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RESEARCH ARTICLE

The Impact of Seaweed Application on Some Growth and Physiological Parameters and Nutrient Uptake in Arugula Under Deficit Irrigation Conditions

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ABSTRACT

Deficit irrigation is a widely used strategy to optimize water use efficiency in agriculture; however, it often causes stress on plant growth and nutrient uptake. This study was conducted to evaluate the effects of seaweed extract on the dry matter content, some physiological responses, and macro and micro nutrient uptake of arugula (*Eruca sativa* L.) under deficit irrigation conditions. A controlled plant growing chamber experiment was conducted using three irrigation regimes (I_{100}: full irrigation-control, I_{75}: 25% deficit irrigation and I_{50}: 50% deficit irrigation of field capacity) with and two seaweed extract application (SW_0: non seaweed extract and SW_1: 2 ml L^{-1}). The experiment was conducted using a factorial design in three replicate randomized blocks. Dry matter content, leaf water content, electrolyte leakage, and the uptake of certain nutrient elements (K, Mg, Fe, Ca, and Na) were measured. The results showed that insufficient irrigation reduced the leaf water content of arugula while increasing electrolyte leakage. Additionally, increased water restriction reduced the uptake of K, Mg, Fe, Ca, and Na. Seaweed application reduced electrolyte leakage by %20 compared to the control and increased the uptake of K, Mg, Fe, and Ca by approximately %7, %6, %10, and %11, respectively. It was observed that plants treated with seaweed reduced Na uptake by approximately %8 compared to untreated plants. Plants treated with seaweed mitigated stress effects under water deficiency and improved yield compared to untreated plants. These findings suggest that seaweed biostimulants could serve as a promising agricultural tool to enhance arugula tolerance to water stress by promoting physiological stability and nutrient uptake under suboptimal water availability.

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1. Introduction

The major factors mitigating crop productivity worldwide are abiotic stresses, which can increase yield losses in agricultural production to over 50% (Francini & Sebastiani, 2019; Singhal et al., 2016). Water scarcity, one of the most important abiotic stress factors, is considered the most destructive environmental threat to global agricultural productivity, especially in arid and semi-arid regions, and is progressing towards becoming an increasingly critical issue (Ahmed et al., 2022; Turan et al., 2023). Agricultural production is vulnerable to climate-related water risks, and according to climate change forecasts, water scarcity will be one of the most significant challenges the world will face in the future (UNESCO, 2024).

Current studies have documented that water stress caused by drought negatively affects nutrient uptake, transport, and

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assimilation processes in various horticultural vegetable species, thereby reducing crop yield and quality (Cakmakci et al., 2017; Farooq et al., 2009; Lee et al., 2024; Sahin et al., 2016; Yildirim et al., 2021). Arugula (*Eruca sativa* L.), a leafy vegetable native to the Mediterranean region, is widely cultivated and preferred for its high nutritional value and therapeutic properties such as diuretic and digestive aid in alternative medicine (Sharma et al., 2012). According to TÜİK (2024) data, arugula production in Türkiye has been gradually increasing in recent years, with approximately 45,000 tons of arugula produced in 2024. The arugula plant is sensitive to water deficiency conditions, which can cause nutritional imbalances and inhibit plant growth (Nikzad et al., 2023).

