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Aqueous Plant Extracts as Eco-Friendly Biostimulants Enhancing Germination and Early Growth of Durum Wheat under Salinity Stress

Imene Brahim[1], Siham Zaaboubi[1]*, Abdelghani Djerah[1], Akram Ben KHemiss[2] and Nacer Salah Neghmouche[3]

[1]*LAPAPEZA Laboratory, Department of Agriculture, Institute of Veterinary and Agricultural Sciences, Batna 1 University, Batna, Algeria, 05000*

[2]*Department of Agriculture, Institute of Veterinary and Agricultural Sciences, Batna 1 University, Batna, Algeria, 05000*

[3]*Department of Chemistry, Faculty of Exact Sciences, University of El Oued, 39000, Algeria*

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Abstract: Salinity is a major factor limiting wheat production in arid and semi-arid regions. This study evaluated the effects of aqueous extracts from *Artemisia herba-alba* (white sagebrush) and *Rosmarinus officinalis* (rosemary) on the germination of durum wheat (*Triticum durum*, cv. Simeto) under saline conditions. Seeds were treated with different extract concentrations and exposed to varying levels of NaCl. Germination parameters, including total germination percentage, corrected germination, daily germination, germination index, germination speed coefficient, and final germination percentage, were recorded over six days. Results showed that rosemary extracts, especially at low doses, significantly improved germination rate and seed vigor, probably due to the antioxidant properties of phenolic compounds present in extract. In contrast, high concentrations of rosemary extracts reduced germination, indicating potential phytotoxicity. Statistical analysis confirmed that both extract type and concentration, as well as salt stress, significantly affected germination traits. These findings suggest that controlled application of rosemary extracts can be an effective, natural, and low-cost strategy to mitigate the negative effects of salinity on durum wheat germination. This approach could contribute to enhancing wheat production in saline-prone areas while minimizing reliance on chemical treatments.

Key words: Durum wheat, salinity stress, germination, rosemary, white sagebrush, plant extracts, antioxidants.

***Correspondence**
Siham Zaaboubi
siham.zaaboubi@univ-batna.dz

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Durum wheat (*Triticum turgidum* subsp. durum) is a staple cereal crop in many Mediterranean and semi-arid regions, valued for its nutritional quality and economic importance. However, its productivity is increasingly constrained by salinity, a major abiotic stress that limits seed germination, seedling establishment, and overall crop yield. Salinity affects more than 20% of irrigated lands worldwide and is expected to intensify due to climate change, inappropriate irrigation practices, and soil degradation (Munns and Gilliham, 2015; Rengasamy, 2010). High concentrations of soluble salts disrupt water uptake, induce osmotic stress, and lead to ion toxicity, ultimately impairing metabolic and physiological processes critical for early plant growth (Zhu, 2016). Conventional approaches to mitigating the effects of soil salinity—such as soil reclamation, breeding for salt-tolerant cultivars, and the application of chemical amendments—are frequently associated with high costs, lengthy development periods, and potential environmental drawbacks (Flowers and Colmer, 2015). In recent years, there has been a growing interest in nature-based solutions that align with sustainable agriculture principles. Among these, plant-derived bio-stimulants have gained attention for their potential to enhance plant resilience under abiotic stress while minimizing ecological impact (du Jardin, 2015; Rouphael and Colla, 2020).

Aqueous extracts of medicinal and aromatic plants are particularly promising due to their rich composition in secondary metabolites such as phenolics, flavonoids, terpenes, and essential oils. These bioactive compounds have been reported to modulate antioxidant defense systems, regulate osmolyte accumulation, and stimulate hormonal pathways, thereby improving germination and early growth under stress conditions (Calvo et al., 2014; Bulgari et al., 2019). White sagebrush (*Artemisia herba-alba*) and rosemary (*Rosmarinus officinalis*) are two species widely distributed in Mediterranean ecosystems and known for their high content of antioxidant and allelopathic compounds (Abd El-Gawad et al., 2018; Boukhatem, 2019). Their aqueous extracts may act as eco-friendly bio-stimulants capable of alleviating salt-induced germination inhibition in cereals.

The present study aims to evaluate the effects of aqueous extracts from *A. herba-alba* and *R. officinalis* on the germination parameters and early growth of durum wheat under salinity stress. By exploring the potential of these plant-based bio-stimulants, this research advances the development of sustainable strategies for cereal cultivation in salt-affected areas, with particular significance for Mediterranean agroecosystems.

