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Sustainable Restoration of Desert Ecosystems Through BIOGEMI-Based Soil Amendment: Improvements in Chlorophyll Content and Soil Properties in Haloxylon ammodendron

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Abstract

Drought is one of the most significant limiting factor for plant growth in arid regions, and traditional methods such as irrigation and fertilization offer limited effectiveness. In this context, BIOGEMI technology presents an innovative approach to mitigating drought stress by improving the biological and physical properties of soil and increasing its water-holding capacity. This study aimed to evaluate the effects of BIOGEMI on improving soil characteristics and chlorophyll content in Haloxylon ammodendron in the Fesaran area of the Sagzi Plain in Isfahan Province, a region characterized by saline and calcareous soils. The experiments were conducted using 144 Haloxylon seedlings, divided into BIOGEMI-treated and control groups. Parameters such as biomass, chlorophyll content, and relative water content (RWC) were measured and compared between treatments. Soil samples were also analyzed at the beginning and end of the experiments to assess physical and chemical changes. Results showed that chlorophyll a and b levels in the treated plants were 15% and 111% higher respectively, than in the control group, indicating a significant improvement in photosynthesis. The fresh and dry weight of aerial parts increased by 48% and 32.8%, respectively. Soil conditions also were improved after treatment: salinity decreased by 88.6%, and organic matter content increased by 50%. Additionally, the RWC in treated plants was 41.6% higher than in the control group, indicating enhanced drought tolerance. Overall, these findings confirm that BIOGEMI technology can serve as an effective tool for desertification control and the sustainable management of soil and water resources.

Keywords: Desert Ecosystem Restoration, Chlorophyll Content, Relative Water Content (RWC), Soil Salinity, Haloxylon ammodendron.

1. Introduction

Drought is one of the most critical environmental stresses in desert and semi-arid regions, directly reducing plant growth, photosynthesis, and survival (Bayat-Movahed, 2010). Water scarcity in these areas poses significant challenges to the growth of species such as Haloxylon and threatens the stability of natural ecosystems. Desert plants have developed specific mechanisms to withstand such harsh conditions, including CAM and C4 photosynthesis, reduced leaf surface area, chlorophyll concentration in stems, and the production of protective compounds such as carotenoids (Xu et al., 2016; Johansson & Li, 2023). Chlorophyll, as the key molecule in photosynthesis, plays a central role in capturing light and converting it into chemical energy. In desert plants—especially species like Haloxylon ammodendron and Calligonum mongolicum, which rely primarily on stem photosynthesis—chlorophyll remains efficient even under extreme temperature fluctuations and intense radiation (Bajgain et al., 2015; Bodner, 2017). The ability of these plants to sustain photosynthetic activity with minimal water use is one of the most important traits for their survival (Smith & Doe, 2023).

In addition to climatic challenges, economic and social changes have placed additional stress on arid regions. The eastern region of

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Isfahan County in Iran, despite its potentials, faces instability due to agricultural decline, water shortages, unemployment, and the accelerating trend of desertification. Soil degradation, increasing salinity, declining organic matter, and dust storms are among the consequences of this crisis (Wang et al., 2024).

In this regard, utilizing bio-based technologies such as the knowledge-based BIOGEMI technology can be an effective approach

for soil amendment, increasing water-holding capacity, and restoring vegetation cover. This new technology, by improving soil structure, reducing lime and salinity, and stimulating soil biological activities, provides more suitable conditions for the growth of species like Haloxylon. Recent studies in regional countries have also confirmed the positive effects of this technology on improving the performance of desert plants (Li et al., 2025).

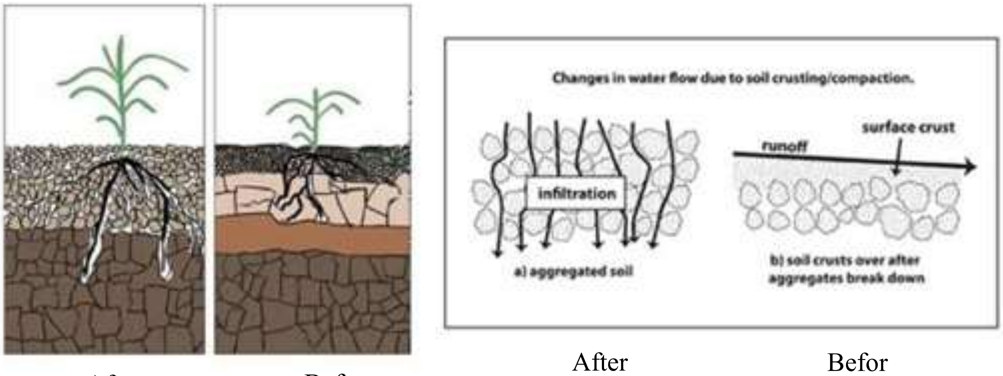
The products used in the BIOGEMI technology are based on organic materials and act as soil improvers and conditioners. Among their effects are improvements on soil texture and structure. These solutions have no negative impact on the soil, and their effectiveness is due to both the organic materials and the increase in ionic flow and cation exchange capacity in the soil. These two products are registered as fertilizers by the Soil and Water Research Institute of the country. The BIOGEMI solution provides the carbon and organic matter needed by the soil. The BIOGEMI compost is made from livestock manure and agricultural residues, in which the ratio of required elements and organic carbon is maintained. Through the BIOGEMI technology,

the composting process is completed in a short time, resulting in compost that is free from weed seeds and has a standard microbial load. The full maturity of the compost and the presence of vital elements for plant growth have created suitable conditions for using this product in orchards and farms.