In recent years, eco-friendly approaches have come to the fore in order to make agricultural production more sustainable and mitigate the harmful effects of restricted water stress. To this end, the use of biostimulants to enhance nutrient efficiency under suboptimal conditions has gained importance as a sustainable agricultural strategy (Bhupenchandra et al., 2022; Sensoy, 2024). Seaweed extracts are widely recognized as the most common biostimulants due to their significant improvement in plant growth and development (Buono, 2021). Seaweed-based biostimulants, primarily derived from brown algae such as *Ascophyllum nodosum*, contain a rich array of bioactive compounds, including polysaccharides, phytohormones, amino acids, and micronutrients, which have been shown to enhance plants' tolerance to drought, salinity, and nutrient deficiencies (W. Khan et al., 2009; Rouphael & Colla, 2020). These biostimulants can increase fruit yield under limited irrigation conditions (Ahmed et al., 2022), improve root development (Chen et al., 2023), modulate stress response pathways (A. H. Ali et al., 2022) and enhance the bioavailability and uptake of essential macro and micro nutrients under adverse environmental conditions (Glauco et al., 2024). Additionally, the foliar application of seaweed extract can mitigate the adverse effects of water stress by increasing antioxidant activity in leaves and reducing electrolyte leakage (Shehata & Nosir, 2019). Although the positive effects of seaweed extracts on crop performance under various stress conditions have been confirmed in numerous studies, research specifically addressing their role in nutrient uptake in leafy vegetables such as arugula grown under restricted irrigation regimes is infrequent. Understanding how seaweed-based biostimulants affect the uptake of macro and micro nutrients, as well as certain yield physiological parameters under water stress conditions, is crucial for optimizing fertilization strategies and enhancing resource use efficiency in sustainable production systems. This study was conducted to evaluate the effect of a seaweed-based biostimulants on macro and micro nutrient uptake, electrolyte leakage, and some yield parameters in *Eruca sativa* L. plants exposed to deficit irrigation stress. The results are expected to provide insights into the potential of seaweed biostimulants to mitigate drought-induced nutrient limitations and contribute to the production of resilient and sustainable leafy vegetables.

2. Materials and Methods

2.1. Material

The study was conducted in the plant growing chamber of the Department of Horticulture, Faculty of Agriculture, Van Yüzüncü Yıl University. Arugula (Bayrok cv., Zeta Tohumculuk) was used as plant material. In the study, 3-liter pots filled with a 2:1 ratio of peat and perlite were used. The liquid seaweed extract obtained from a commercial firm (Allnature, Türkiye). Seaweed extract contains, by weight (w/w): 20% organic matter, 0.4% alginic acid, 3% water-soluble potassium oxide (K_2O), and a pH of 7-9.

2.2. Planting and Experimental Treatment

The experiment was conducted using a factorial design in three replicate randomized blocks. Two seaweed treatments (SW_0: without seaweed SW_1: 2 ml L^{-1}) and 3 irrigation application (I_{100}: full irrigation-control, I_{75}: 25% deficit irrigation and I_{50}: 50% deficit irrigation) were set up for the pot.

Arugula seeds were sown in plastic pots and thinned out so that there were 4 plants in each pot. Seaweed extract was applied four times in total, once a week, in accordance with the product's instructions for use. For control treatments (SW_0), water was used (the same amount of seaweed extract).

2.3. Irrigation Treatments

To determine the field capacity of water held in pots, the pots were saturated with water and left to drain freely. After drainage was complete (approximately 40 hours), the moisture content in the pots was considered to be the water content of the growing medium and was measured using an HD2 sensor (IMKO Soil Moisture Meter, Ettlingen, Germany). The moisture content at 100% field capacity (FC) was determined using the IMKO-HD2 Time Domain Reflectometer (TDR), with TDR probes inserted into the pot soil. Based on the average soil moisture level at 100% FC, the amount of moisture retained by the soil at subsequent field capacities was determined, and these values were used to obtain 75% and 50% FC values. Drought treatments in the pots were maintained by controlling soil moisture using an HD2 moisture sensor calibrated according to the experimental soil and pot size.

2.4. Dry Matter Ratio

For fresh weights leaves weighed to obtain fresh weight (FW). Subsequently, the same leaf samples were dried in an oven at 65°C for 48 hours, after which they were weighed again to obtain the dry weight (DW). The dry matter ratio (DMR) was determined according to the following formula

$$DMR\ (\%) = 100*(FW-DW)/FW \quad (1)$$

2.5. Determination of Leaf Relative Water Content (LRWC)

To determine the relative water content (LRWC) of the leaves, leaf samples with a diameter of 10 mm were taken before harvest. The samples were weighed using a sensitive scale, and the recorded weight was referred to as the leaf fresh weight (FW). These leaf samples were then soaked in distilled water for 4 hours. After the soaking process, the same samples were weighed again to determine the leaf turgor weight (TW). The samples were then dried in an oven set at 65°C for approximately 48 hours to obtain the leaf dry weight (DW). LRWC was calculated using the following equation described by Mullan and Pietragalla (2012).

