Iraqi Journal of Desert Studies 2026, 16 (1): 94-103 **Original Article**

Improving Sugar Beet Seeds Germination Under Salinity Stress Using Natural Biostimulants

Ahmed A. Kandil*, Mohsen A. Badawi , Saleh E. Seadh, Hend S. S. Arafat
Department of Agronomy, Faculty of Agriculture, Mansoura University, Mansoura, Egypt.

Abstract

At the Agronomy Department Laboratory of Seed Testing, Faculty of Agriculture, Mansoura University, Egypt, a lab experiment was conducted throughout October, 2022. This study aimed to improve sugar beet seed germination under salinity stress using selected natural substances. The experiment was conducted as a factorial arrangement in completely randomized design (CRD). Salinity levels (0, 20, 40, 60, 80, 100, and 120 mM of NaCl) comprised the first factor. The second aspect was soaking seed treatments in natural substances (distilled water, 100, 200, and 300 ml l^{-1} of moringa leaf extract "MLE", 75, 150, and 225 ml l^{-1} of algae extract "AE", and 100, 150, and 200 ml l^{-1} of yeast extract "YE"). The control treatment (without salinity stress) or soaking sugar beet seeds in moringa leaf extract (MLE) at a level of 300 ml l^{-1} yielded the highest values of germination percentage, speed of germination index, germination index, co-efficient of germination, mean germination time, energy of germination, and the lowest values of abnormal and rotten seed %. It may be advised to soak seeds in MLE at 300 ml l^{-1} YE at 200 ml l^{-1} or AE at 225 ml l^{-1} for eighteen hours in order to improve germination parameters of the sugar beet Hossam cultivar under salinity stress conditions.

Keywords: Sugar beet, salinity stress, natural Extracts, germination parameters.

تحسين صفات إنبات بنجر السكر باستخدام بعض المواد الطبيعية تحت ظروف الملوحة

أحمد أبو النجا قنديل، محسن عبدالعزيز بدوى، صالح السيد سعده وهند سعد سعد الدين عرفات
قسم المحاصيل، كلية الزراعة، جامعة المنصورة، المنصورة، مصر.

المستخلص

أجريت تجربة معملية بقسم المحاصيل، كلية الزراعة، جامعة المنصورة، مصر، خلال شهر أكتوبر 2022 م، وذلك لدراسة تأثير بعض المواد الطبيعية (بدون نقع، النقع فى الماء المقطر، النقع في مستخلص أوراق المورينجا بتراكيز شملت 100، 200 و300 مل لتر$^{-1}$، النقع في مستخلص الطحالب بتراكيز هي 75، 150 و225 مل لتر$^{-1}$ والنقع في مستخلص الخميرة بتركيزات 100، 150 و200 مل لتر$^{-1}$ لتحسين إنبات بذور بنجر السكر صنف Hossam تحت ظروف الملوحة (0، 20، 40، 60، 80 و 120 ملليمول كلوريد الصوديوم) فى الظروف المعملية. تم إجراء التجربة المعملية في تجربة عاملية في تصميم تام العشوائية (CRD). أدت زيادة مستويات الملوحة من 0 إلى 20، و 40، و 60، و 80، و 120 ملليمول كلوريد الصوديوم إلى انخفاض كبير في النسبة المئوية للإنبات، معدل سرعة الإنبات، معدل الإنبات، معامل الإنبات، متوسط زمن الإنبات، طاقة الإنبات وزيادة النسبة المئوية للبادرات الغير طبيعية والبذور العفنة. نتجت أعلى القيم من صفات النسبة المئوية للإنبات، معدل سرعة الإنبات، معدل الإنبات، معامل الإنبات، متوسط زمن الإنبات، طاقة الإنبات وأقل القيم من صفات النسبة المئوية للبادرات الغير طبيعية والبذور العفنة من بنجر السكر من معاملة المقارنة (بدون إجهاد ملحى) و نقع بذور بنجر السكر في مستخلص أوراق المورينجا بمعدل 300 مل لتر$^{-1}$. لتحسين صفات الإنبات لتقاوى بنجر السكر صنف Hossam تحت ظروف الإجهاد الملحى، يمكن التوصية بنقع البذور لمدة 18 ساعة في مستخلص أوراق المورينجا بمعدل 300 مل لتر$^{-1}$ أو مستخلص الخميرة بمعدل 200 مل لتر$^{-1}$ أو مستخلص الطحالب بمعدل 225 مل لتر$^{-1}$.

Introduction

One of the primary sugar crops in Egypt and many other countries worldwide is the sugar beet (*Beta vulgaris* var. *saccharifera* L.). In agriculture, sugar beets are crucial for the production of numerous other goods in addition to sugar. In Egypt's crop rotation system, sugar beetroot has recently assumed an important, particularly on poor, saline, alkaline, and calcareous soils. Thus, in Egypt, sugar beet has become the first crop for sugar production, hence the total cultivated area in 2024 season reached about 603 319 feddan and the total production exceeded 13.880-million-ton roots with an average of 22.022 t fed^{-1} (FAO, 2026).

Today, one of the most detrimental environmental conditions that restricts crop plant growth and productivity is salinity, which affects about 800 million hectares of the world's land area. Numerous morphological, physiological, and biochemical processes-such as seed germination, plant growth, and the intake of nutrients and water-are impacted by salinity. Sugar beet seed germination and seedling characteristics are impacted by salt stress. One of the sugar beet crop's most susceptible stages to salinity is the germination phase, and salt stress reduces germination and seedling growth. Therefore, applying the right amount of an appropriate hormone to seeds can somewhat mitigate the detrimental effects of high salinity on germination and early growth of seedlings (Munnus, 2002). Abdelraouf (2017) indicated that increasing salt concentration decreased

*Corresponding author.
Email: seseadh04@mans.edu.eg
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the shoot and root height. In many irrigated arid and semi-arid regions of the world, salinity is a growing issue that affects agricultural productivity, according to Moreno *et al.* (2018). The osmotic effect of high concentrations of soluble salts in the root medium reduces water availability; ion toxicity is caused by the buildup of Na+ and Cl; oxidative stress is caused by an excess of reactive oxygen species (ROS); and acute K+ deficiency is caused by massive K+ leakage from depolarized cells. According to Noor-Ullah *et al.* (2018), germination speed and other germination characteristics revealed that the seedling had no resistance to salt. Rates of NaCl-induced salinity more than 9 dSm-1 significantly hindered beet germination. Yang and Guo (2018) indicated that the adaptive responses of plants to salt stress can be grouped into three categories: osmotic stress tolerance, ion exclusion, and tissue tolerance to salinity. Different plant species, genotypes, and cultivars react differently to salinity stress at every stage of growth. The majority of crop species are susceptible to salt stress during the germination and seedling establishment phases of their growth (Feghhenabi *et al.*, 2020 ; Hossain *et al.,* 2021; Shokouhian and Omidi, 2021).