The BIOGEMI solution, by supplying the materials needed by the soil, improves soil structure, which leads to increased overall plant vigor.What distinguishes this product from similar ones is its organic base, through which essential nutrients for growth enter the soil. The BIOGEMI solution, in addition to chemical elements, contains organic substances needed by the soil. Upon entering the soil, these substances not only amending the soil, also facilitate the absorption of nutrients and enhance nutrient uptake by the plant. This solution contains essential organic acids and both micro- and macro elements. Since it is categorized among organic compounds, it increases fertility and reduces soil erosion. Therefore, it causes plant greenness, stimulates microbial activities in the soil, and increases plant enzymatic activities, which in turn leads to complete development, increased volume, and timely ripening. In desert plants, root expansion plays an important role in plant stability under drought and environmental stresses. In this technology, through soil granulation, suitable conditions for root expansion are provided.

In desert conditions, planting seedlings and new shrubs often fails because the plants are destroyed by unfavorable conditions before they become established.

As mentioned, using BIOGEMI technology promotes root expansion and plant establishment by creating porosity in the soil. Secondly, if water infiltration and water-holding capacity in the soil increase with this method, then the water available to the plant during drought stress will be greater than under normal conditions, thereby supporting plant growth. The improvement of conditions and the increase in plant growth depend on the cultivar, environmental conditions, soil fertility, and other factors. In BIOGEMI technology, with soil amendment, we will have conditions for root expansion, proper nutrient uptake, and consequently better performance (Figure 1).



After Befor After Befor

Figure 1. Schematic representation of BIOGEMI's effects on soil before and after application.

According to the studies of Finck (1992), the addition of humus to the soil can increase water-holding capacity by 3 to 5 times. Organic matter enhances the accessible water capacity for plants by improving soil structure and creating fine pores (Evans et al., 1996). Emerson (1995) also showed that increasing the percentage of organic carbon in the soil, especially in pores smaller than 30 microns, has a linear relationship with increased pore volume under a 0.3 bar moisture tension. Likewise, Hudson (1994) reported that increasing soil organic matter by 1 to 3 percent could double the water-holding capacity, and with a 4 percent increase in organic matter, plant-available water increases by more than 60 percent. In a study by Asgari & Golchin (2005), it was shown that the presence of organic matter in the soil affects soil moisture at field capacity more than at the wilting point. Ghaderi & Mohammadi (2005) also demonstrated that using organic hydrogels at the bottom of planting pits was more effective than the control and is recommended for storing moisture in dryland orchard development, particularly in arid areas. Razaghi & Rezaei (2017), in a study using biochar at four application rates (0, 25, 50, and 75 tons per hectare) on different soils, showed that applying 75 tons of biochar increased plant-available water by 45%, porosity by 13%, hydraulic conductivity by 95%, and cation exchange capacity by 52%. This study concluded that biochar improved drainage in heavy soils and enhances water-holding capacity in light soils. Similar research by Yazdanpanahi et al. (2019) also confirmed that adding biochar significantly affects field capacity, available water, and irrigation intervals, while simultaneously decreasing saturated hydraulic conductivity, and both bulk and particle density.

In studies on the use of mineral hydrogels, Zare-Zad Reihani and Sadeghzadeh (2012), by adding perlite to planting pits for Elaeagnus saplings in a volumetric ratio of 2:1:1 (soil: organic matter: perlite), showed that this mixture was superior in promoting sapling height and diameter growth compared to using clay pots and the control.

Likewise, Sadeghzadeh-Reihani (2017) recommended using pumice as a hydrophilic material in rainwater harvesting systems for afforestation and green space development in arid regions.

However, limited studies have been conducted on desert plants under conditions of highly saline and gypsum-rich soils and other environmental constraints, indicating a need for further research in this area.

Previous studies on improving soil water retention have mainly focused on traditional organic materials such as humus, compost, and biochar, or mineral hydrogels like perlite and pumice. Although these methods have achieved partial success, they often require large volumes of material, incur high transportation costs, take long timeframes to observe effects, and have limited effectiveness in highly saline and calcareous soils.

In contrast, BIOGEMI technology – with its low-volume usage, rapid impact, significant reduction in soil salinity, notable increase in organic matter, improvement of soil physical texture, and enhancement of plant physiological indicators – presents an innovative and efficient approach. These characteristics make BIOGEMI a superior alternative to conventional methods for sustainable reclamation of desert soils and

drought stress management in desert plants.
Objectives:
- Quantify the effect of BIOGEMI on plant water status and photosynthetic pigments of *Haloxylon ammodendron* at the Fesaran site (Sagzi Plain; 1-ha field design).
- Evaluate treatment-induced changes in topsoil (0–30 cm) salinity and fertility relative to controls using paired pre/post measurements.