$$LRWC\ (\%) = 100*(FW-DW)/(TW-DW) \quad (2)$$

2.6. Determination of Electrolyte Leakage (EL)

Electrolyte leakage (EL) from leaf cells was determined using the method described by Hatsugai and Katagiri (2018) and Yildirim et al. (2008). Disks were taken from the fresh leaves of each plant and left to stand in 50 ml of deionized water at room temperature for 24 hours. The electrical conductivity (EC) value of the water solution was measured and recorded as EC_1. The same leaf discs were then subjected to a water bath at 95°C for 20 minutes. After cooling to room temperature, the EC value was measured again and recorded as EC_2. The EI value was calculated using the following equation:

$$EL=(EC_1/EC_2)*100 \quad (3)$$

2.7. Determination of Leaf Mineral Concentration

The mineral concentration analysis of the leaves was performed using the dry combustion method (Kacar & İnal, 2010). The dry leaf samples were dried at 65°C for 48 hours and ground in porcelain mortars. From the ground samples, 0.5 grams were taken and burned in an oven at 550°C. After the combustion process, a washing process was performed using 10 mL of 1 N H_2SO_4. Potassium (K), magnesium (Mg), iron (Fe), calcium (Ca), and sodium (Na) concentrations were determined using atomic absorption spectrophotometry.

2.8. Statistical Analysis

All multivariate analyses were performed with IBM SPSS Statistics version 21.0. One-way analysis of variance (One-way ANOVA) was used for data comparison and Duncan's multiple comparison test (0.05 probability) was used to determine differences between groups. All values are presented as mean ± standard deviation (SD). Pearson correlation heatmap was created by using OriginPro 2024b software.

3. Results

3.1. Dry Matter Ratio

The effect of deficit irrigation conditions and seaweed on the dry matter content of arugula plants is shown in Figure 1. Seaweed application significantly increased the dry matter content ($p<0.05$). Compared to the control, seaweed application increased the dry matter content by approximately 2%. On the other hand, the effect of deficit irrigation applications on dry matter and the interaction between the treatments were not found to be significant.

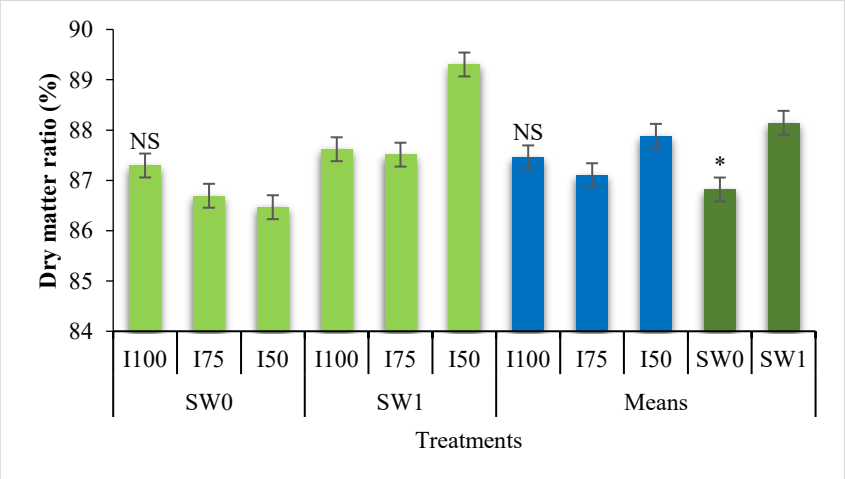


Figure 1. Effect of seaweed application on dry matter ratio (%) under deficit irrigation conditions. '*' indicate significant levels at $p<0.05$, 'NS' indicates non-significant. I_{100}: full irrigation-control; I_{75}: 25% deficit irrigation; I_{50}: 50% deficit irrigation; SW_0: without seaweed extract and SW_1: 2 ml L^{-1} seaweed extract.

3.2. Leaf Relative Water Content (LRWC)

The effect of deficit irrigation applications ($p<0.01$) and seaweed treatment ($p<0.05$) on leaf water content was found to be statistically significant (Figure 2) Leaf water content decreased depending on the level of deficit irrigation. Under the 25% deficit irrigation application (I_{75}), the leaf water content reduced by ~2% compared to the control, while under the 50% deficit irrigation application (I_{50}), it decreased by ~4%. In contrast, seaweed application increased leaf water content by ~2% compared to water control. Although the effects of seaweed and irrigation applications are clearly observed, the interaction between the applications was not found to be statistically significant.

