgid weight (TW) was obtained. Finally, the leaves were dried at 80°C for 48 h and dry weight (DW) was obtained. The RWC was calculated by the following formula:

$$RWC (\%) = \frac{FW - DW}{TW - DW} \times 100$$

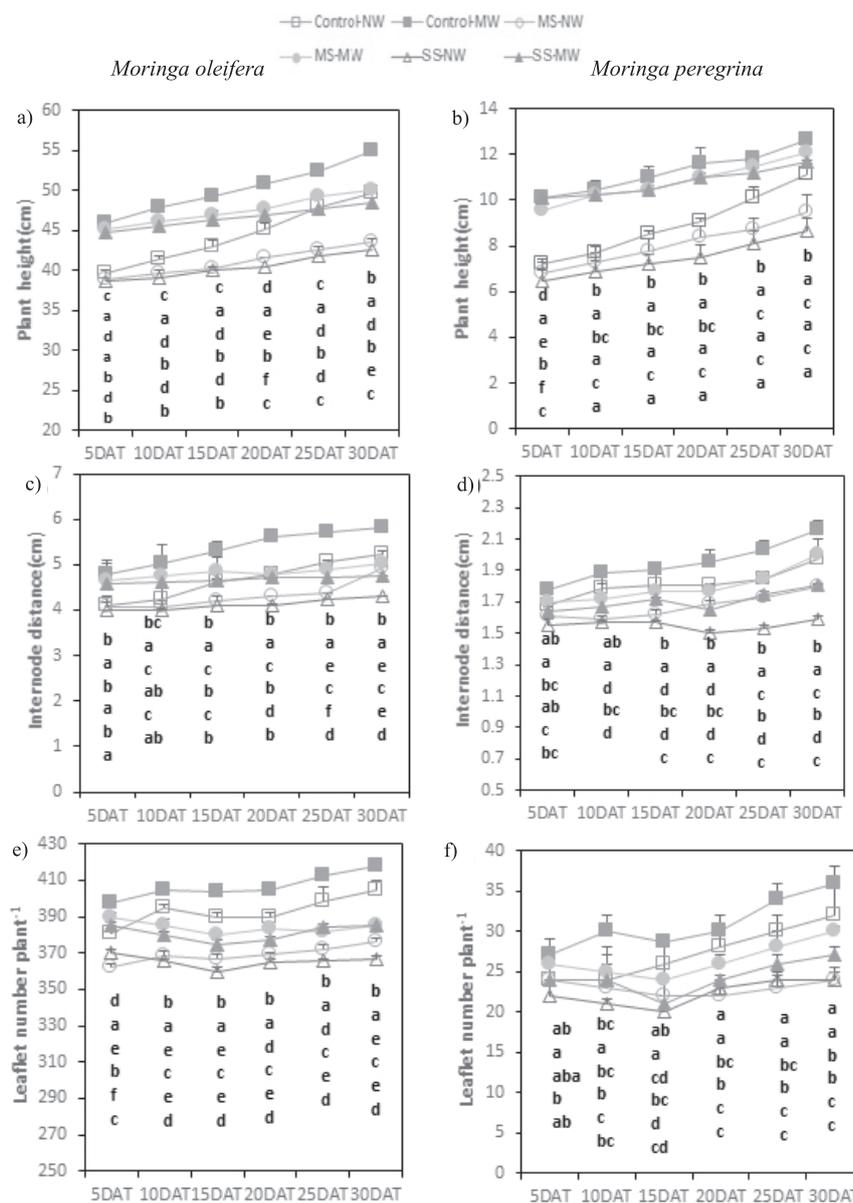


Fig. 1. Effect of magnetic water (MW) on plant height (a, b), internode distances (c, d), and leaflet number (e, f) of two *Moringa* species (*Moringa oleifera*, *Moringa peregrina*) seedlings under drought stress at 5 to 30 days after treatment; vertical bar represents the standard deviation, and different letters below the series denote statistically significant ( $P \leq 0.05$ ) differences among treatments.