Primary endpoints: leaf relative water content (RWC), chlorophyll a/b. Secondary endpoints: carotenoids, above-/below-ground biomass, soil EC, soil pH, soil organic matter/carbon (OM/OC), SAR, available P, K, and micronutrients

2. Methods

The study area is located within the desertification control project zone of the Fesaran region in the Sagzi Plain, covering an area of 200 hectares. The Sagzi Plain is situated 30 km from the metropolitan city of Isfahan. The maximum elevation of the area is 1,640 meters, and the minimum is 1,510 meters above sea level, with a slope ranging between 0 to 2%. This region is located in a wind erosion crisis center of the county.

According to 30 years of data from the East Isfahan synoptic station, the average annual precipitation in the region is 108.8 mm. The average annual temperature is 15.15°C. The average annual relative humidity is approximately 39.76%, with the minimum and maximum annual relative humidity recorded as 23.33% and 61.76%, respectively. The region's annual potential evapotranspiration is 1,666.9 mm. The dominant wind speed throughout the year ranges between 0.5 and 6 m/s, with an average of 2.3 m/s. On average, 59 days per year are associated with dust storms. According to the Ambrother classification, the region's climate is cold-arid, and based on the Gossen method, it is classified as strongly semi-desert.

From a vegetation standpoint, the region is divided into three main zones: agricultural lands, Haloxylon plantations, and rangeland types.

Soil test results at various depths in the study area indicate that soil salinity (EC) in the surface layers is extremely high. At a depth of 0–10 cm, the EC was measured at 156.2 dS/m, indicating extremely high salinity, intolerable for most plant species. Although this value decreases at lower depths, it still falls within the range of severe salinity—for example, 53.7 dS/m at 30–40 cm and 33.9 dS/m at 40–60 cm. Additionally, the soil organic carbon (OC) content was reported to be very low across all depths (e.g., only 0.84% at 0–10 cm depth), indicating severe nutrient deficiency and poor water-holding capacity in the soil.

This study was conducted in the desert region of Sagzi, located in eastern Isfahan County, Iran, with the objective of evaluating the effects of BIOGEMI technology on the physiological characteristics of the desert plant *Haloxylon ammodendron*.

This study was implemented as a two-arm, parallel design over a 1-ha field, divided into two equal plots (each 5,000 m^2) with similar baseline conditions (soil and irrigation). The treatment plot received irrigation with the BIOGEMI solution, whereas the control plot received routine irrigation only. Due to infrastructural constraints (fixed irrigation lines), plot-level randomization was not feasible; therefore, the plots were treated as matched blocks to control spatial heterogeneity. The experimental unit for plant traits was the individual seedling (72 seedlings per plot), and for soil variables, the plot served as the unit of analysis. Soil variables (0–30 cm) were analyzed by comparing values before the initiation of irrigation with the BIOGEMI solution and after the irrigation period, with between-group contrasts performed on change scores. For plant traits, the group effect (Treatment vs. Control) was evaluated while accounting for plot grouping.

The treatment involved the application of BIOGEMI solution via foliar spraying at a concentration of 150 cc per 60 liters of irrigation water, applied three times during the first year. Irrigation was carried out every 25 days following the standard method of the Natural Resources Department.

To evaluate the effect of BIOGEMI, indices such as seedling survival rate, biomass production of aerial and underground parts, relative water content (RWC) of leaves, and flowering were measured and compared between the treatment and control groups. Initial measurements were taken at the start of the experiment and repeated at the end of each growing season to compare treatment performance.

To assess aerial biomass, three of the best-performing seedlings in each replication were selected and evaluated annually. Soil samples were taken at the beginning and end of the experiment, and their physical and chemical properties were independently analyzed (Figure 2).

Additionally, water use and leaf greenness were assessed through the measurement of chlorophyll a and b. For chlorophyll measurement, leaves were extracted using 80% acetone and absorbance was measured at 645 nm and 663 nm using a spectrophotometer. Standard formulas were then used to calculate chlorophyll a, chlorophyll b, and total chlorophyll content.

The annual recorded data were compiled and statistically analyzed using independent t-tests in SAS software. For calculating chlorophyll a, chlorophyll b, and total chlorophyll in plant samples, the following standard formulas were applied (Arnon, 1949).

Chlorophyll a (mg/g) =

$$(12.7 \times OD_{663} - 2.69 \times OD_{645}) \times (V / (1000 \times W)) \quad (1)$$

Chlorophyll b (mg/g) =

$$(22.9 \times OD_{645} - 4.68 \times OD_{663}) \times (V / (1000 \times W)) \quad (2)$$

Total Chlorophyll (mg/g) =

$$(20.2 \times OD_{645} + 8.02 \times OD_{663}) \times (V / (1000 \times W)) \quad (3)$$

- OD_{663} and OD_{645} are optical densities (absorbance) of the extract solution at wavelengths of 663 nm and 645 nm, respectively.
- V is the final volume of the extract solution (in milliliters).
- W is the weight of the plant sample (in grams).