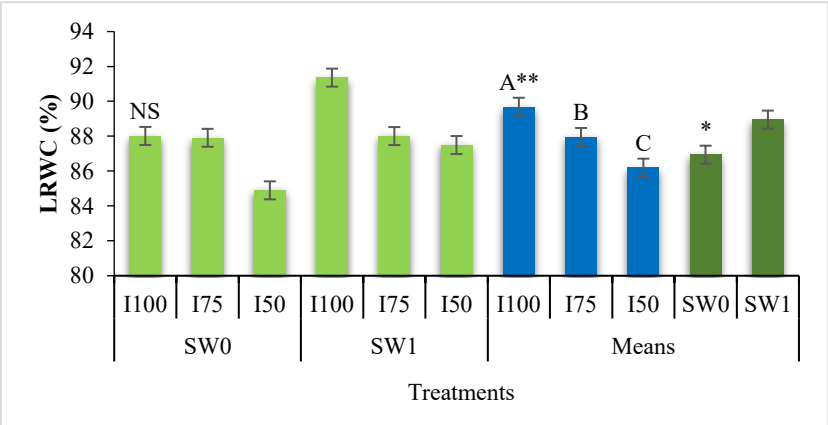


Figure 2. Effect of seaweed application on leaf relative water content (LRWC) (%) under deficit irrigation conditions. '*', '**'indicate significant levels at $p<0.05$, $p<0.01$, respectively. 'NS' indicates insignificant. I_{100}: full irrigation-control; I_{75}: 25% deficit irrigation; I_{50}: 50% deficit irrigation; SW_0: without seaweed extract and SW_1: 2 ml L^{-1} seaweed extract.

3.3. Electrolyte Leakage (EL)

Deficit irrigation ($p<0.01$) and seaweed ($p<0.05$) application considerably affected to electrolyte leakage (Figure 3). Electrolyte leakage progressively increased subject to the deficit irrigation practice. The I_{75} deficit irrigation application increased electrolyte leakage by ~2 times compared to control, while the I_{50} deficit application increased electrolyte leakage by 3 times compared to control. On the other hand, the interaction between irrigation and seaweed application has been found to be significant in terms of electrolyte leakage. The electrolyte leakage increased by deficit irrigation applications has been mitigated by seaweed applications. The highest EL value (42.27%) was found in the SW_0I_{50} application, while the lowest value (12.10%) was determined in the SW_0I_{100} application.

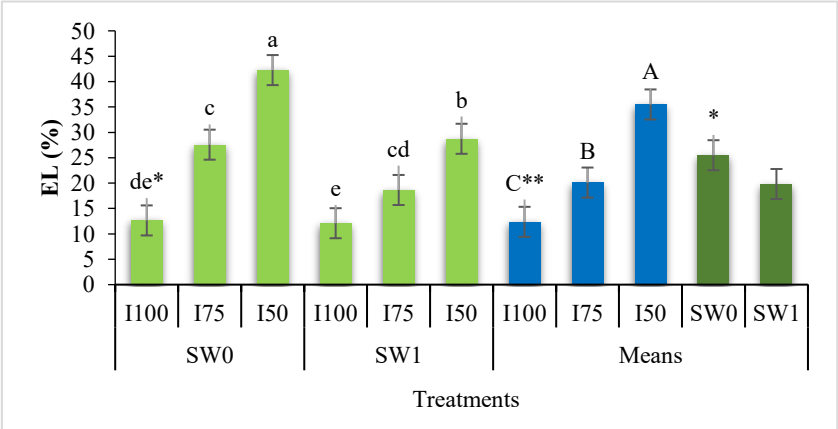


Figure 3. Effect of seaweed application on electrolyte leakage (EL) (%) under deficit irrigation conditions. '*', '**'indicate significant levels at $p<0.05$, $p<0.01$, respectively. I_{100}: full irrigation-control; I_{75}: 25% deficit irrigation; I_{50}: 50% deficit irrigation; SW_0: without seaweed extract and SW_1: 2 ml L^{-1} seaweed extract.