Leaf Gas Exchange and Fv/Fm Ratio

Leaf gas exchanges were measured by the CIRAS 3 portable photosynthesis system (PP systems, USA). The leaf gas exchange parameters included assimilation rate (A, CO<sub>2</sub>m<sup>-2</sup>s<sup>-1</sup>), stomatal conductance (gs, mol CO<sub>2</sub> m<sup>-1</sup> s<sup>-1</sup>), transpiration rate (E, mmol CO<sub>2</sub>m<sup>-2</sup>s<sup>-1</sup>), vapor pressure deficit (VPD, kPa), and water use efficiency (WUE, μmolCO<sub>2</sub>mmol<sup>-1</sup>H<sub>2</sub>O). The young, fully developed and healthy leaves were selected for measurement. The leaf was measured between 12:00 and 14:00 h (solar radiation is at maximum intensity) in ambient conditions. Three readings from each treatment were taken carefully out on randomly chosen leaves.

The maximum quantum yield of PSII photochemistry (Fv/Fm) was measured during the experiment at the altered period and at the end of relief on the same leaves used for gas exchange measurements. The leaves of both species were measured after dark adaption of leaf for 30 min with leaf cuvette. A CIRAS 3 portable photosynthesis system (PP systems, USA) machine was used to generate the data.

Chlorophyll Content

Chlorophyll contents or photosynthetic pigments were determined using Arnon (1949) [31] methods by homogenizing leaf samples (0.5 g) with 10 milliliters (ml) of acetone (80% v/v), followed by centrifuging at 5,000g for 10 min. The absorbance was measured with a UV-visible spectrophotometer (VIS-723G) at 663, 645, and 470 nm, respectively, according to Lichtenthaler and Wellburn (1983) [32].

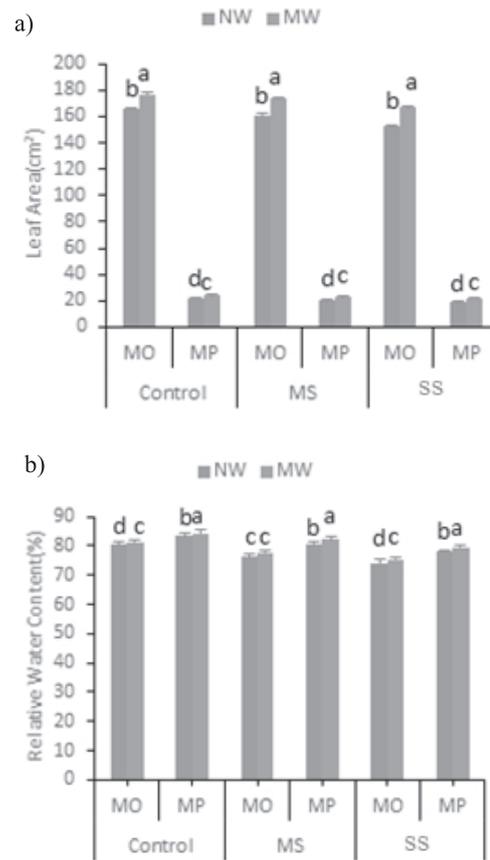


Fig. 2. Leaf area a) and relative water content b) of the two *Moringa* species (*Moringa oleifera*, MO; *Moringa peregrina*, MP) under drought stress; dissimilar letters with mean are significantly different at p ≤ 0.05 level of significance by applying Fisher’s LSD test.

Table 1. Effect of magnetic water on the fresh and dry weights of root, stem, and leaf under drought stress.