Materials and Methods

The experiment was conducted under controlled laboratory conditions at the Institute of Veterinary Sciences and Agronomic Sciences, University of Batna, Algeria. The trial was carried out between 21 April and 6 May 2025, during the spring season. Environmental parameters, including temperature and relative humidity, were monitored daily to ensure consistent experimental conditions. The durum wheat (*Triticum turgidum* subsp. *durum*) cv. Simeto was selected for this study. This variety is well-adapted to the highland agro-ecological zones of northern and eastern Algeria, where it is widely cultivated for its tolerance to moderate drought and suitability for pasta production. Certified seeds were obtained from a local agricultural cooperative and stored under ambient laboratory conditions prior to use.

Two aromatic and medicinal plant species were selected for extract preparation due to their ethnopharmacological relevance and documented bioactivity in antimicrobial, antioxidant, and anti-inflammatory assays. The first species, *Artemisia herba-alba* Asso (locally known as *shih*), is a perennial shrub widely distributed in arid and semi-arid ecosystems of North Africa. It is traditionally used for treating gastrointestinal disorders, respiratory infections, and inflammatory conditions, with its bioactivity largely attributed to sesquiterpene lactones, flavonoids, and essential oils. Samples were collected on 11 November 2024 from the Sabkha region, Ain M'lila (35°52′10″N, 6°29′48″E Oum El Bouaghi, Algeria). The second species, *Rosmarinus officinalis* L. (rosemary), is a perennial aromatic shrub of the Lamiaceae family, known for its culinary use and medicinal properties. Its pharmacological activities—including antimicrobial, antioxidant, and neuroprotective effects—are linked to its high content of phenolic diterpenes (e.g., carnosic acid, carnosol) and rosmarinic acid. Plant material was harvested on 12 November 2024 from the Bouhilef region (35°35′37″N, 6°12′25″E Batna 1, Algeria). Both plant species were taxonomically identified and authenticated by experts from the Botany Department, University of Batna 1. Voucher

Table 1. Experimental treatments

Extract Type	Dilution (dose)	Treatement Code	Salinity Levels	Final Codes
white sagebrush (Artemisia herba-alba)	Low Dose	E11	D0, D1, D2	E11D0, E11D1, E11D2
	Medium Dose	E12	D0, D1, D2	E12D0, E12D1, E12D2
	High Dose	E13	D0, D1, D2	E13D0, E13D1, E13D2
Rosmarinus officinalis (rosemary)	Faible dose	E21	D0, D1, D2	E21D0, E21D1, E21D2
	Moyenne dose	E22	D0, D1, D2	E22D0, E22D1, E22D2
	Forte dose	E23	D0, D1, D2	E23D0, E23D1, E23D2
Control absolute	–	T0	Without extract without NaCl	T0

specimens were deposited in the department herbarium for future studies.

The harvested plants were dried in the shade for two weeks at a temperature below 40°C to preserve the thermolabile bioactive compounds. The dried samples were then finely ground using a mechanical grinder until a homogeneous powder was obtained.

For extraction, 50 g of plant powder was macerated in 500 mL of distilled water preheated to 80°C for 20 minutes to facilitate the release of soluble phytochemicals. The mixture was then stirred at regular intervals for 2 hours 30 minutes and then allowed to settle for 24 hours at 4°C. The supernatant was filtered off using Whatman No. 1 filter paper. The resulting aqueous extracts were stored at 4°C in amber glass bottles until use. From the concentrated extract, three dilutions were prepared: 1 (1:1, v/v), 2 (1:10, v/v), and 3 (1:100, v/v). All dilutions were freshly prepared before application to ensure the stability and reproducibility of the bioactive compounds.

The experiment was set up on April 28, 2025, in the laboratory of the Department of Agricultural Sciences at the University of Batna. The design adopted was a randomized factorial block design with four replicates. Two main factors were studied:

the treatment factor, consisting of aqueous extracts of Artemisia herba-alba (E1) and Rosmarinus officinalis (E2), each applied at three doses (low "1", medium "2", high "3");

The salinity factor was applied at three NaCl concentration levels (D0 = 0%, D1 = 2%, and D2 = 4%). Concentrations are expressed as % (w/v), corresponding to the number of grams of solute dissolved in 100 mL of solution.

An untreated control (seeds watered only with distilled water) was included. A total of 19 experimental treatments were tested. Each treatment was repeated four times, representing 76 Petri dishes each containing 10 seeds, for a total of 760 seeds.