3.4. Mineral Uptake

Deficit irrigation applications significantly affected ($p<0.01$) the uptake of K, Mg, Fe, Ca, and Na in arugula leaves (Figure 4A-E). On the other hand, seaweed applications affected Mg, Ca, and Na uptake at the $p<0.01$ significance level, while K and Fe content were affected at the $p<0.05$ significance level.

Increased deficit irrigation application negatively affected K uptake. In the I_{75} and I_{50} irrigation treatments, K uptake was reduced by ~33% and 31%, respectively, compared to the control treatment (Figure 4A). Conversely, seaweed application increased K uptake by ~7%. However, no significant interaction was detected between the applications.

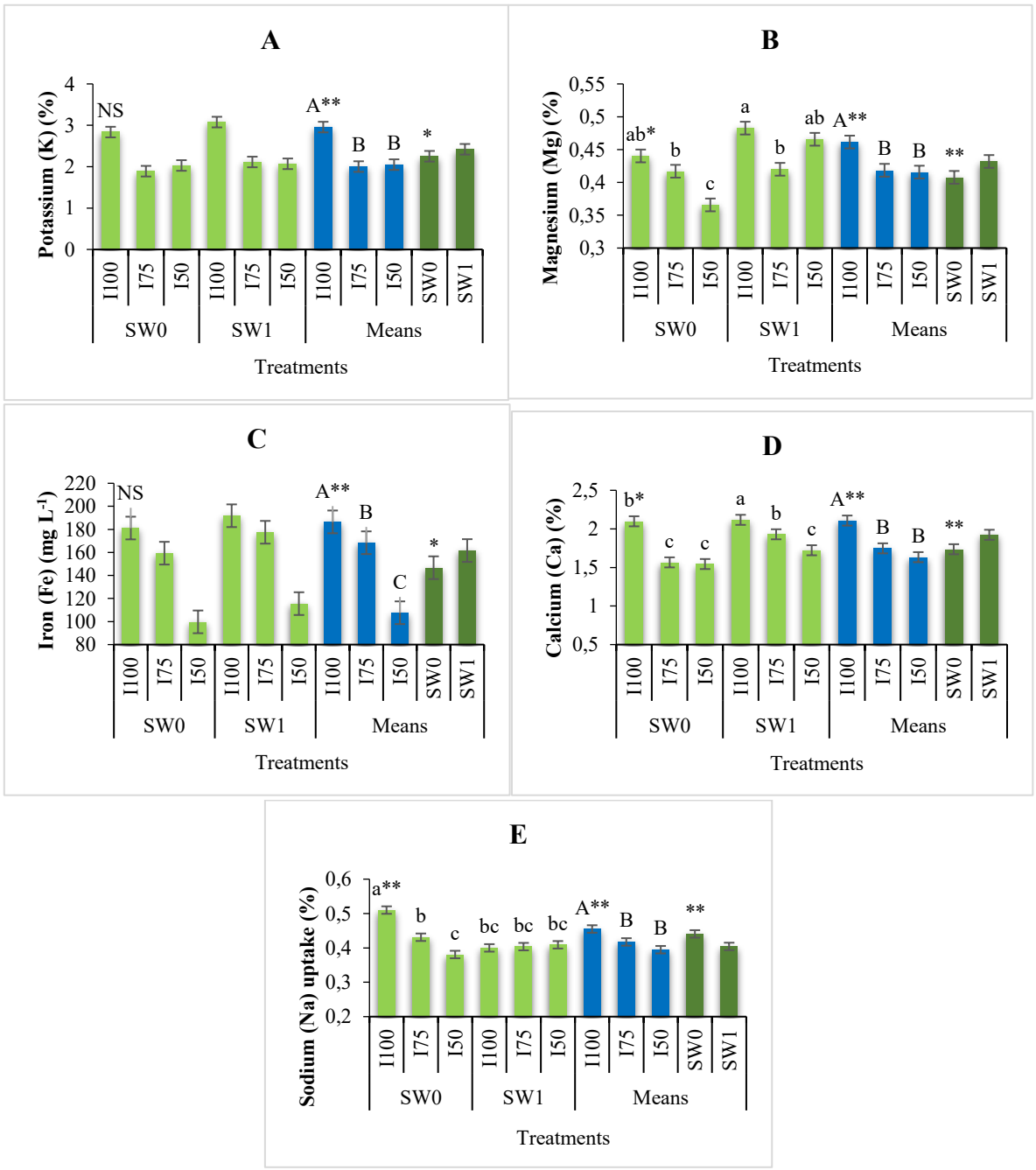


Figure 4. Effect of seaweed application on some nutrients (K, Mg, Fe, Ca and Na) uptake under deficit irrigation conditions. '*', '**'indicate significant levels at $p<0.05$, $p<0.01$, respectively. 'NS' indicates non-significant. I_{100}: full irrigation-control; I_{75}: 25% deficit irrigation; I_{50}: 50% deficit irrigation; SW_0: without seaweed extract and SW_1: 2ml L^{-1} seaweed extract.

Deficit irrigation applications have led to a decrease in Mg uptake (Figure 4B) The I_{75} and I_{50} treatments reduced Mg uptake by approximately 9% and 10%, respectively, compared to the control. On the other hand, the seaweed application increased Mg intake by ~6% compared to the control. In terms of magnesium uptake, interactions between applications were

found to be significant ($p<0.05$). In general, Mg uptake decreased with deficit irrigation applications, while seaweed application improved Mg uptake. The highest magnesium uptake (0.48%) was observed in the SW_1I_{100} application, while the lowest Mg uptake (0.37%) was determined in the SW_0I_{50} application.

Fe uptake has severely decreased along with the increasing level of deficit irrigation (Figure 4C). The I_{75} and I_{50} applications reduced Fe uptake by approximately 10% and 42%, respectively, compared to the control. In contrast, seaweed applications improved Fe uptake by approximately 10% compared to the control. The interaction between the applications was not found to be statistically significant.