	Treatment Combinations	Root		Shoot		Leaf	
		FW	DW	FW	DW	FW	DW
<i>Moringa oleifera</i>	Control+NW	13.44±1.3a	2.54±0.13ab	13.1±0.95bc	2.3±0.2ab	24.06±0.2b	4.06±0.04a
	Control+MW	14.3±1.41a	2.62±0.1a	14.53±1.03a	2.45±0.1a	25.06±1.06a	4.13±0.13a
	MS+NW	12.6±0.8ab	2.08±0.17cd	12.5±0.4c	2.04±0.041c	21.03±0.6c	3.7±0.09bc
	MS+MW	13.06±0.2ab	2.3±0.06abc	13.8±0.45ab	2.1±0.2bc	22.8±0.9b	3.8±0.08b
	SS+NW	11.5±0.7b	1.95±0.15d	12.3±0.62c	1.94±0.08c	18.53±1d	3.42±0.02d
	SS+MW	12.6±1.05ab	2.27±0.29bc	13.1±0.4bc	1.97±0.03c	20.76±1.05c	3.65±0.03c
<i>Moringa peregrina</i>	Control+NW	15±0.65bc	2.81±0.09a	1.13±0.05bc	0.31±0.01cd	6.16±0.6bc	1.55±0.14bc
	Control+MW	17.1±1.05a	3±0.24a	1.7±0.4a	0.45±0.05a	7.1±0.4	1.7±0.1a
	MS+NW	14.2±0.6cd	2.3±0.05b	1.14±0.04bc	0.33±0.04bc	5.73±0.3cd	1.48±0.03c
	MS+MW	15.8±0.5ab	2.85±0.1a	1.36±0.06b	0.37±0.04b	6.6±0.3ab	1.62±0.02ab
	SS+NW	13.16±0.66d	2.4±0.26b	1.02±0.02c	0.23±0.005e	5.16±0.4d	1.46±0.03c
	SS+MW	15.2±0.6bc	2.76±0.1a	1.09±0.01bc	0.27±0.01de	5.83±0.4bcd	1.55±0.05bc

Dissimilar letters within mean and between columns are significantly different at p ≤ 0.05 level of significance by applying Fisher’s LSD Test.

Ion Content

The plant samples (root, shoot, and leaves) were prepared using Humpheric's (1956) method [33]. The plant samples were dried and crushed into fine powder. The fine powder from each sample was taken into a digestion tube and 1 ml sulphuric acid (H<sub>2</sub>SO<sub>4</sub>) was added. The samples were transferred to a sand heater for 15-20 min until a dark color appeared. Each of the digestion tubes were cooled. We added one ml mixture of sulphuric acid (H<sub>2</sub>SO<sub>4</sub>) and perchloric acid (HClO<sub>4</sub>) (1:1) and heated for 30-40 min. Distilled water was added up to 100 ml into each sample containing tubes until transparent colour occurred. The samples were finally transferred to an optima ICP-OECS machine (PerkinElmer Inc., UK) to determine ion.

Statistical Analysis

Analysis of variance (ANOVA) and the mean differences of data were tested by Fisher's LSD test using Minitab (17) statistical software. The differences between the data at P≤0.05 were regarded as significant.

Results

Growth Parameters

In the present study we observed that magnetic water treatment (MWT) had a statistically significant effect in terms of plant height (*M. oleifera* and