Increased germination, improved germination uniformity, improved seedling establishment, and stimulated vegetative growth in more field crops have all been achieved through the application of the seed soaking approach.

Plant biostimulants, also known as natural substances, are any substance or microorganism that is applied to plants, seeds, or roots with the goal of stimulating their natural processes, improving their ability to absorb nutrients efficiently and withstand biotic stress. The multipurpose *Moringa oleifera* Lam., also known as the "miracle tree," is indigenous to Pakistan and India's sub-Hamaylian region (Shahzad *et al.*, 2013). Because of its tremendous nutritional value, it has many uses and remarkable advantages. Antioxidants, vitamins, minerals, phytonutrients, proteins, and other nutrients abound in the moringa plant. As a result, numerous researchers have emphasized how its leaf extract improves crop germination and growth. Zeatin concentrations in moringa leaves gathered from various parts of the world are considerable, ranging from 5 to 200 µg/g of leaves (El-Award, 2003). Seed priming or soaking with moringa leaf extract is considered to improve germination percentage, growth and development of crops (Semida and Rady, 2014 ; Khan *et al.,* 2017 and Ehtaiwesh and Yarboa, 2020). Because algae extract is organic and biodegradable, it is regarded as a vital nutritional supply for sustainable agriculture, particularly in recently recovered soil. Gibberellins promote lateral growth, and chemical analysis of algae extract has shown the presence of a wide range of plant growth regulators, which are known to boost the establishment and elongation rate of root hairs as well as increase their quantity (Zhang and Ervin, 2004). According to Godlewska *et al.* (2016), polyphenols, micro- and macro-elements, lipid content, and antibacterial qualities were used to describe algal extracts. Seaweed extract had positive effects on plants include early seed germination and establishment as well as resistance to biotic and abiotic stress (Barone *et al.*, 2018 ; Begum *et al.*, 2018 and Puglisi *et al.*, 2020).

Numerous growth chemicals, cytokinins, nutritional elements, and organic compounds can all be found naturally in yeast extract. In addition to being used as a fertilizer for plants, yeast extract is also used to boost soil microbial activity, encourage the quick growth of beneficial microorganisms to increase soil enzyme activity, improve plant resistance (particularly to saline-alkali), stimulate seed enzyme activity, and speed up seed germination (Barnett *et al.*, 1990 and Nagodawithana, 1991). Yeast extract's beneficial effects are mostly ascribed to its ability to make nutrient components available for plants; its macro and micronutrient content, growth regulators, and vitamins encourage the plant to accumulate dry matter (Nemeat Alla *et al.*, 2015 ; Kasim *et al.*, 2017 and Badawi *et al.*, 2020).

This study aimed to investigate the effect of certain natural compounds at different concentrations on improving the germination of sugar beet (cv. Hossam) seeds under salinity stress, as a key manifestation of soil degradation associated with desertification in arid and semi-arid regions.

Materials and Methods

In October 2022, a lab test was conducted in the Agronomy Department Laboratory of Seed Testing, Faculty of Agriculture, Mansoura University, Egypt. This lab experiment's goal was to investigate how different amounts of natural compounds could enhance the germination parameters of the sugar beet Hossam cultivar under salinity stress. The Hossam cultivar is a multigerm sugar beet variety, and annually imported from France by Dakahlia Sugar Company at Bilkas. It is one of short duration cultivars (180-210 days) and recommended to be grown under Egypt conditions.

A factorial experiment with a completely randomized design (CRD) in four replications was used in the lab. Seven salinity levels of sodium chloride (NaCl) were included in the first factor: 0, 20, 40, 60, 80, 100, and 120 mM of NaCl, or no salinity (control treatment).

The second factor included eleven soaking seed treatments in some natural substances at various levels for 18 hours, *i.e.* without soaking (untreated "control treatment"), soaking in distilled water, moringa leaf extract (MLE) at the levels of 100, 200 and 300 ml l^{-1} algae extract (AE) at the levels of 75, 150 and 225 ml/L and yeast extract (YE) at the levels of 100, 150 and 200 ml l^{-1}.

Moringa leaf extract (MLE) was prepared according to Culver *et al.* (2012). Algas extract (AE) in the form of *Spirulina platensis* extract from Wadi El-Natrun, El-Buhira Governorate was scaled up to massive scale at Algal biotechnology Unit, National Research Centre. Yeast extract (YE) as natural biostimulants was prepared by using a technique modified by Spencer *et al.* (1983).

In sterile foam dishes measuring 20 by 30 cm, a random sample of 400 seeds for each treatment were sowed on top filter paper. In accordance with the guidelines of the International Seed Testing Association (ISTA, 2015), four foam-dishes containing 25 seeds each were kept close to one another and evaluated as if they were one 100-seed replication under the environmental conditions of the Laboratory for Seed Testing in the Agronomy Department, Faculty of Agriculture, Mansoura University, Egypt, during the first week of October, 2022. Every day, foam dishes—aside from the control were examined and moistened with a water solution containing varying amounts of NaCl.

The first count of the germinated seeds was determined by counting the number of seeds that had sprouted by the fourth day. The number of seeds that germinated was then tallied every 24 hours until the 14-day germination test was over. According to ISTA (2015), seeds were classified as either nonviable (abnormal, dead, or infected) or germinated (radicle 2 mm long).