The biomass of the plant's aerial and underground parts were determined through collection, weighing, and drying in an oven at 70°C.

Additionally, Relative Water Content (RWC) was calculated by measuring fresh weight, turgid weight (after immersion in water), and dry weight of the leaf.

RWC calculation formula is (Weatherley, 1950):

$$\text{RWC } (\%) = 100 \times \frac{FW - DW}{TW - DW} \quad (4)$$

- FW is fresh weight of the leaf (weight immediately after harvesting).
- DW is dry weight of the leaf (weight after complete drying in an oven).
- TW is turgid weight of the leaf (weight after full saturation in water).

These methods provide valuable information about the growth, drought adaptation, and water status of *Haloxylon* and can be applied in desert reclamation studies and the improvement of drought-resistant species.

Figure 2. Procedures for measuring above- and below-ground biomass, laboratory chlorophyll assay, and soil sampling.

3. Measurements

3-1. Analysis of Chlorophyll Status in Haloxylon Plants

Following regular foliar application and irrigation, a number of Haloxylon plant samples from the treatment and control plots were collected for chlorophyll analysis. The samples were transferred to the laboratory, and according to the procedure described in Chapter 3, the amounts of chlorophyll a, chlorophyll b, and carotenoids were measured for each sample in the laboratory of the Natural Resources Department at the Agricultural and Natural Resources Research Center of Isfahan Province.

Fresh leaves of the plant were weighed and ground using 80% acetone. The solution was centrifuged, and the resulting supernatant was placed in a spectrophotometer to measure absorbance at different wavelengths. The results of these measurements are presented in Table 1.

The columns for absorbance at 470, 645, and 663 nanometers represent the actual values used in chlorophyll calculations. The columns Cha, Chb, and Car contain the values of chlorophyll a, chlorophyll b, and carotenoids, respectively, for each sample. A comparison between treatments and control samples was conducted based on the chlorophyll indices Cha, Chb, and Car, with the data presented in Table 2 and the comparative chart shown in Figure 2. This analysis illustrates how chlorophyll content varies between the control and treated groups.

Table 1. Results of Light Absorbance at Different Wavelengths in Treated and Control Samples.

				Cha (mg g^{-1} FW)	Chb (mg g^{-1} FW)	Car (mg g^{-1} FW)
Number	470	645	663	12.25 A663−2.79 A646	21.5 A646−5.1 A663	(1000 A470−1.82 Chlorophyll a−85.02Chlorophyll b)/ 198
Treatment1	0.34	0.11	0.27	3.0006	0.988	1.667456566
Treatment2	0.21	0.04	0.11	1.0406	0.299	1.698984848
Treatment3	0.26	0.06	0.15	1.5306	0.525	1.690029293
Treatment4	0.27	0.09	0.21	2.2656	0.864	1.67659596
Treatment5	0.37	0.2	0.27	3.0006	2.923	1.628811111
Treatment6	0.28	0.15	0.23	2.5106	2.052	1.650648485
Control1	0.31	0.08	0.19	2.0206	0.751	1.681073737
Control2	0.46	0.09	0.24	2.6331	0.711	1.676320202
Control3	0.23	0.05	0.13	1.2856	0.412	1.694507071
Control4	0.34	0.08	0.21	2.2656	0.649	1.680889899
Control5	0.36	0.07	0.18	1.8981	0.587	1.685459596
Control5	0.25	0.06	0.15	1.5306	0.525	1.690029293

□ A663 / A645 / A470 → **A663 (AU)** / **A645 (AU)** / **A470 (AU)** *(AU = Absorbance Units)*

Table 2. Comparison of Chlorophyll Indices in Treated and Control Groups.

	Control	Treatment
Cha	1.938933	2.224767
Chb	0.6058336	1.275167
Car	1.684713	1.668754

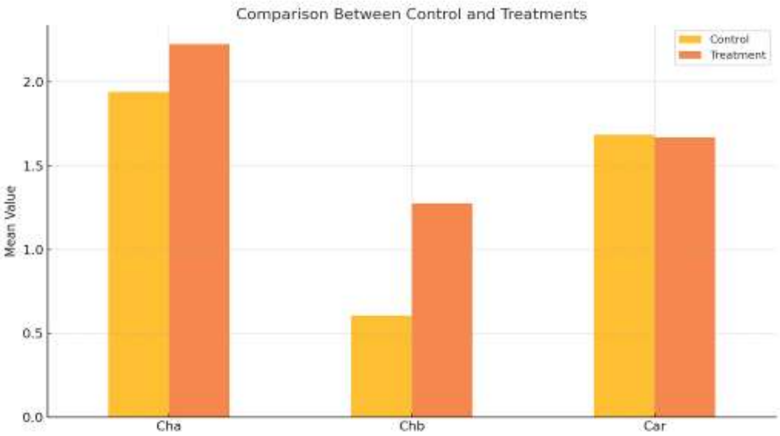


Figure 2. Comparative Chart of Chlorophyll Values Between Control and Treatment Groups.