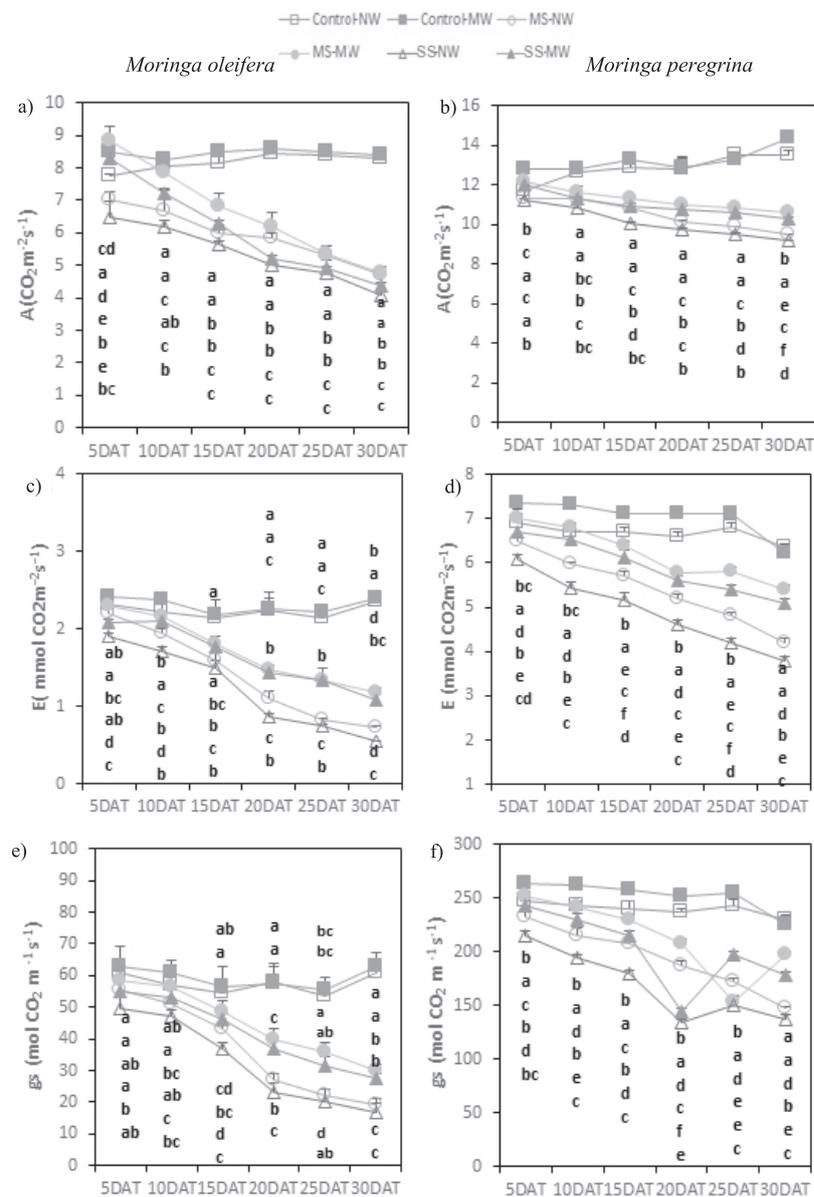


Fig. 3. Effect of magnetic water on assimilation, A; (a, b), transpiration, E; (c, d), and stomatal conductance, gs ;(e, f), of the two *Moringa* species (*Moringa oleifera*, *Moringa peregrina*) under drought stress at 5 to 30 days after treatment; vertical bars represent standard deviation, and different letters above and below the series denote statistically significant (P≤0.05) differences among treatments.

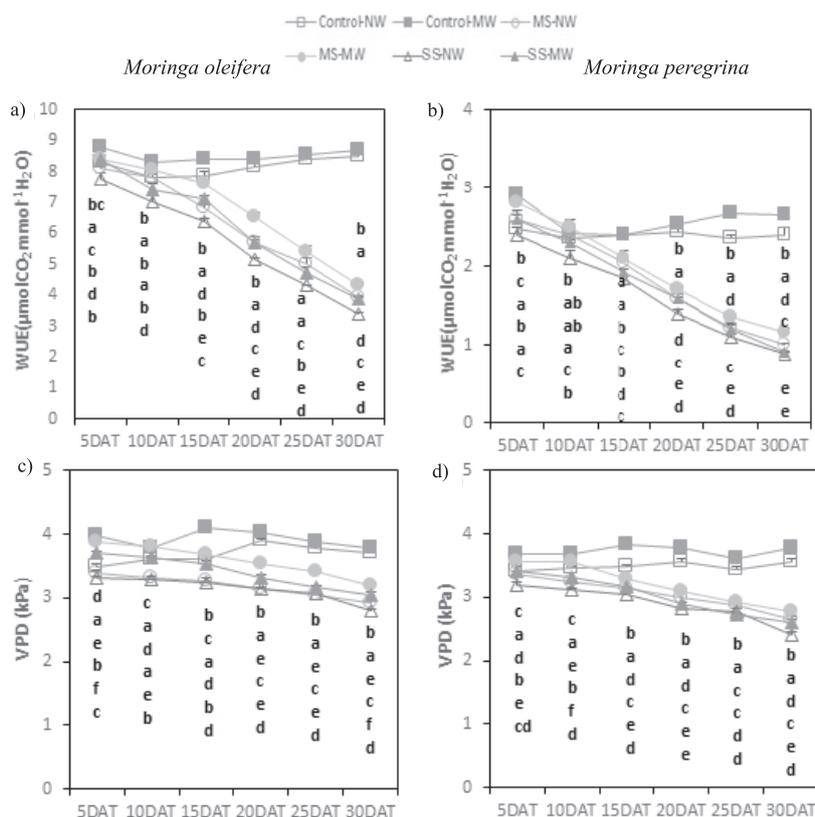


Fig. 4. Water use efficiency, WUE; (a, b), and vapour pressure deficit, VPD; (c, d) of the two *Moringa* species (*Moringa oleifera*, MO; *Moringa peregrina*, MP) under drought stress at 5 to 30 days after treatment; vertical bars represent standard deviation, and different letters above and below the series denote statistically significant ( $P \leq 0.05$ ) differences among treatments.