Germination parameters:

1. Germination percentage (%) was counted according to the following equation described by ISTA (2015):

$$\text{Germination percentage (\%)} = \frac{\text{Number of normal seedlings}}{\text{Number of total seeds}} \times 100$$

2. Speed germination index (SGI) was calculated by the following formula (ISTA, 2015):

$$\text{SGI} = \frac{\text{No. of germinated grains}}{\text{Days to first count}} + \frac{\dots\dots\dots}{\dots\dots\dots} + \frac{\text{No. of germinated grains}}{\text{Days to final count}}$$

3. Germination index (GI) was calculated according to the following equation (Karim *et al.* 1992):

$$\text{GI} = \frac{\textbf{Germination percentage in each treatment}}{\textbf{Germination percentage in control treatment}}$$

4. Co-efficient of germination (CG) was calculated using the following formula according Copeland (1976):

$$\text{CG} = \frac{100\,(A_1 + A_2 + \dots\dots + A_n)}{A_1 T_1 + A_2 T_2 + \dots\dots\ A_n T_n}$$

Where;

A = Number of seed germinated.

T = Time (days) corresponding to A.

n = No. of days to final count.

5. Mean germination time (MGT) was calculated based on the following equation of Ellis and Roberts (1981):

$$\text{MGT} = \frac{\sum \text{Dn}}{\sum \text{n}}$$

Where (n) is the number of seeds, which were germinated on day, D is number of days counted from the beginning of germination.

6. Energy of germination (EG) was determined as Ruan *et al.* (2002).
7. Abnormal seedlings (%) and rotten seeds (%) were counted according to ISTA (2015).

statistically analysis

Using the Statistix-9 computer software program, the collected data were statistically analyzed using the analysis of variance (ANOVA) technique for the factorial totally randomized design as reported by Gomez and Gomez (1984). Duncan's multiple range tests were used to compare the treatment means at the 5% level of probability, as explained by Duncan (1955).

Results and Discussion

Effect of salinity levels

Significant variations in germination parameters, such as germination percentage (GP), speed germination index (SGI), germination index (GI), co-efficient of germination (CG), mean germination time (MGT), energy of germination (EG), and percentages of abnormal (AS) and rotten seeds (RS), were found among the salinity levels under investigation (0, 20, 40, 60, 80, and 120 mM of NaCl).

In general, raising the salinity levels from 0 to 20, 40, 60, 80, and 120 mM of NaCl dramatically decreased the percentages of sugar beet GP, SG, GI, CG, MGT, and EG while increasing the percentages of AS and RS (Table 1). Salinity stress at a level of 20 mM of NaCl was followed by salinity stress at levels of 40, 60, 80, and 100 mM of NaCl. The control treatment (without salinity stress) yielded the highest values of GP, SG), GI, CG, MGT, EG, and the lowest values of AS and RS percentages of sugar beet. While the greatest salinity level of 120 mM of NaCl produced the highest values of AS and RS percentages of sugar beet, the lowest values of GP, SG, GI, CG, MGT, and EG.

Table 1: Averages of germination percentage, speed germination index (SGI), germination index (GI), co-efficient of germination (CG), mean germination time (MGT), energy of germination (EG), abnormal seedlings and rotten seeds percentages of sugar beet seeds as affected by salinity levels and soaking in some natural substances at various levels as well as their interaction.

Characters / Treatments	Germination percentage (%)	Speed germination index (SGI)	Germination index (GI)	Co-efficient of germination (CG)	Mean germination time (MGT)	Energy of germination (EG)	Abnormal seedlings percentage (%)	Rotten seeds percentage (%)
A. Salinity concentrations:								
0 mM of NaCl	93.90 a	5.57 a	0.987 a	23.37 a	23.84 a	84.81 a	1.00 c	0.52 d
20 mM of NaCl	93.86 a	5.53 ab	0.987 a	22.22 b	23.70 ab	81.00 ab	1.63 c	1.31 cd
40 mM of NaCl	90.68 b	5.38 ab	0.955 b	22.00 b	22.72 bc	80.45 ab	2.27 c	1.40 cd
60 mM of NaCl	89.02 b	5.26 bc	0.937 b	21.80 b	22.52 c	77.63 b	2.63 c	1.68 bc
80 mM of NaCl	81.68 c	4.99 c	0.859 c	21.60 b	20.65 d	76.36 b	3.09 c	2.68 b
100 mM of NaCl	51.45 d	3.61 d	0.529 d	20.56 c	16.00 e	50.18 c	15.90 b	2.72 b
120 mM of NaCl	44.18 e	2.83 e	0.463 e	19.45 d	12.97 f	37.63 d	23.68 a	5.81 a
F. test	*	*	*	*	*	*	*	*
B. Soaking seeds in some natural substances at various levels:								
Without	69.71 e	3.56 d	0.732 f	18.42 b	16.82 e	44.71 c	8.28 a	20.53 a
Distilled water	74.25 d	4.45 c	0.768 ef	21.32 a	18.75 d	67.14 b	8.27 a	3.50 b
Moringa leaf extract (100 ml/L)	78.64 abc	4.86 ab	0.827 abc	21.88 a	20.89 abc	73.00 ab	7.00 ab	0.00 c
Moringa leaf extract (200 ml/L)	80.07 abc	5.00 ab	0.831 abc	22.08 a	21.10 abc	73.85 ab	6.00 ab	0.00 c
Moringa leaf extract (300 ml/L)	82.07 a	5.08 a	0.863 a	22.44 a	21.85 a	76.71 a	5.35 b	0.00 c
Algas extract (75 ml/L)	74.57 d	4.70 bc	0.779 de	21.38 a	19.96 cd	68.00 b	8.14 ab	1.35 c
Algas extract (150 ml/L)	77.21 cd	4.79 abc	0.811 cd	21.40 a	20.17 bc	70.14 ab	8.00 ab	0.00 c
Algas extract (225 ml/L)	80.78 abc	5.01 ab	0.850 abc	22.17 a	21.39 ab	74.14 ab	8.00 ab	0.00 c
Yeast extract (100 ml/L)	78.07 bcd	4.71 bc	0.822 bc	21.87 a	20.53 bc	70.57 ab	7.71 ab	0.00 c
Yeast extract (150 ml/L)	79.00 abc	4.91 ab	0.842 abc	22.03 a	20.92 abc	73.14 ab	6.14 ab	0.00 c
Yeast extract (200 ml/L)	81.71 ab	5.06 ab	0.859 ab	22.28 a	21.39 ab	75.57 a	6.00 ab	0.00 c
F. test	*	*	*	*	*	*	*	*
C. Interaction (F. test):								
A × B	*	*	*	*	*	*	*	*

The germination of sugar beet seeds may be impacted by the decrease in germination parameters brought on by the concentration of salinity stress, either by the toxic effects of Na^{+} and Cl^{-} ions on the germination seeds or by the creation of an osmotic potential external to the seed that prevents water uptake (El-Arqan *et al.*, 2002). These findings are in good accord with those of Shokouhian and Omidi (2021) and Noor-Ullah *et al.* (2018).