In general, chlorophyll and carotenoid levels were higher in the treatment group compared to the control, which can be due to the effect of the treatment in enhancing the production of these compounds.

To examine the relationship between the treatment and the type of chlorophyll (chlorophyll a, chlorophyll b, and the chlorophyll ratio), we can analyze the effect of the treatments on these indices.

This relationship may indicate a direct or indirect influence of the treatment on chlorophyll production and composition in the plant.

Overall, the increase in chlorophyll a and b in the treatment groups reflects a positive impact of the treatment on plant photosynthesis. However, the carotenoid levels showed less variation compared to the control, suggesting greater stability or lower sensitivity of this index to the treatment.

The correlation between A663 and Cha, as well as A645 and Chb, indicates the role of these wavelengths in light absorption related to chlorophylls (Table 3 and Figure 3).

Table 3. Correlation Matrix Between Chlorophyll Indices.

	A470	A645	A663	Cha	Chb	Car	
A470	1	0.441407	0.733172	0.733172	0.3024250	0.45044	
A645	0.441407	1	0/820031	0.820031	0.979701	-0.9999	
A663	0.733172	0.820031	1	1	0.688656	-0.82796	
Cha	0.733172	0.820031	1	1	•/688656	-0.82796	
Chb	0.302425	0.979701	0.688656	0.688656	1	-0.9768	
Car	-0.45044	-0.9999	-0.82796	-0.82796	-0.9768	1	

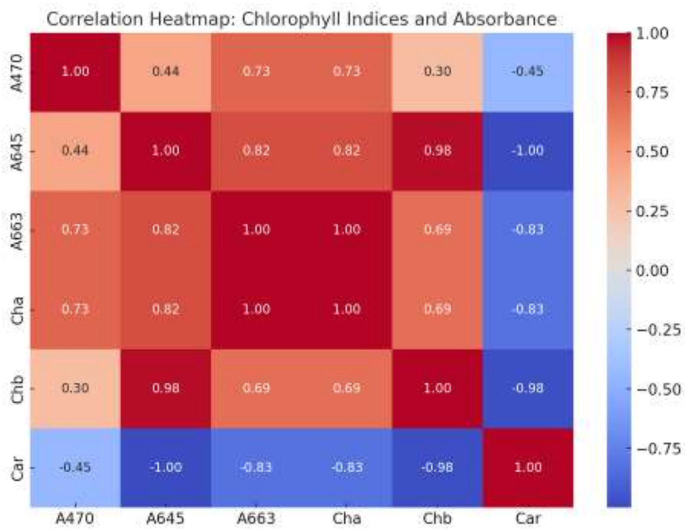


Figure 3. Heatmap and Relationships Between Chlorophyll Parameters.

3-2. Analysis of Aerial and Underground Biomass in Haloxylon Plants

To evaluate the status of aerial and underground plant parts, at the end of the year, three of the best-performing seedlings from each replication in both the control and treatment groups were selected, harvested, and transferred to the laboratory for analysis.

The fresh weight of the samples was measured using a digital scale. The samples were then placed in an oven at 70°C for 48 to 72 hours, until their weight stabilized. The dry weight of the samples was then measured, representing the aerial biomass.

For measuring underground biomass, the fresh weight of the root samples was also recorded using a scale. The roots, like the aerial parts, were dried in an oven, and their dry weight was measured. This final dry weight represents the underground biomass (see Tables 4 and 5).

The results in Table 4 indicate that the treatment group is the most suitable option for arid conditions, as it exhibited higher root biomass, an appropriate root-to-shoot ratio, and balanced growth.

The treated plants developed stronger root systems, which are more effective in withstanding drought and enhancing water uptake. In contrast, the control group showed a greater focus on shoot growth and may be more suitable for favorable conditions, such as soils rich in nutrients and with adequate irrigation.

The results in Table 5 show that the treatment group is the most suitable option for arid environments or areas with limited water resources. It exhibited a higher root-to-shoot ratio and produced greater biomass in both roots and shoots. The control group's results suggest it may be more appropriate for environments with better soil and water availability. If the goal is to select plants with stronger roots and greater drought resistance, the treatment group is recommended. A decrease in the root-to-shoot ratio was observed across the samples, indicating a decline from the treated samples to the control. This indicates that as the ratio decreases, plants allocate more biomass to aerial parts (stems and leaves) rather than roots.

Higher ratios (such as in Treated Sample 1) reflect balanced or even root-dominant growth, which is advantageous under drought stress or nutrient deficiency, as the plant prioritizes root development for enhanced water and nutrient uptake.

Lower ratios (such as in Control Sample 2) suggest that the plant has allocated more energy to aerial growth, which typically occurs under more favorable environmental conditions, such as sufficient irrigation or nutrient-rich soil.