*M. peregrina*) measured at 5 DAT to 30 DAT (Fig. 1a, b). Drought-induced stress retarded plant height, internode distances, and leaflet number (Fig. 1a-f), respectively.

The application of MWT to the drought stress seedlings significantly restored plant growth compared to the seedlings treated with normal water alone. In addition,

Table 2. Effect of magnetic water on chlorophyll content under different levels of drought stress ( $\text{mg g}^{-1}\text{FW}$ ).

	Treatment Combinations	Chl a	Chl b	Chl (a+b)	Carotenoids
<i>Moringa oleifera</i>	Control+NW	0.84±0.03b	0.61±0.02bc	1.45±0.05b	0.92±0.01c
	Control+MW	0.97±0.01a	0.7±0.03a	1.68±0.045a	1.13±0.02a
	MS+NW	0.77±0.02c	0.56±0.03d	1.33±0.01c	0.84±0.02e
	MS+MW	0.87±0.02b	0.64±0.03b	1.51±0.01b	0.98±0.01b
	SS+NW	0.6±0.05d	0.41±0.02e	1.01±0.03d	0.7±0.01f
	SS+MW	0.73±0.02c	0.56±0.02d	1.3±0.05c	0.87±0.01d
<i>Moringa peregrina</i>	Control+NW	1.13±0.02c	0.73±0.03bc	1.86±0.02c	1.23±0.02c
	Control+MW	1.3±0.03a	0.85±0.04a	2.16±0.07a	1.41±0.03a
	MS+NW	1.09±0.02cd	0.66±0.03d	1.75±0.01d	1.14±0.03d
	MS+MW	1.21±0.04b	0.77±0.01b	1.99±0.05b	1.33±0.03b
	SS+NW	0.88±0.03e	0.54±0.02e	1.42±0.05e	0.97±0.01e
	SS+MW	1.16±0.04d	0.72±0.03c	1.88±0.01c	1.22±0.02c

Dissimilar letters within mean and between columns are significantly different at  $p \leq 0.05$  level of significance by applying Fisher's LSD Test.