Ca uptake considerably affected to deficit irrigation (Figure 4D). The I_{75} application reduced Ca uptake by ~17% compared to the control, while the I_{50} application reduced Ca uptake by ~22%. On the other hand, seaweed application significantly improved Ca uptake. Seaweed increased Ca uptake by approximately 11% compared to the control. In addition, interaction between applications was found to be significant. The highest Ca uptake (2.1%) was detected in the SW_1I_{100} application, while the lowest Ca uptake (1.54%) was determined in the SW_0I_{50} application.

Deficit irrigation applications have reduced Na uptake (Figure 4E). The I_{75} and I_{50} treatments reduced Na uptake by approximately 8% and 13%, respectively, compared to the control. Similarly, seaweed application considerably reduced Na uptake. In the seaweed treatment, Na uptake decreased by approximately 8% compared to the control. Interactions between the applications were found to be significant ($p<0.01$). The highest Na value (0.51%) was determined in the SW_0I_{100} application, while the lowest Na uptake (0.38%) was detected in the SW_0I_{50} application.

3.5. Correlation

The correlation heat map showed the correlation between the parameters of dry matter ratio (DMR), leaf relative water content (LRWC), electrolyte leakage (EL), and some nutrient element contents (K, Mg, Fe, Ca, and Na) (Figure 5). DMR showed a significant positive correlation with Mg uptake at the $p<0.05$ level. DMR content also showed a negative correlation with other parameters; however, these relationships were not statistically significant. On the other hand, leaf relative water content (LRWC) showed a significant negative correlation with EL at the $p<0.01$ level. Conversely, a significant positive relationship was found between LRWC values and K ($p<0.05$), Mg ($p<0.05$), Fe ($p<0.01$), and Ca ($p<0.01$) uptake. A negative and significant ($p<0.01$) correlation was determined between electrolyte leakage and K, Mg, Fe, and Ca uptake. When examining the relationships between nutrient element uptake, K uptake showed a positive correlation with Ca ($p<0.01$), Fe ($p<0.01$), and Mg ($p<0.05$) uptake.