Effect of soaking seed treatments in some natural substances:

Average germination percentage (GP), speed germination index (SGI), germination index (GI), co-efficient of germination (CG), mean germination time (MGT), energy of germination (EG), and percentages of abnormal (AS) and rotten seeds (RS) percentages of sugar beet seeds that were significantly affected by soaking seed treatments in different natural substances at different levels for 18 hours (i.e., without soaking (untreated "control treatment"), soaking in distilled water, algas extract (AE) at levels of 75, 200, and 200 ml l^{-1}), and yeast extract (YE) at levels of 100, 200, and 200 ml l^{-1}) (Table 1).

The obtained results clearly showed that soaking sugar beet seeds in 300 ml l^{-1} of moringa leaf extract (MLE) outperformed the other seed treatments in some natural substances in germination parameters, resulting in the lowest values of AS and RS percentages of sugar beet and the highest values of GP, SG, GI, CG, MGT, and EG. After that, sugar beet seeds were soaked in 200 ml/L of yeast extract (YE) (Table 1). Algae extract (AE) at 225 ml l^{-1} moringa leaf extract (MLE) at 200 ml l^{-1} yeast extract (YE) at 150 ml l-1 moringa leaf extract (MLE) at 100 ml l^{-1} yeast extract (YE) at 100 ml l-1 algas extract (AE) at 150 ml l^{-1} algas extract (AE) at 75 ml l^{-1} and distilled water were the arrangement of other investigated soaking seed treatments. On the other hand, sugar beet seeds without soaking (untreated "control treatment") produced the lowest values of germination percentage, speed germination index (SGI), germination index (GI), co-efficient of germination (CG), mean germination time (MGT), energy of germination (EG), and highest percentages of abnormal and rotten seeds.

These outcomes could be explained by the fact that moringa leaf extract is high in minerals, growth hormones, ascorbate, zeatin, antioxidants, amino acids, macro and micronutrients, and other substances that are known to promote growth (Latif and Mohamed, 2016). Because yeast extract stimulates cell division and expansion as well as the creation of proteins and nucleic acids, it may have the desired effect (Wanas, 2002). Additionally, the beneficial effects of algal extract include improving plant efficiency in absorbing nutrients like nitrogen, which is directly related to the concentration of chlorophyll in leaves, and enhancing cell membrane permeability. Furthermore, by slowing the deterioration of chlorophyll, algal extract's cytokinin concentration may contribute to a delay in leaf aging. Furthermore, the balance between photosynthesis and respiration activities in plants is impacted by algal extract as a bio-regulator (Raupp and Oltmanns, 2006). These findings concur with those published by Puglisi *et al.* (2020), Ehtaiwesh and Yarboa (2020), and Badawi *et al.* (2020).

Effect of interaction

The results clearly demonstrated that the interaction between salinity levels and soaking seed treatments in some natural substances at different levels had a significant impact on the germination percentage (GP), speed germination index (SGI), germination index (GI), co-efficient of germination (CG), mean germination time (MGT), energy of germination (EG), and percentages of abnormal (AS) and rotten seeds (RS) percentages of sugar beet (Table 1).

When soaking sugar beet seeds in moringa leaf extract (MLE) at a level of 300 ml l^{-1} without salinity stress (control treatment), the highest values of germination percentage (Fig. 1), speed germination index (Fig. 2), germination index (Fig. 3), co-efficient of germination (Fig. 4), mean germination time (Fig. 5), energy of germination (Fig. 6), and lowest values of abnormal (Fig. 7) and rotten seeds (Fig. 8). However, after the previously mentioned interaction treatment, soaking sugar beet seeds in yeast extract (YE) at a level of 200 ml l^{-1} without salinity stress ranked first. This was followed by soaking sugar beet seeds in algas extract (AE) at 225 ml l^{-1} moringa leaf extract (MLE) at 200 ml l^{-1} yeast extract (YE) at 150 ml l^{-1} and algas extract (AE) at 150 ml l^{-1} under salinity stress of 20 mM NaCl. However, under salinity stress of 120 mM of NaCl, the control treatment (without soaking in natural substances) had the lowest values of germination percentage, speed germination index (SGI), germination index (GI), co-efficient of germination (CG), mean germination time (MGT), energy of germination (EG), and highest values of abnormal and rotten seeds percentages of sugar beet.