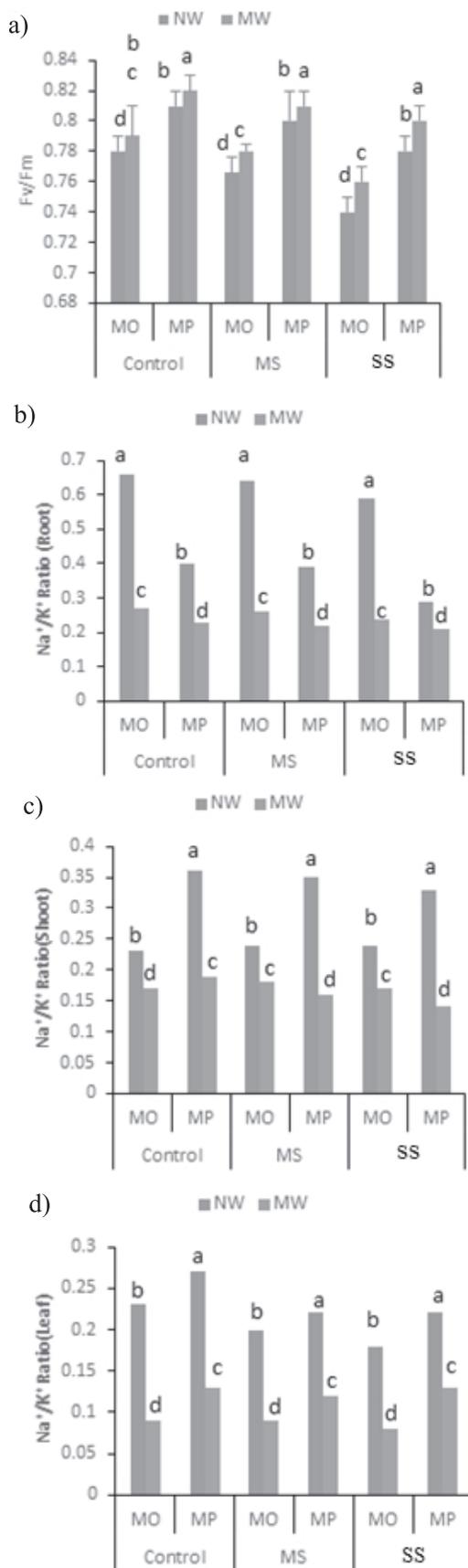


Fig. 5. Effect of magnetic water on the Fv/Fm a) and Na<sup>+</sup>/K<sup>+</sup> ratio in the root b), shoot c), and leaf d) of two *Moringa* species (*Moringa oleifera*, MO; *Moringa peregrina*, MP) under drought stress; dissimilar letters with mean are significantly different at p<0.05 level of significance by applying Fisher's LSD test.

morphological components such as root, shoot, leaf, and dry weight were found to be mostly influenced by the MS and SS drought level under normal water conditions and MWT (Table 1).

### Leaf Area and Relative Water Content

Drought stress significantly reduced the leaf area in the *M. oleifera* seedlings by 3.01% and 8.4% respectively, exposed to MS and SS levels as compared to control under normal water conditions. In addition, a significant decrease in leaf area was observed in the *M. peregrina* seedlings (Fig. 2a). The *M. oleifera* and *M. peregrina* seedlings exposed to drought stress (MS, SS) showed 4.85%, 7.4% and 3.71%, 6.1% decrease in RWC as compared to control seedlings under normal water conditions (Fig. 2b).

### Leaf Gas Exchange

Data regarding the leaf gas exchange traits of *Moringa* species were significantly affected under drought stress conditions. Assimilation, transpiration, and stomatal conductance rates were high in *Moringa oleifera* and *Moringa peregrina* at 5DAT to 30 DAT (Fig. 3a-f) under 100% field capacity. At 30 DAT, drought stress caused a significant decrease in transpiration in *M. oleifera* and *M. peregrina* by 68.2%, 75.1%, and 29.4%, 38.2% exposed to drought stress (MS, SS) level under normal water conditions. In addition, MWT seedlings showed significantly higher transpiration rate than normal water-treated seedlings. Treating the *Moringa* seedlings with drought considerably decreased stomatal conductance compared with the control seedlings, whereas MW increased stomatal conductance compared with the seedlings treated with drought alone. Water use efficiency (WUE) and vapor pressure deficit (VPD) significantly affected by the different treatments. Different times of drought stress were also significantly affected by the MW (Fig. 4).

### Fv/Fm Ratio

F<sub>v</sub>/F<sub>m</sub> ratio was decreased in *M. oleifera* and *M. peregrina* seedlings by 2.56%, 5.12%, and 1.2%, 3.84% exposed to drought stress (MS, SS) level under normal water conditions (Fig. 5a). The F<sub>v</sub>/F<sub>m</sub> ratio increased in the drought-stressed seedlings with MWT.

### Chlorophyll Content

Chlorophyll content (Chl a, Chl b, Chl (a+b), carotenoids) increased under MWT (Table 2). Chl a, Chl b, Chl (a+b), and carotenoids were decreased in *M. oleifera* and *M. peregrina* by 28.57%, 32.7%, 30.3%, 23.9% and 22.1%, 26.02%, 23.6%, 21.1% respectively, exposed to SS under normal water conditions as compared to control seedlings.

Table 3. Effect of magnetic water on ion content (mg/L) under drought stress.