Carefully selected durum wheat seeds (Triticum durum, Simeto variety) (whole and healthy grains) were sterilized in a 1% bleach solution for 10 minutes, then rinsed with distilled water. They were then soaked in the different extract dilutions for 12 hours at room temperature. Germination was carried out in Petri dishes lined with filter paper (10 seeds/dish). After distribution, the seeds were watered daily with 3 mL of saline solution (NaCl) corresponding to their treatment. The controls received the same amount of distilled water. Incubation was carried out at room temperature (22°C).

Germination was monitored daily for six consecutive days. The following quantitative parameters were determined: germination rate (TG), corrected germination (GC), germination reduction percentage (PRG), final germination percentage (%GF), mean daily germination (MJG), germination index (IG), germination rate index (ITG), mean germination time (TM), and coefficient of velocity of germination (CVG). These indices were calculated according to standard seed physiology methodologies to provide an integrated assessment of seed performance under different extract treatments and dilution levels (Table 1 and 2).

Germination parameters were used for regression analysis. Although the regression model occasionally produced predicted values slightly exceeding the biological limits (0–100%), these are statistical artifacts and do not affect the interpretation of overall trends. Data were subjected to a two-way analysis of

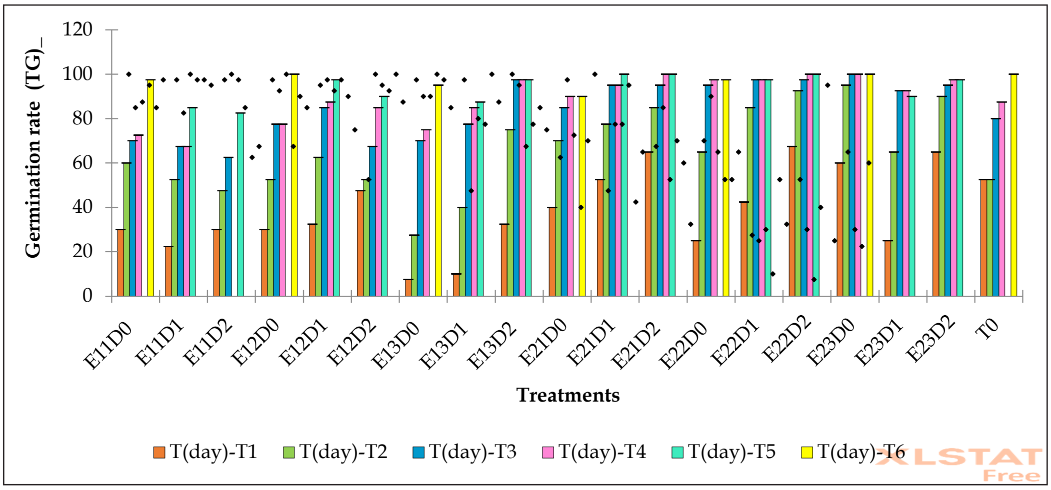

Fig. 1. Germination ratio (TG) of Simeto seeds over six days under different plant extract treatments and dilutions.

variance (ANOVA) using XLSTAT (Addinsoft, Paris, France) and python3.13. Differences between means were considered statistically significant at $p < 0.05$. When appropriate, post-hoc comparisons were performed to identify significant interactions between treatment type and concentration.

Results and Discussion

Germination rate (TG): The germination rate (TG) was significantly influenced by salinity, extract type, dilution level, and incubation duration (Figure 1; Table 3). Across all treatments, TG increased progressively during the first four days, after which values

Table 2. Method of calculating measured parameters

Parameter	Formula	Symbols meaning	Interpretation
Germination rate (TG)	TG = (NGi / S) × 100	NGi: number of germinated seeds until day i; S: total number of seeds sown	Percentage of germinated seeds relative to tested seeds.
Corrected germination (GC) (Smith and Dobrenz, 1987)	GC = 100 × (Nix / Nix)	Nix: seeds germinated at i days under x mM NaCl; Nix: seeds germinated at i days under 0 mM NaCl	Adjusts germination under salt stress relative to the control.
Percentage reduction of germination (PRG)	PRG = 100 × [1 - (Nx / N0)]	Nx: seeds germinated under x mM NaCl; N0: seeds germinated in control (0 mM NaCl)	Measures germination reduction caused by salinity compared to control.
Mean daily germination (MJG) (Osborne *et al*., 1993)	MJG = %GF / X	%GF: final germination percentage; X: day when maximum germination is reached	Gives the average daily germination rate.
Final germination percentage (%GF)	%GF= (Nf / S) × 100	Nf: total germinated seeds at the end (day 6); S: number of tested seeds	Final germination rate at the end of the experiment.
Germination index (IG) (Scott *et al*., 1984)	IG = Σ (Ni × Ti) / S	Ni: number of seeds germinated on day i; Ti: time (days); S: total tested seeds	Evaluates both speed and intensity of germination.
Average germination time (TM) according to Czabator (1962)	TM=∑Ni Ti / ∑Ni	Ni: number of newly germinated seeds at time Ti;	N_{i+1} is the number of seeds germinated between time Ti and T_{i+1}.
Germination speed coefficient (CVG) (Kotowski, 1926)	CVG = 100 × (N1+N2+…+Nx) / (N1T1 + N2T2 + …+ NxTx)	Ni: seeds germinated each day; Ti: corresponding day; x: last day	Measures germination speed (higher CVG = faster germination).