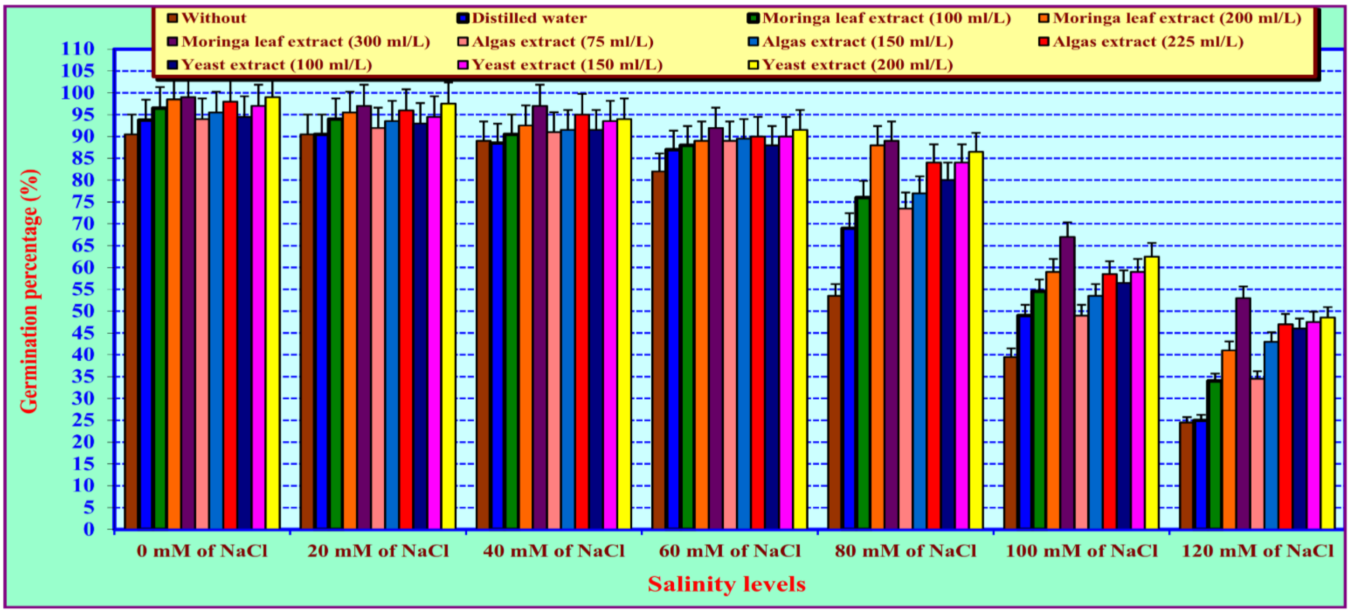

Fig. 1: Averages of **germination percentage (%)** of sugar beet as affected by the interaction between salinity levels and soaking seed treatments in some natural substances at various levels.

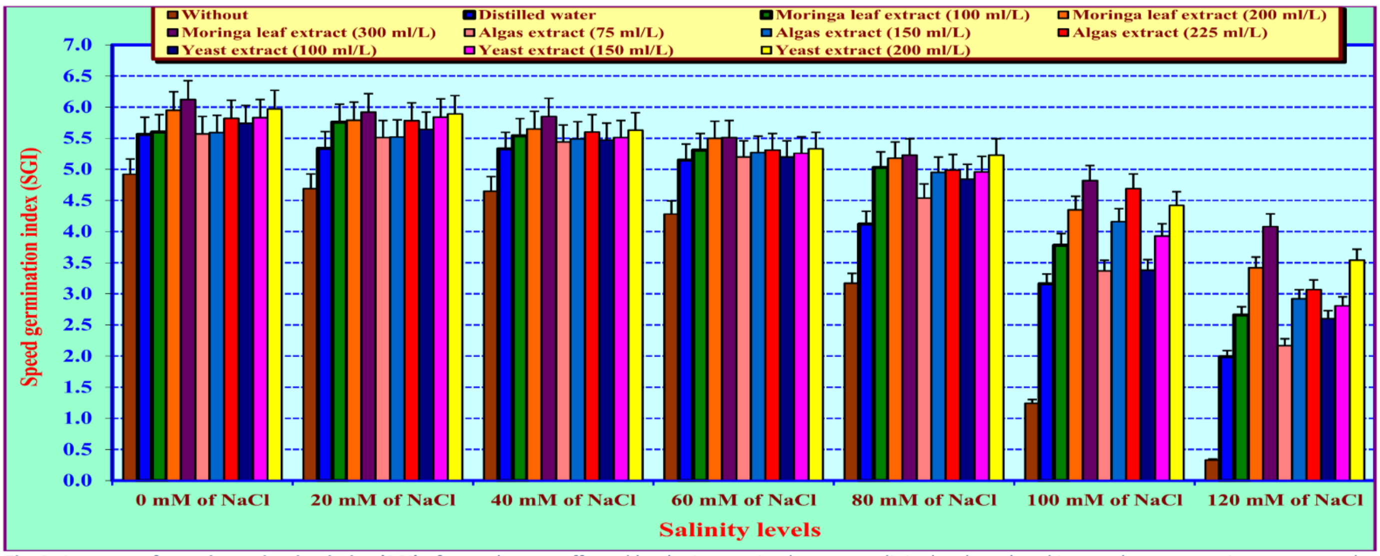

Fig. 2: Averages of **speed germination index (SGI)** of sugar beet as affected by the interaction between salinity levels and soaking seed treatments in some natural substances at various levels.