	Treatment Combination	Ca <sup>2+</sup> (mg/L)	Mg <sup>2+</sup> (mg/L)	Mn <sup>2+</sup> (mg/L)	P <sup>2+</sup> (mg/L)	Zn <sup>2+</sup> (mg/L)
Root						
<i>Moringa oleifera</i>	Control+NW	24.5±1.8bc	11.3±1.2bc	0.13±0.02abc	18±1c	1.01±0.01a
	Control+MW	28.31±2.19a	15.4±1.15a	0.16±0.015a	26±2a	1.24±0.03b
	MS+NW	22.34±1.8c	9.27±1.17cd	0.12±0.02bc	16.3±0.57c	0.91±0.06d
	MS+MW	26.13±1.9ab	13.41±1.1ab	0.15±0.02ab	23.66±0.57b	1.1±0.02
	SS+NW	18.2±1.8d	8.8±1.19d	0.09±0.02c	13±1d	0.85±0.01e
	SS+MW	22.06±1.8c	12.1±1.22b	0.13±0.02abc	22±1b	0.97±0.02cd
<i>Moringa peregrina</i>	Control+NW	26±1.8ab	10.01±1.1abc	0.17±0.01a	15±1c	0.75±0.03bc
	Control+MW	28.9±1.9a	12.3±1.2a	0.16±0.01ab	23±1a	0.91±0.05a
	MS+NW	24.3±1.8bc	9.6±1.2bc	0.16±0.01ab	14±1cd	0.65±0.02d
	MS+MW	28.2±1.2a	11.31±1.17ab	0.15±0.02ab	22±1ab	0.8±0.03b
	SS+NW	21.2±1.8c	8.8±1.2c	0.13±0.02b	12.66±1.15d	0.55±0.01e
	SS+MW	23.4±1.8bc	10.41±1.1bc	0.13±0.02b	21±1b	0.7±0.02c
Shoot						
<i>Moringa oleifera</i>	Control+NW	34.2±2.5cd	16.5±1.14a	0.19±0.06a	20±1c	0.97±0.02b
	Control+MW	40.5±2a	17.22±1.17a	0.18±0.05a	27.66±1.5a	1.03±0.02a
	MS+NW	32.1±2de	12.5±1.14b	0.18±0.04a	18±1c	0.89±0.02c
	MS+MW	38.2±2.51ab	15.3±1.09a	0.18±0.03a	26±2ab	0.95±0.01b
	SS+NW	30.2±2e	10.2±1.14c	0.16±0.05a	15.3±0.57d	0.88±0.04c
	SS+MW	36.3±2.05bc	13.3±1.17b	0.17±0.06a	23.66±1.52b	0.91±0.01c
<i>Moringa peregrina</i>	Control+NW	48.4±2.1a	18.24±1.2c	0.3±0.06bc	16.6±0.57c	1.2±0.03a
	Control+MW	50.2±2.1a	24.3±1.14a	0.49±0.06a	24.6±1.52a	1.15±0.02b
	MS+NW	41.6±2.51c	12.4±1.14d	0.28±0.05c	16.3±0.57cd	1.0±0.01
	MS+MW	46.5±2ab	22.4±0.97b	0.45±0.06b	22±1b	1.03±0.02c
	SS+NW	40.2±2.07c	10.4±1.14e	0.26±0.05c	14±2d	0.91±0.015e
	SS+MW	43.2±2.2bc	20.9±1.07b	0.4±0.06ab	21.3±1.52b	0.96±0.01d
Leaf						
<i>Moringa oleifera</i>	Control+NW	62.4±2.1cd	18±1.7c	0.6±0.08ab	26.3±1.15c	0.76±0.02c
	Control+MW	70.5±2.18a	25.96±1.6a	0.7±0.07a	36±1a	0.89±0.01a
	MS+NW	59.3±2.1d	15.2±1.75cd	0.58±0.08ab	25±1cd	0.73±0.02d
	MS+MW	66.33±2.008b	24.1±1.7ab	0.67±0.08a	35.33±1.5ab	0.79±0.015b
	SS+NW	55.3±2.1e	13.1±1.65d	0.48±0.08b	22.3±2.08d	0.62±0.005e
	SS+MW	64.3±2.1bc	22.03±1.6b	0.58±0.08ab	33±2.64b	0.72±0.01d
<i>Moringa peregrina</i>	Control+NW	70.4±2.1d	19.8±1.7c	0.4±0.07a	20.33±0.57b	0.71±0.02c
	Control+MW	102.3±2.1a	27.9±1.65a	0.4±0.08a	22.6±1.52a	0.78±0.02a
	MS+NW	65.5±2.53e	14.3±1.75d	0.35±0.082a	18±1cd	0.73±0.015b
	MS+MW	90.5±2.1b	25.5±1.65ab	0.38±0.081a	19.33±0.57bc	0.74±0.01b
	SS+NW	60.6±2.1f	11.9±1.4d	0.3±0.08a	16.6±0.57d	0.65±0.01d
	SS+MW	85.2±2.05c	23±1.7b	0.34±0.06a	17.6±1.52cd	0.71±0.01c

Dissimilar letters within mean and between columns are significantly different at  $p \leq 0.05$  level of significance by applying Fisher's LSD Test.