Table 3. Analysis of variance (Germination Rate TG%)

Source	Value (Is it %)	Standard Error	t	Pr > |t|	Lower Bound (95%)	Upper Bound (95%)	Significance Codes for p-Values
Constante	95.079	4.340	21.906	**<0.0001**	86.427	103.731	***
T1	-56.184	2.862	-19.631	**<0,0001**	-61.889	-50.479	***
T2	-29.342	2.862	-10.252	**<0.0001**	-35.047	-23.637	***
T3	-10.395	2.862	-3.632	**0.001**	-16.100	-4.690	***
T4	-6.974	2.862	-2.437	**0.017**	-12.679	-1.268	*
E11D1	-15.500	5.579	-2.778	**0.007**	-26.621	-4.379	**
E11D2	-16.500	5.579	-2.958	**0.004**	-27.621	-5.379	**
E13D0	-19.500	5.579	-3.495	**0.001**	-30.621	-8.379	***
E13D1	-14.500	5.579	-2.599	**0.011**	-25.621	-3.379	*
E21D1	9.500	5.579	1.703	0.093	-1.621	20.621	.
E21D2	14.500	5.579	2.599	**0.011**	3.379	25.621	*
E22D1	9.500	5.579	1.703	0.093	-1.621	20.621	.
E22D2	17.000	5.579	3.047	**0.003**	5.879	28.121	**
E23D0	16.500	5.579	2.958	**0.004**	5.379	27.621	**
E23D1	-1.500	5.579	-0.269	0.789	-12.621	9.621	°
E23D2	14.500	5.579	2.599	**0.011**	3.379	25.621	*
T0	0.000	0.000					

Meaning codes: 0 < *** < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1 < ° < 1

stabilized below 100%. A two-way ANOVA revealed very highly significant (p <0.001) effects of incubation time, treatment, and their interaction (treatment x duration), indicating that the impact of plant extracts varied over time (Fig.1; Table 3). Compared to the control *Rosmarinus officinalis* extract at 1:10 and 1:100 dilutions, which showed positive deviations from the constant term (Table 3), several *Artemisia herba-alba* treatments (e.g., E11D1, E11D2, E13D0) exhibited a significant reduction