Table 4. Fresh Weight of Plants.

Sample ID	Fresh Weight of Sample (g)	Root Biomass (g)	Root Length (cm)	Root-to-Shoot Ratio	Shoot Biomass (g)
Treatment 1	126	126	50	0.33870977	372
Treatment 1	53	53	36	0.274611399	193
Control 1	26	26	37	0.25	104
Control 2	19.6	19.6	43	0.236144578	83

Table 5. Dry Weight of Plants

Dry Weight of Samples (g)	**Root Biomass (g)**	**Shoot Biomass (g)**	**Root Length (cm)**	**Root-to-Shoot Ratio**
Treatment 1	72	138	28	0.52173913
Treatment 1	25	77	26	0.324675325
Control 1	18	49	34	0.367346939
Control 2	12.4	33	40	0.375757576

3-3. Analysis of Relative Water Content (RWC) in Haloxylon Leaves

All samples were placed in distilled water and kept in a cold room at 4°C for 24 hours. After this period, the turgid weight of the leaves was measured. Then, the leaves were placed in an oven at 70°C for another 24 hours, and their dry weight was recorded (Table 6).

The treatments can have a significant effect on root development in *Atriplex*. The impact of treatments depends on both the type of treatment and the environmental conditions. The RWC values for both treated groups are above 85%, indicating a high water-retention capacity in the plants. Such plants are well-adapted to relatively favorable environmental conditions and are likely to exhibit better drought tolerance.

In contrast, RWC values for the control group are around 62–63%, indicating a considerable reduction in the plant's ability to retain water. Soil tests conducted after several rounds of irrigation with the treatment solution showed that, in the treated plots, soil salinity (EC) decreased by 63.5%, sodium adsorption ratio (SAR) dropped by 71.3%, and soil pH decreased by 5%.

Furthermore, the treatment results showed that BIOGEMI technology effectively improved soil quality, with organic matter (OM) increasing by 98.4%, and nutrients such as iron and phosphorus also rising, thereby enhancing soil fertility and creating better conditions for plant growth. It also aided in removing excess sodium and improving nutrient uptake, mitigating the adverse effects of saline-sodic soils.

Throughout the study period, the plants that received BIOGEMI treatment and irrigation successfully reached the flowering stage. This indicates enhanced plant health and reproductive capacity due to the treatment. In contrast, none of the control group plants flowered, which highlights the likely role of improved nutritional and biological conditions in the treatment plots.

The treated plants showed initial signs of flowering by the end of the first growing season (about three months after treatment). This occurred approximately one month earlier than the typical flowering time for this species under optimal conditions. The increased chlorophyll content and enhanced photosynthesis contributed to greater energy and nutrient production, facilitating growth and flowering. Flowering is a key indicator of plant health and reproductive maturity, serving as a principal measure of a treatment's effectiveness in improving plant conditions. The successful flowering of treated plants, especially under the harsh conditions of the Sagzi region, serves as strong evidence for the high efficiency of BIOGEMI technology.

By reducing soil salinity by 88.6% and increasing soil moisture content, BIOGEMI treatment created a more favorable environment for plants, which directly stimulated flowering. The 50% increase in soil organic matter also improved plant nutrition and strengthened the root system, ultimately leading to enhanced reproductive growth.

Table 6. Sample Weights in Distilled Water and After Drying.

Sample ID	Initial Stem Weight	Stem Weight After Soaking in Distilled Water	Stem Weight After Drying
Treatment 1	4	4.9	0.65
Treatment 1	5	5.8	0.67
Control 1	2.3	3	0.77
Control 2	3.8	4.79	1

Table 7. Interpretation of Relative Water Content (RWC) Status.

Sample ID	Interpretation	RWC %
Treatment 1	Favorable water status; the plant has a high capacity to retain water.	86.7%
Treatment 1	The plant is in a well-watered condition.	85.3%
Control 1	A decrease in RWC indicates water stress and reduced water-holding capacity.	63.4%
Control 1	A decrease in RWC indicates water stress and reduced water-holding capacity.	63.4%
Control 2	The plant was likely under water stress conditions.	62.6%

4. Discussion

The BIOGEMI treatment technology aims to improve conditions for sustainable agriculture in arid regions by enhancing biological activity in the soil, reducing erosion, increasing infiltration, and preserving groundwater resources. The BIOGEMI treatments lead to an increase in the production of chlorophyll a, chlorophyll b, and carotenoids in *Haloxylon*, which indicates enhanced photosynthesis and plant growth (Fig. 4).

The results also showed that the treatments significantly increased the fresh and dry biomass of both aerial and underground parts of *Haloxylon* compared to the control group.

Following treatment, the physical and chemical properties of the soil improved, including reduced salinity and lime content, and increased organic matter. Additionally, soil porosity was increased, contributing to improved root growth conditions. The BIOGEMI treatment was effective in enhancing the plant's tolerance to water and salt stress, ensuring better plant survival under harsh desert conditions.