### Ion Content

Ion content ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Cu}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Mn}^{2+}$ ) in the root, shoot, and leaf decreased under drought stress (Table 3). The stress induced by drought decreased Ca, Mg, Mn, P, and Zn in the shoots of *Moringa oleifera* and *Moringa peregrina* by 11.69%, 38.18%, 15.7%, 23.5%, 9.27% and 16.9%, 42.85%, 13.3%, 15.6%, 24.1% respectively, exposed to SS under normal water conditions. However, MW improved the nutrient content in *Moringa oleifera* and *Moringa peregrina*. The  $\text{Na}^+/\text{K}^+$  ratio increased in the roots, shoot, and leaf in the drought-stressed seedlings and decreased with MW application (Fig. 5b-d).

### Discussion

Drought stress is known to affect the physiology and phenology of plants [30,34]. In our study, plant height, internode distances, and leaflet number were decreased under MS and SS levels (Fig. 1), and significant improvement was found under MWT during drought stress, possibly by improving cell division and cell expansion. The higher leaf area, FW, and DW was observed under MWT, which might be due to the enhancing the photosynthesis rate. These results were in agreement with Souza et al. (2006) [35], who suggested that DW significantly increased under MW-treated seedlings as compared to control. In corn plants, MW alleviated the drought-induced adverse effects on the growth of the plant [36]. *Moringa* seedlings with drought exhibited lower RWC (Fig. 2b), which indicated that drought stress induced water imbalance and osmotic stress. Magnetic water restored the water loss by increasing the RWC in the drought-affected seedlings.

Our study suggested that assimilation (A), transpiration rate (E), stomatal conductance (gs), water use efficiency (WUE), and vapour pressure deficit (VPD) were increased in both of the *Moringa* species under MWT. Similar results were observed in *Zea mays* under mild stress conditions with MWT [37]. The photosynthesis rate improving in *Moringa* may be due to the improvement of chlorophyll a and photochemical quenching and non-photochemical quenching.

Fluorescence parameter Fv/Fm was used to detect stress in plants [38], and our data showed that Fv/Fm was decreased due to the adverse effects of drought on the *M. oleifera* and *M. peregrina*. The photosystem II damage might be responsible for the reduction of Fv/Fm. However, Fv/Fm ratio was found to be higher in both *Moringa* species under MWT. Magnetic water probably helps to alter the photochemical efficiency of photosystem II in the two *Moringa* species. In soybean plants, higher chlorophyll fluorescence yield [39] was found under MWT, which supported our study outcome.

Our data showed that the Chl a, Chl b Chl(a+b) and carotenoid contents were significantly decreased during drought stress. The chlorophyll content was increased

in the leaves of *Moringa* seedlings under MWT (Table 2). This result is supported by previous studies [40-44] in which, MW enhanced the chlorophyll content in soybean and maize leaves. Anand et al. (2012) [45] reported that the chlorophyll content was increased in corn plants under MW during abiotic stress conditions.

The data showed that the ion content ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Cu}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Mn}^{2+}$ ) decreased under drought stress conditions (Table 3). MW helped to increase the ion content and this result was supported by previous studies [46]. We have observed that the  $\text{Na}^+$  increased in the roots and shoots of the *Moringa* species under drought stress. A higher  $\text{Na}^+/\text{K}^+$  ratio was found in the *Moringa* seedlings due to the higher accumulation of  $\text{Na}^+$ , and similar results were found in the rice seedlings under salt stress [47]. The  $\text{Ca}^{2+}$  content was decreased, which might be due to the displacement of  $\text{Ca}^{2+}$  by  $\text{Na}^+$ .

### Conclusions

We observed that drought stress has significant effects on growth parameters as well as physiological characteristics of the *Moringa* species. MW assisted in alleviating the drought stress-induced adverse effects on growth, leaf gas exchange, Fv/Fm ratio, and chlorophyll and ion contents of the *Moringa* species. This study may help to understand some adaptive mechanisms developed by *Moringa* species with MWT.

### Abbreviations

**MWT**, magnetic water treatment; **FC**, field capacity; **MS**, moderate drought stress; **SS**, severe drought stress; **WUE**, water use efficiency; **RWC**, relative water content.

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### Conflict of Interest

The authors declare no conflict of interest.

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