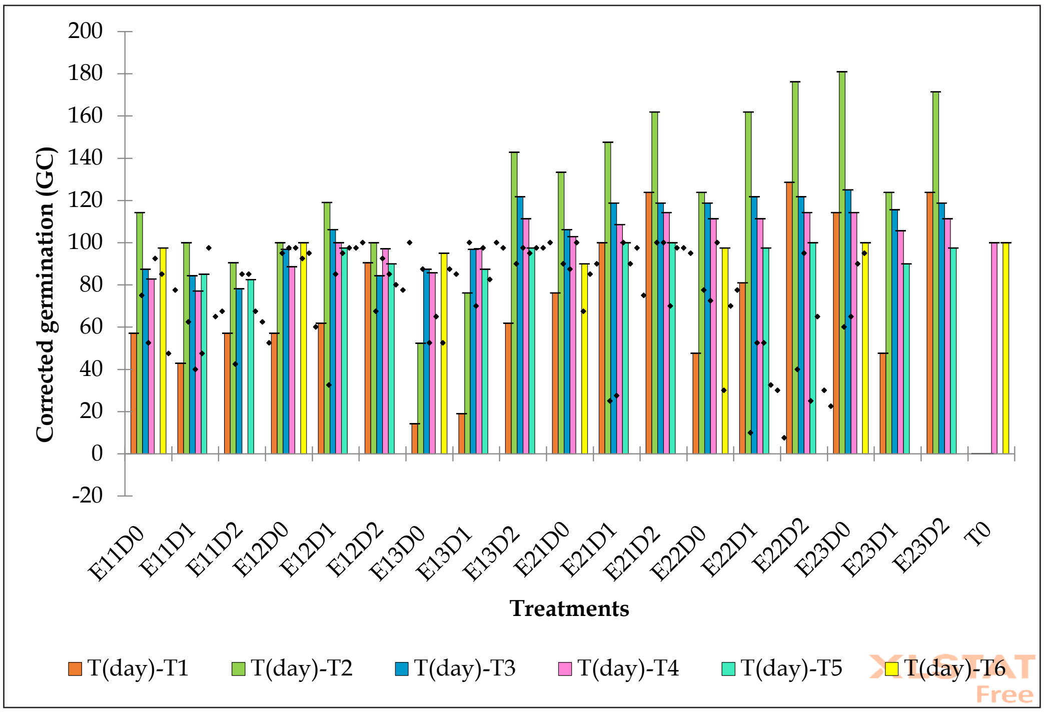

Fig. 2. Corrected germination (GC) of Simeto seeds over six days under different plant extract treatments and dilutions.

Table 4. Two-way ANOVA results for corrected germination (GC) showing the effects of treatment, dose, and their interaction

Source	Value	Standard Error	t	Pr > |t|	Lower Bound (95%)	Upper Bound (95%)	Significance Codes for p-Values
Constante	38.087	10.588	3.597	**0.001**	16.980	59.193	***
T1	-26.328	6.981	-3.771	**0.000**	-40.246	-12.411	***
T2	24.799	6.981	3.552	**0.001**	10.882	38.717	***
E11D0	47.857	13.609	3.516	**0.001**	20.727	74.987	***
E11D1	37.875	13.609	2.783	**0.007**	10.745	65.005	**
E11D2	37.077	13.609	2.724	**0.008**	9.948	64.207	**
E12D0	48.518	13.609	3.565	**0.001**	21.388	75.648	***
E12D1	56.940	13.609	4.184	**<0,0001**	29.811	84.070	***
E12D2	52.399	13.609	3.850	**0.000**	25.269	79.529	***
E13D0	26.976	13.609	1.982	0.051	-0.154	54.106	.
E13D1	35.351	13.609	2.598	**0.011**	8.221	62.481	*
E13D2	67.113	13.609	4.931	**<0,0001**	39.983	94.243	***
E21D0	61.726	13.609	4.536	**<0,0001**	34.596	88.856	***
E21D1	74.988	13.609	5.510	**<0,0001**	47.858	102.118	***
E21D2	83.750	13.609	6.154	**<0,0001**	56.620	110.880	***
E22D0	59.821	13.609	4.396	**<0,0001**	32.692	86.951	***
E22D1	74.732	13.609	5.491	**<0,0001**	47.602	101.862	***
E22D2	88.185	13.609	6.480	**<0,0001**	61.055	115.314	***
E23D0	86.905	13.609	6.386	**<0,0001**	59.775	114.035	***
E23D1	56.554	13.609	4.155	**<0,0001**	29.424	83.683	***
E23D2	84.583	13.609	6.215	**<0,0001**	57.453	111.713	***
T0	0.000	0.000					

Meaning codes: 0 < *** < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1 < ° < 1

in TG, suggesting possible inhibitory effects at higher concentrations.

The stabilization of germination rate after fourth day aligns with the typical saturation phase of seed germination under controlled conditions, where most viable seeds have already emerged. The variation among treatments highlights the importance of

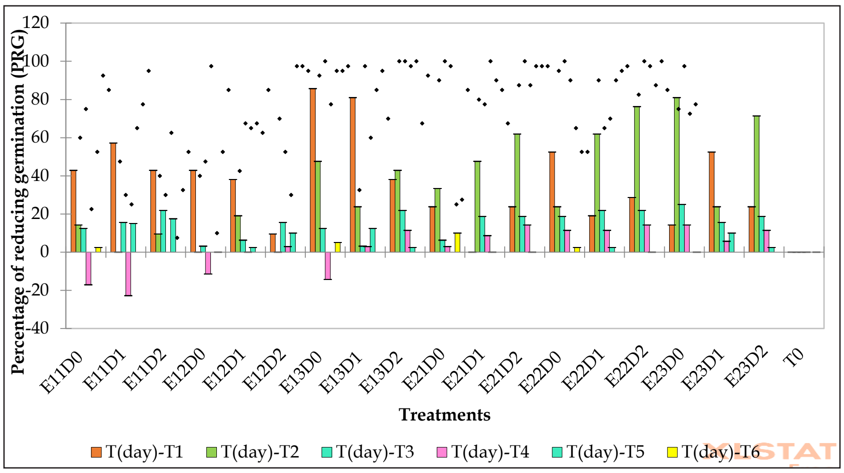

Fig. 3. Percentage of reducing germination (PRG) of Simeto seeds under different plant extract treatments and dilutions over six days.