As an innovative and knowledge-based solution, BIOGEMI technology has shown remarkable effectiveness in improving soil quality and promoting plant growth in dry and desert areas.

The results of this project demonstrate that this technology can serve as an effective tool in natural resource management and sustainable agriculture programs. Figures 4, 5, and 6 clearly illustrate the differences between treated and control plants in terms of chlorophyll and carotenoid indices, biomass, soil characteristics, relative water content (RWC), and growth parameters.

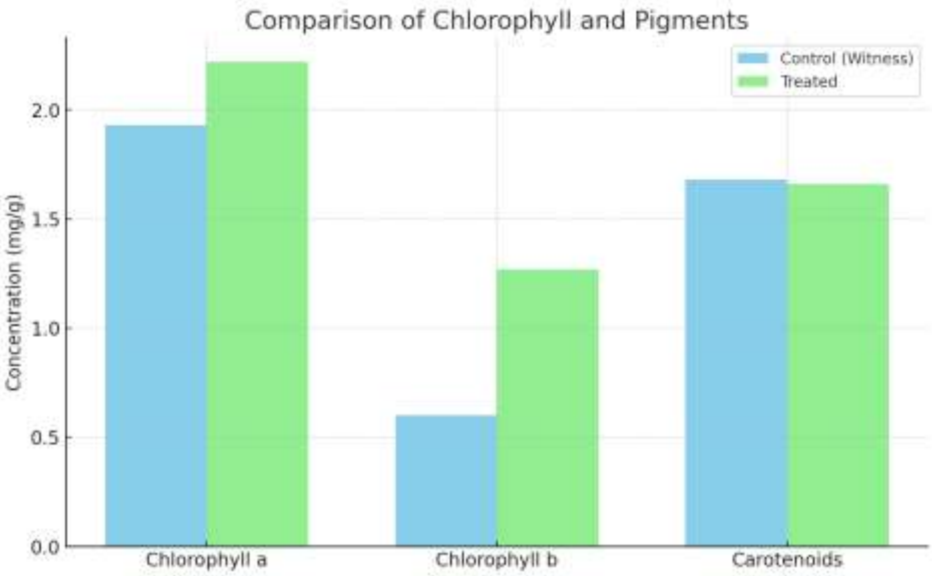


Figure 4. Comparison of Chlorophyll Levels Between Control and Treatment Groups.

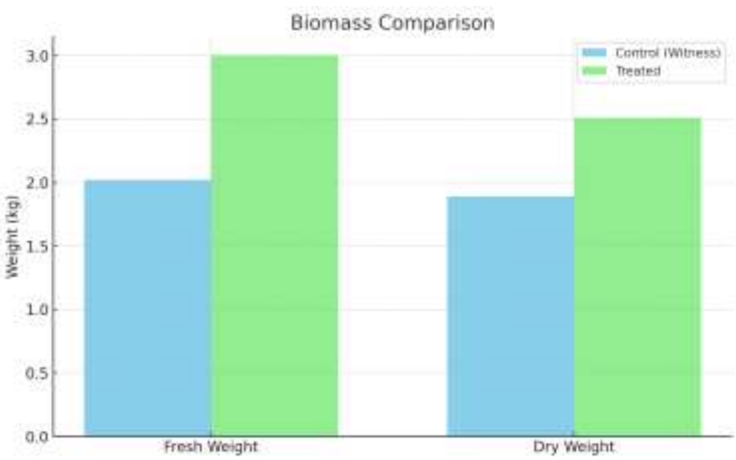


Figure 5. Comparison of Plant Biomass (Fresh and Dry Weight) Between Control and Treatment Groups.

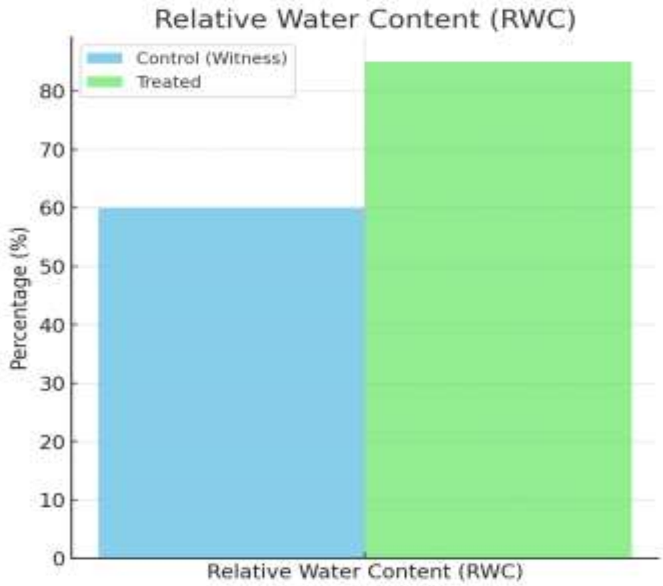


Figure 6. Comparison of Leaf Relative Water Content (RWC) Between Treatment and Control Groups.