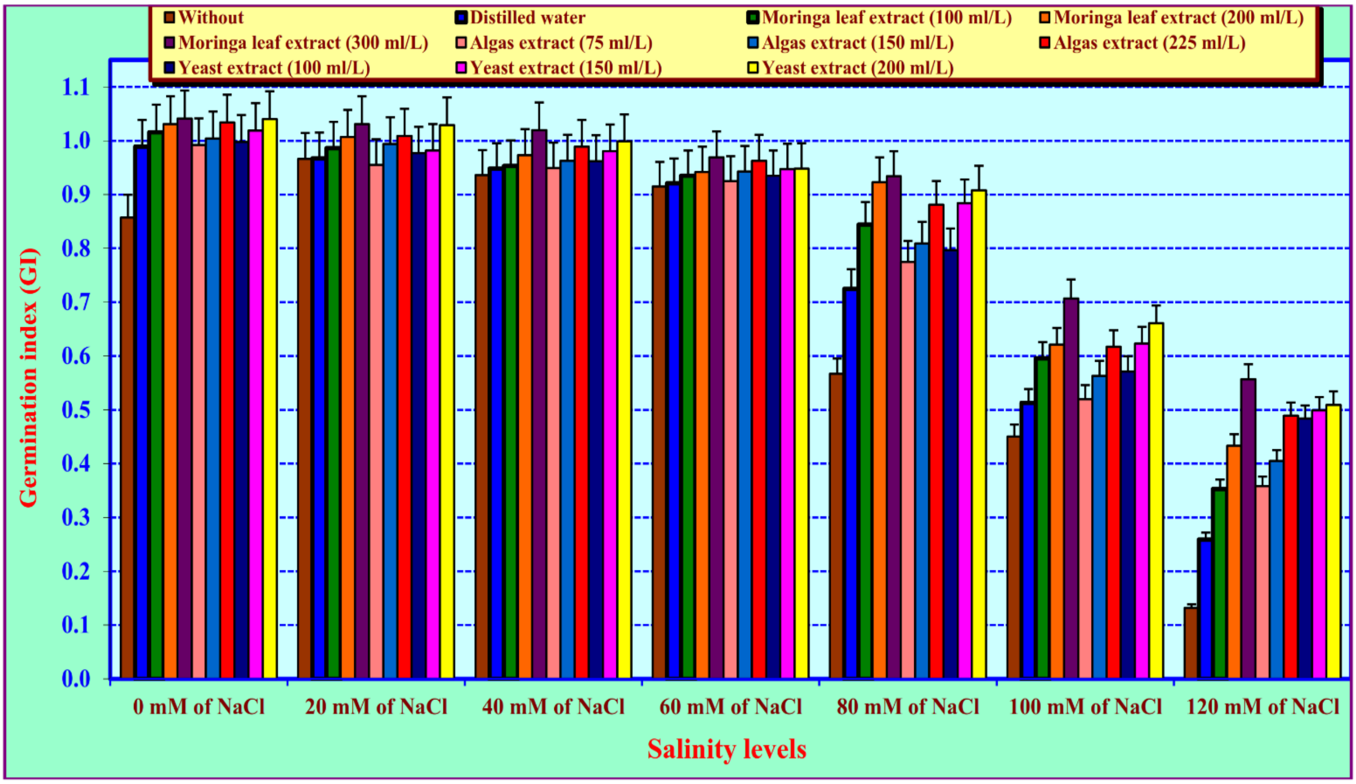

Fig. 3: Averages of **germination index (GI)** of sugar beet as affected by the interaction between salinity levels and soaking seed treatments in some natural substances at various levels.

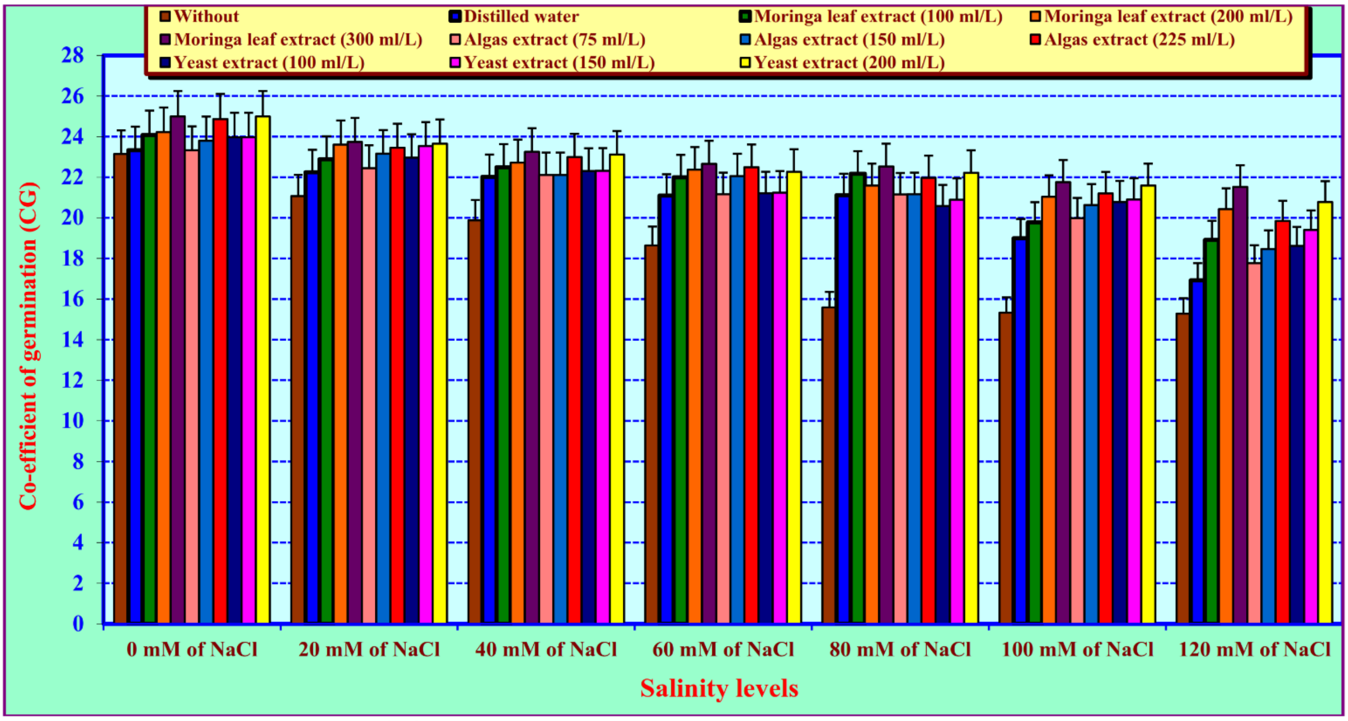

Fig. 4: Averages of **co-efficient of germination (CG)** of sugar beet as affected by the interaction between salinity levels and soaking seed treatments in some natural substances at various levels.