Table 5. Two-way ANOVA results for PRG showing the effects of treatment, duration, and their interaction.

Source	Value	Standard Error	t	Pr > |t|	Lower Bound (95%)	Upper Bound (95%)	Significance Codes for p-Values
Constante	-13.484	8.622	-1.564	0.122	-30.672	3.704	°
T1	30.589	5.685	5.380	**<0,0001**	19.256	41.922	***
T2	28.584	5.685	5.028	**<0,0001**	17.251	39.917	***
T3	9.638	5.685	1.695	0.094	-1.695	20.972	.
T4	-1.391	5.685	-0.245	0.807	-12.724	9.942	°
E11D2	22.923	11.083	2.068	**0.042**	0.830	45.015	*
E13D0	27.310	11.083	2.464	**0.016**	5.217	49.402	*
E13D1	24.649	11.083	2.224	**0.029**	2.556	46.742	*
E13D2	23.351	11.083	2.107	**0.039**	1.258	45.444	*
E21D2	23.750	11.083	2.143	**0.035**	1.657	45.843	*
E22D0	21.774	11.083	1.965	0.053	-0.319	43.867	.
E22D1	23.351	11.083	2.107	**0.039**	1.258	45.444	*
E22D2	28.185	11.083	2.543	**0.013**	6.092	50.277	*
E23D0	26.905	11.083	2.428	**0.018**	4.812	48.998	*
E23D1	21.506	11.083	1.941	0.056	-0.587	43.599	.
E23D2	25.583	11.083	2.308	**0.024**	3.490	47.676	*
0	0.000	0.000					

Meaning codes : 0 < *** < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1 < ° < 1

both species and dilution in modulating the physiological response of durum wheat under salinity stress.

Corrected Germination (GC) :The corrected germination (GC) of Simeto seeds exhibited a notable increase from the first day, reaching a peak value of 110% on the second day, followed by stabilization around 100% for the remaining period (Figure 2). The progression of GC was generally gradual, regardless of the extract type or dose applied. Statistical analysis revealed highly significant differences ($p < 0.001$) for the effects of duration, treatment, and their interactions (Table 4). Seeds treated with both Artemisia herba-alba and Rosmarinus officinalis extracts demonstrated variable responses depending on the concentration applied. In particular, moderate dilutions (D1 and D2) of rosemary extract (E2) significantly enhanced GC compared to the control, whereas higher concentrations of Artemisia extract (E1) showed less pronounced effects or slight inhibition. These results suggest that the efficacy of plant extracts in enhancing germination is dose-dependent and species-specific, highlighting

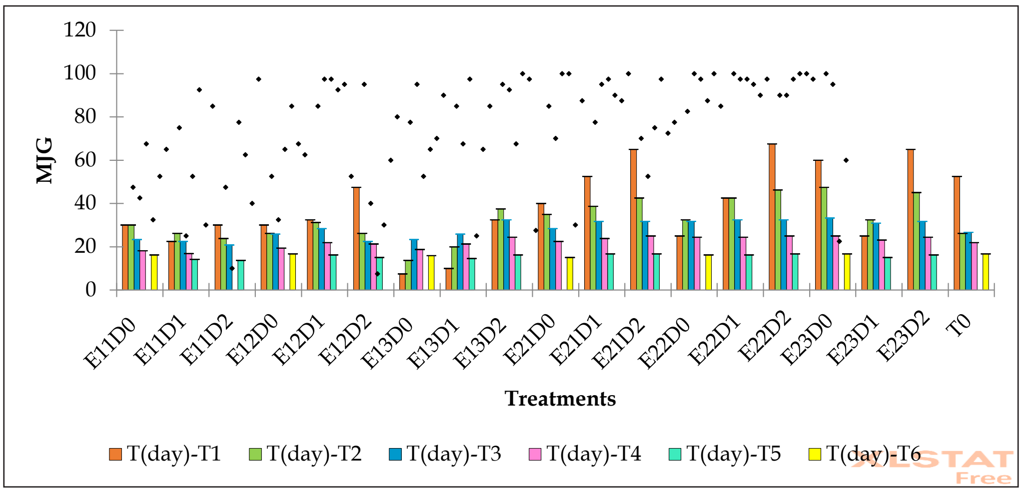

Fig. 4. Daily average germination (MJG) of Simeto seeds under different plant extract treatments and dilutions over six days.