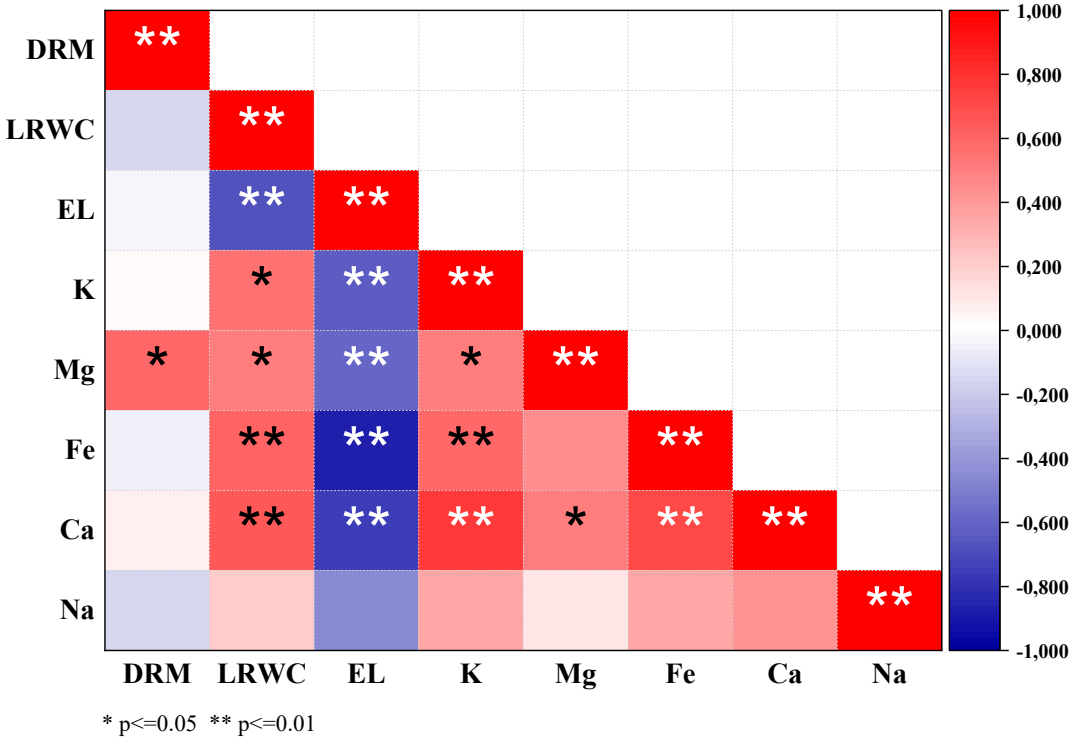


Figure 5. Pearson correlation plot between parameters. DMR: Dry matter ratio, LRWC: Leaf relative water content, EL: Electrical leakage.

4. Discussion

This study evaluated the physiological responses and nutrient uptake of arugula (*Eruca sativa L.*) plants to seaweed extract application under deficit irrigation conditions. The findings clearly demonstrate that seaweed application mitigates the adverse impacts of water stress and enhances plant performance through improvements in dry matter accumulation, water status, membrane stability, and nutrient acquisition.

At increasing water deficiency levels (I_{75} and I_{50}), the dry matter ratio (DMR) decreased in untreated plants, while seaweed-treated plants exhibited significantly higher DMR values, especially under severe stress (I_{50}). In plants with insufficient irrigation, growth is negatively affected; in this case, physiological and biochemical processes essential for maintaining plant metabolism are disrupted, leading to impaired leaf growth (Khapte et al., 2019). The decrease in vegetative parameters can be attributed to negative effects on the photosynthesis process and transpiration rate (Mattar et al., 2020); likely, fewer metabolites are synthesized to support plant growth. On the other hand, the results indicate that seaweed extract can increase dry matter accumulation under suboptimal water availability. Similar findings have been reported for sugar beet (Chen et al., 2023) and tomato (Villa e Vila et al., 2023); in these studies, it was demonstrated that phytohormones derived from seaweed, such as cytokinin and auxin, promote cell division and growth even under drought stress.