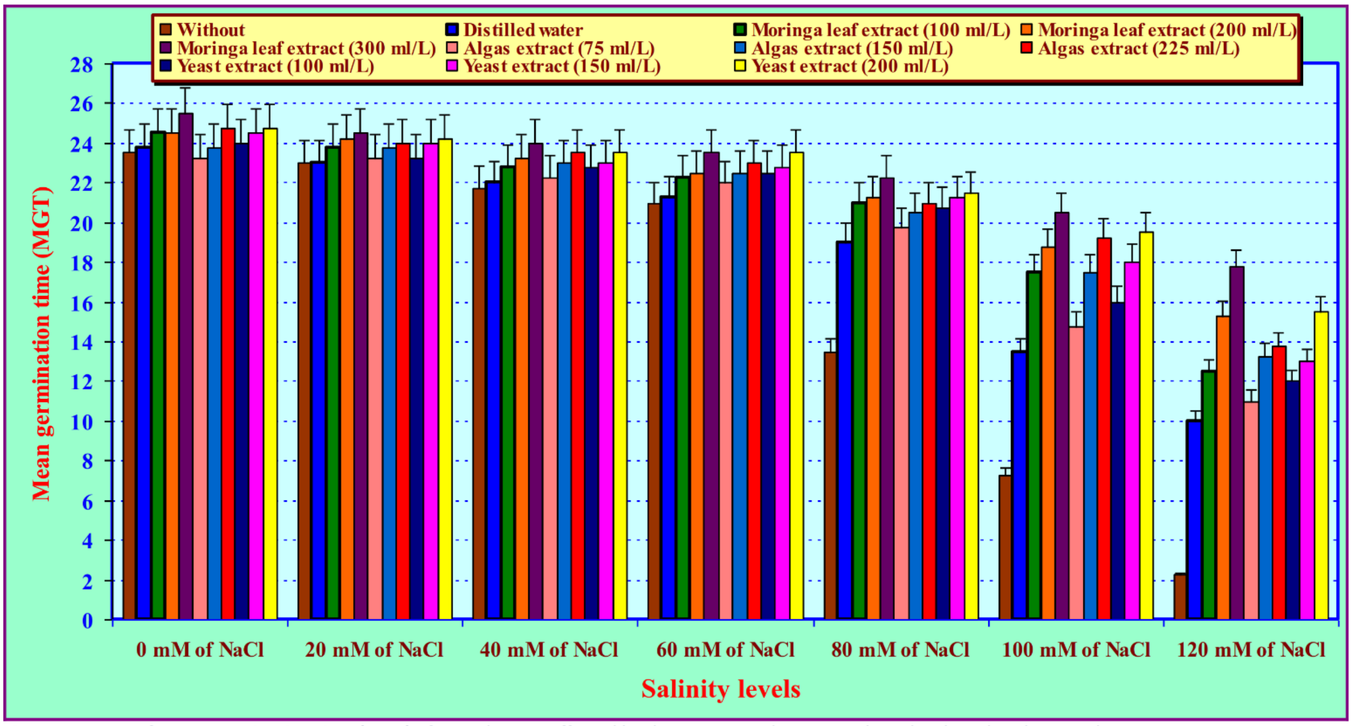

Fig. 5: Averages of **mean germination time (MGT)** of sugar beet as affected by the interaction between salinity levels and soaking seed treatments in some natural substances at various levels.

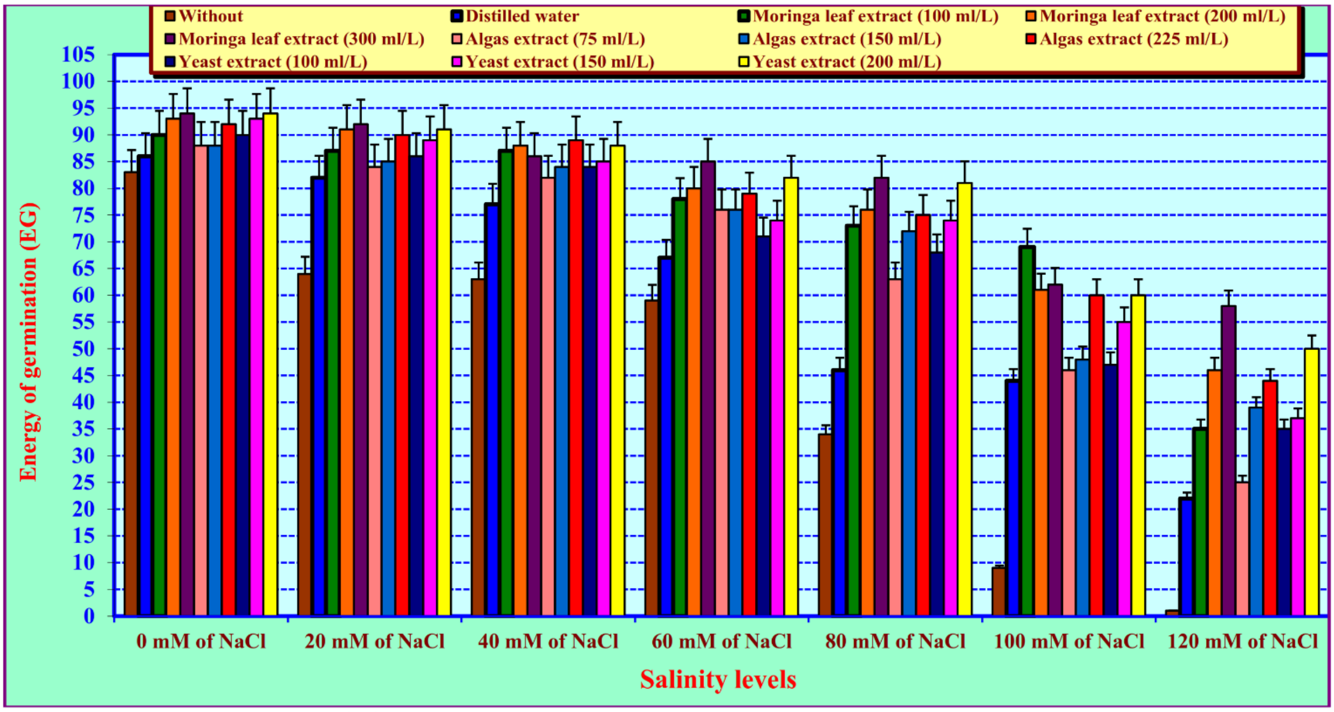

Fig. 6: Averages of **energy of germination (EG)** of sugar beet as affected by the interaction between salinity levels and soaking seed treatments in some natural substances at various levels.