Table 6. Two-way ANOVA results for MJG showing the effects of treatment, duration, and their interaction

Source	Value	Standard Error	t	Pr > |t|	Lower Bound (95%)	Upper Bound (95%)	Significance Codes for p-Values
Constante	17.088	3.781	4.519	**<0,0001**	9.550	24.625	***
T1	22.982	2.493	9.218	**<0,0001**	18.012	27.953	***
T2	16.996	2.493	6.817	**<0,0001**	12.025	21.966	***
T3	12.368	2.493	4.961	**<0,0001**	7.398	17.339	***
T4	6.173	2.493	2.476	**0.016**	1.203	11.143	*
E11D1	-8.333	4.860	-1.715	0.091	-18.022	1.355	.
E13D0	-12.958	4.860	-2.666	**0.009**	-22.647	-3.270	**
E13D1	-10.458	4.860	-2.152	**0.035**	-20.147	-0.770	*
E22D2	8.792	4.860	1.809	0.075	-0.897	18.480	.

Meaning codes: 0 < *** < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1 < ° < 1

the potential of aqueous extracts as eco-friendly biostimulants under saline stress conditions.

Percentage of Reducing Germination (PRG): For Simeto seeds, the percentage of reducing germination (PRG) remained relatively stable at approximately 35% during the first two days and then gradually decreased, approaching zero by the fourth day (Figure 3). Specific treatments, such as E13D0 and E22D2, exhibited distinct effects on PRG, indicating that both the type of extract and its concentration influence germination dynamics.

Statistical analysis demonstrated significant differences ($p < 0.05$) for the effects of duration, treatment, and their interactions (Table 5). Classification based on the data revealed two distinct groups for the duration factor, whereas only one group was identified for the variety (Simeto) and for the treatments. These findings suggest that certain extract treatments can modulate the reduction in germination under saline stress, potentially enhancing early seedling establishment.

Daily Average Germination (MJG): The daily average germination (MJG) for Simeto seeds reached its highest value of 40 on the first day and then gradually decreased over the subsequent days (Figure 4). Although the response varied depending on the type and concentration of plant extract applied, the overall MJG remained moderate throughout the observation period.

Statistical analysis revealed very highly significant differences ($p < 0.01$) for the effects of duration, treatments, and their interactions (Table 6). Certain treatments, such as E13D0 and E13D1, showed a negative effect on MJG, whereas E22D2 exhibited a slight positive effect, highlighting the differential influence of extract type and dilution on daily germination performance. These results underscore the importance of both treatment selection and

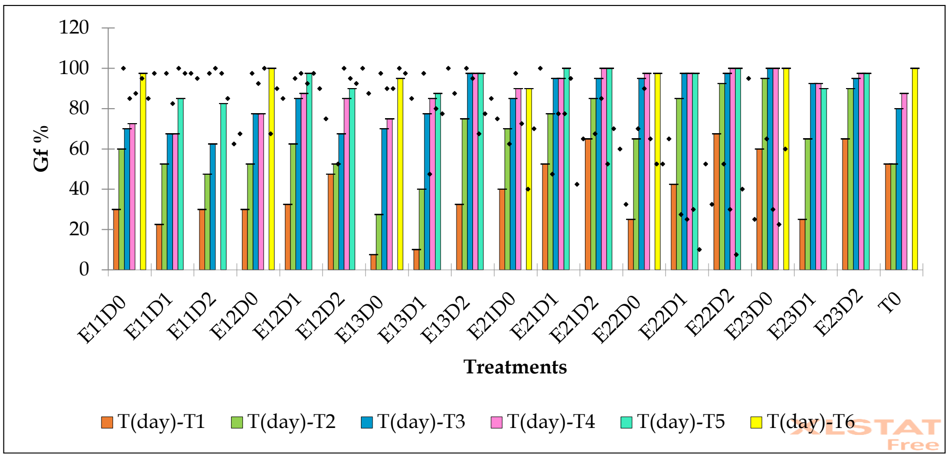

Fig. 5. Final Germination Percentage of Simeto seeds under different plant extract treatments and dilutions over six days.