The study results showed that chlorophyll a, b, and carotenoids significantly increased in the treated plants compared to the control group. The rise in chlorophyll a, which is primarily responsible for light absorption in the photosynthetic process, reflects the plant's enhanced capacity for energy production.

Moreover, the 111% increase in chlorophyll b compared to the control group indicates improved efficiency in the plant's energy transfer system. This highlights the positive impact of BIOGEMI technology on the photosynthetic ability of plants in harsh and saline environments. Biomass production in both the aerial and underground parts of the treated plants was significantly higher than in the control group. The fresh weight of aerial organs showed a 48% increase, demonstrating that the treated plants achieved better growth under improved soil conditions.

Furthermore, the increase in dry weight – which reflects nutrient accumulation and biological stability – was 32.8%, confirming that BIOGEMI technology enhances plant development even under stress conditions. One of the most prominent results of this project was the remarkable reduction in soil salinity by 88.6%.

Salinity is one of the primary factors limiting plant growth in desert areas, and its reduction directly improves water and nutrient infiltration into the soil.

Additionally, a 50% increase in soil organic matter demonstrated that the technology successfully enhanced the soil's biological environment by stimulating microbial activity and improving soil structure. These changes create a favorable foundation for sustainable plant growth in the long term. The relative water content (RWC) of leaves in treated plants reached 85%, while it was only 60% in the control group – a 41.6% difference that reflects the treated plants' greater ability to retain water and withstand drought. Such a trait is especially critical in arid and desert regions, where water resource management is one of the key challenges.

Comparison with previous studies revealed that the addition of organic materials such as biochar can have similar effects on water retention and soil quality improvement. Razaghi (2017) reported that applying 75 tons of biochar per hectare increased available water capacity by 45% and soil porosity by13%. However, biochar requires a high volume of material and incur transport costs, whereas BIOGEMI technology achieved comparable results with a lower volume and faster effectiveness.

Moreover, compared to the use of superabsorbent polymers studied by Li et al. (2025), BIOGEMI improved soil water-holding capacity and plant growth without synthetic inputs or additional environmental costs. Evans et al. (2021) also showed that combining organic materials with superabsorbent polymers enhanced plant growth, but noted the economic and

environmental limitations of such polymers – disadvantages not found in the natural BIOGEMI approach. Similarly, Zhang et al. (2023) investigated the use of silica nanoparticles to improve soil and found increased water retention capacity, but concerns about nanoparticle safety remain an important challenge—risks that BIOGEMI, as a biocompatible compound, does not pose.
Studies by Borhani & Hajehforooshnia (2021) using Plantbac absorbent sheets for establishing Haloxylon seedlings in the saline playa of Sagzi showed that, over time, there was a significant decline in parameters such as height, canopy cover, and seedling survival. This performance drop was attributed to salt accumulation in the root zone, caused by the disruption of capillary water flow, which exacerbated moisture stress and reduced plant growth.
In contrast, the current study – using the bio-based BIOGEMI solution – recorded completely different results: increased chlorophyll levels, higher biomass, and improved RWC. Simultaneously, soil salinity was reduced by 88.6% and organic matter increased by 50%. Unlike the negative impacts of physical barriers such as absorbent sheets – especially in saline soils—BIOGEMI not only improved soil texture and chemistry but also stimulated biological activity, enhanced water uptake, and boosted plant resistance to drought stress. This comparison highlights that in high-salinity and nutrient-poor soils, biological soil amendment methods such as BIOGEMI are more effective than physical solutions like absorbent membranes.

5. Conclusions

The present study demonstrated that the application of the knowledge-based BIOGEMI technology in the desert region of Fesaran, Sagzi Plain, Isfahan, effectively improved the physiological traits of *Haloxylon* plants, enhanced soil properties, and increased plant resistance to environmental stress. The results showed significant increases in chlorophyll a and b indices, fresh and dry biomass of both aerial and underground organs, and improved physical and chemical properties of the soil, including an 88.6% reduction in salinity and a 50% increase in organic matter, along with a 41.6% increase in relative water content (RWC). These findings consistently point to the high efficacy of this technology under desert conditions.
In conclusion, BIOGEMI technology offers numerous advantages over conventional methods such as biochar, synthetic polymers, and nanoparticles, including faster results, lower cost, ease of use, environmental sustainability, and minimal ecological risks. This technology holds significant potential for expansion in desert and semi-arid areas, not only in Iran but also across other arid regions of the world.
Limitations: this was a single-site, two-plot study without plot-level randomization; plot-level replication for soil was limited, and the monitoring window was short. Only the BIOGEMI solution was tested, and key plant-physiology/soil-biology metrics were not measured, restricting generalizability and mechanistic insight.
Recommendations: Conduct multi-site, multi-year randomized block trials with greater replication; evaluate dose–response and compare the solution vs. the compost (and their combination); include deeper soil profiling and standardized EC protocols; add plant-physiology and soil-biology endpoints; and incorporate seedling survival tracking, cost–benefit analysis, and hydrological assessment.

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