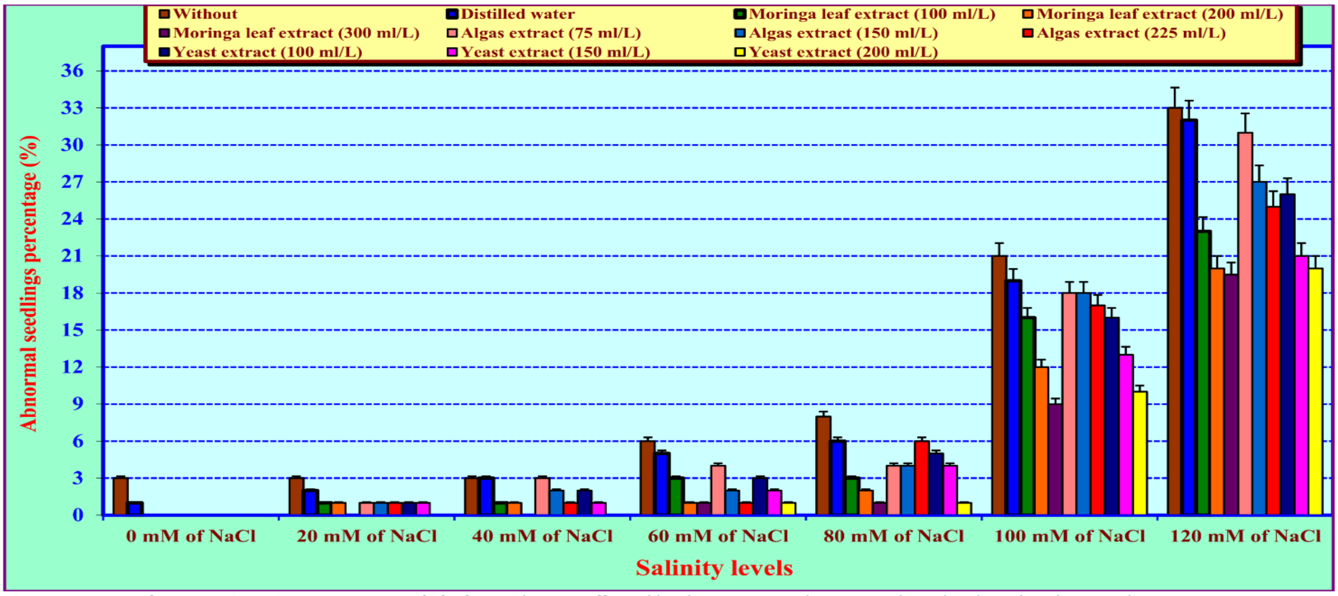

Fig. 7: Averages of **abnormal seedlings percentage (%)** of sugar beet as affected by the interaction between salinity levels and soaking seed treatments in some natural substances at various levels.

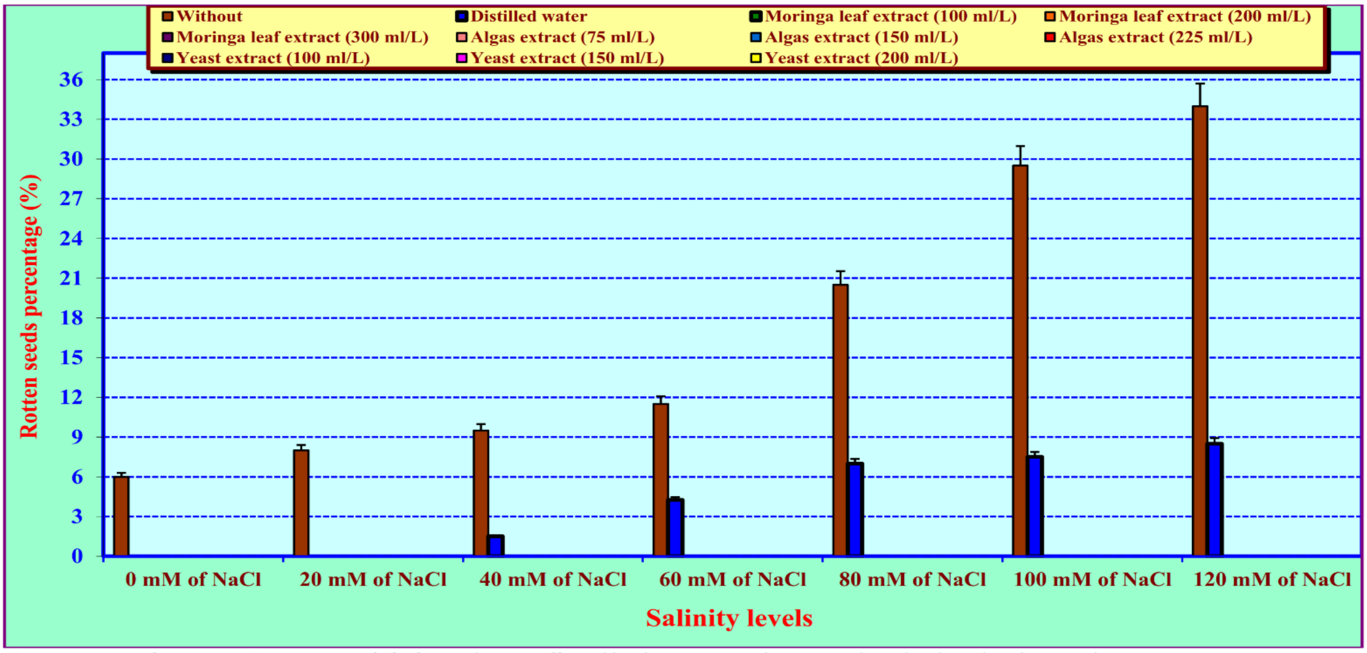

Fig. 8: Averages of **rotten seeds percentage (%)** of sugar beet as affected by the interaction between salinity levels and soaking seed treatments in some natural substances at various levels.

Conclusion

It may be advised to soak seeds in moringa leaf extract (MLE) at a level of 300 ml l^{-1} yeast extract (YE) at a level of 200 ml l^{-1} or algae extract (AE) at a level of 225 ml l^{-1} for 18 hours in order to improve germination parameters of the sugar beet Hossam cultivar under salinity stress conditions.

Sustainability Statement

This study emphasizes the role of natural bio-stimulants in improving sugar beet (*Beta vulgaris* L.) seed germination under salinity stress conditions. The findings support sustainable agricultural practices by promoting environmentally friendly seed enhancement techniques that improve germination performance, increase stress tolerance, and enhance crop establishment in salt-affected soils, thereby contributing to sustainable crop production and soil resource conservation.

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. All data generated or analyzed during this study are included in the published article and its supplementary materials, where applicable.

Author Contributions (CRediT)

First author: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft. Second author: Supervision, Validation, Methodology, Writing – review & editing. Third author: Supervision, Resources, Project administration, Writing – review & editing. Fourth author: Supervision, Validation, Writing – review & editing. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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