Leaf relative water content (LRWC) decreased significantly in response to deficit irrigation, confirming the deterioration of water status in plants. However, plants treated with seaweed exhibited higher LRWC values under both moderate and severe stress conditions. This improvement can be attributed to the osmoprotective effects of seaweed extracts rich in betaines, proline, and polysaccharides, which enhance water retention and cellular hydration (Craigie, 2011; W. Khan et al., 2009). The increase in LRWC may also be associated with better stomatal regulation and membrane functionality under stress conditions (O. Ali et al., 2021). Additionally, previous studies have reported that seaweed application promotes root development (Chen et al., 2023; Mattner et al., 2018; Mukherjee & Patel, 2020). A well-developed root system improves water uptake and enhances nutrient absorption (Yi et al., 2022).

Electrolyte leakage (EL) is an important indicator of membrane damage, and the damage caused by water deficiency has led to a significant decrease in membrane stability, resulting in these types of membranes exhibiting considerably higher values in terms of EL. Electrolyte leakage increased significantly under water deficiency in plants untreated with seaweed, while it decreased significantly with seaweed application. This may indicate that seaweed extract enhances membrane integrity and reduces lipid peroxidation. The increase in water-holding capacity of seaweed can be explained by its ability to mitigate the damage caused by water stress on membrane stability (Chen et al., 2023). Additionally, natural antioxidants such as ascorbic acid, polyphenols, and flavonoids present in seaweed formulations have been shown to scavenge reactive oxygen species and protect cellular structures. (Kumari et al., 2011).

In terms of mineral nutrition, seaweed application significantly affected the uptake of K, Mg, Fe, Ca, and Na under stress conditions. Potassium and magnesium uptake have increased significantly with seaweed application, particularly under I_{75} and I_{50} regimes. These elements play important roles in osmotic adaptation and chlorophyll synthesis, and their increased uptake contributes to improved stress tolerance (Hammad et al., 2016). Iron uptake, which was particularly inhibited under water stress in untreated plants, improved significantly with seaweed application. This may be due to the chelating effect of alginates and other organic acids in seaweed, which increase the solubility and availability of iron (Craigie, 2011; Kumar & Sahoo, 2011).

Seaweed treatment moderately improved calcium uptake, indicating improved ion transport and cell wall stability, while sodium accumulation decreased in treated plants, demonstrating improved ion selectivity and reduced salt stress, as also observed by M. I. R. Khan et al. (2015). Reducing sodium uptake is crucial for maintaining ionic homeostasis under osmotic stress conditions.

The Pearson correlation analysis supported these findings by showing strong positive correlations between LRWC and DMR, and negative correlations between EL and nutrient uptake. This implies a synergistic relationship between water status, membrane stability, and efficient nutrient absorption. Notably, Fe, K, and Mg showed strong correlations with LRWC, underlining their physiological importance in drought resilience.

In summary, the application of seaweed extract under deficit irrigation conditions significantly improves physiological performance and nutrient uptake in arugula plants. These results are consistent with numerous studies reporting that seaweed-based biostimulants can enhance plant tolerance to abiotic stresses (Chen et al., 2023; Rouphael & Colla, 2020; Sensoy, 2024). Therefore, seaweed extracts can be considered a sustainable agronomic strategy for improving leafy vegetable production in water-limited environments.

5. Conclusion

The findings of this study clearly demonstrate that seaweed extract has the potential to effectively mitigate the adverse effects of insufficient irrigation on arugula (*Eruca sativa* L.) by improving physiological characteristics such as dry matter

accumulation, relative water content, and membrane stability, as well as increasing the uptake of essential nutrients such as potassium, magnesium, and iron. Under moderate and severe water stress conditions, plants treated with seaweed exhibited consistently better performance compared to the untreated control group. This indicates that seaweed formulations possess strong biostimulatory potential in supporting plant growth and resilience.

These results highlight the multifaceted benefits of seaweed-based biostimulants as sustainable agricultural tools for improving crop performance under abiotic stress conditions, particularly in water-limited environments. The integration of seaweed extracts into production systems of leafy vegetables such as arugula could contribute to water use efficiency, nutrient quality, and stress reduction. Future research should focus on understanding the underlying molecular mechanisms of these responses and evaluating the long-term effects of seaweed application under various environmental and soil conditions.

Compliance with Ethical Standards

This study does not require ethical committee approval.

Conflict of Interest

The author has no competing interests to declare that are relevant to the content of this article.

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