Table 7. Two-way ANOVA results for %GF showing the effects of treatment, duration, and their interactions

Source	Value	Standard Error	t	Pr > |t|	Lower Bound (95%)	Upper Bound (95%)	Significance Codes for p-Values
Constante	95.079	4.340	21.906	**<0,0001**	86.427	103.731	***
T1	-56.184	2.862	-19.631	**<0,0001**	-61.889	-50.479	***
T2	-29.342	2.862	-10.252	**<0,0001**	-35.047	-23.637	***
T3	-10.395	2.862	-3.632	**0.001**	-16.100	-4.690	***
T4	-6.974	2.862	-2.437	**0.017**	-12.679	-1.268	*
E11D1	-15.500	5.579	-2.778	**0.007**	-26.621	-4.379	**
E11D2	-16.500	5.579	-2.958	**0.004**	-27.621	-5.379	**
E13D0	-19.500	5.579	-3.495	**0.001**	-30.621	-8.379	***
E13D1	-14.500	5.579	-2.599	**0.011**	-25.621	-3.379	*
E21D1	9.500	5.579	1.703	0.093	-1.621	20.621	
E21D2	14.500	5.579	2.599	**0.011**	3.379	25.621	*
E22D1	9.500	5.579	1.703	0.093	-1.621	20.621	.
E22D2	17.000	5.579	3.047	**0.003**	5.879	28.121	**
E23D0	16.500	5.579	2.958	**0.004**	5.379	27.621	**
E23D2	14.500	5.579	2.599	**0.011**	3.379	25.621	*

Meaning codes: 0 < *** < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1 < ° < 1

extract concentration in modulating early germination dynamics under saline stress.

Final Germination Percentage (%GF): The final germination percentage (%GF) of Simeto seeds increased gradually, reaching a stable value on the fourth day, although it remained below 100%, indicating that complete germination was not achieved under the applied treatments. The response varied depending on both the type and concentration of plant extract, highlighting differential effects of the treatments on seed germination (Figure 5).

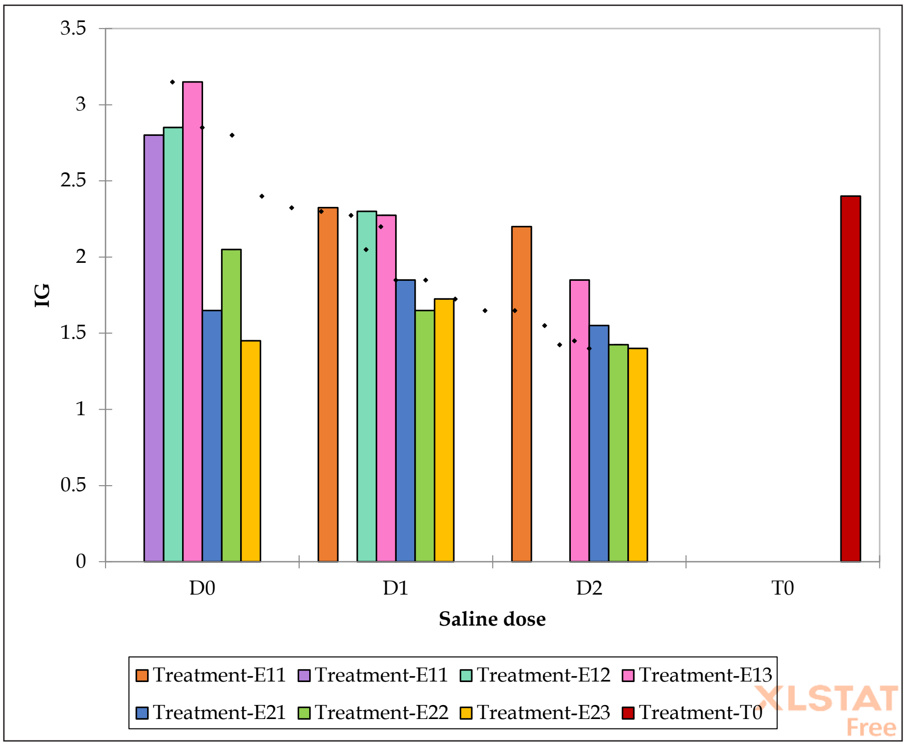

Figure 6. Germination Index of Simeto seeds under different plant extract treatments and dilutions over six days.

Table 8. Two-way ANOVA results for IG showing the effects of treatment, duration, and their interactions

Source	Value	Standard Error	t	Pr > |t|	Lower Bound (95%)	Upper Bound (95%)	Significance Codes for p-Values
Constante	2.119	0.112	18.894	**<0,0001**	1.895	2.343	***
E11D0	0.080	0.144	0.555	0.581	-0.207	0.367	°
E11D1	-0.015	0.144	-0.104	0.917	-0.302	0.272	°
E11D2	-0.040	0.144	-0.277	0.782	-0.327	0.247	°
E12D0	0.090	0.144	0.624	0.534	-0.197	0.377	°
E12D1	-0.020	0.144	-0.139	0.890	-0.307	0.267	°
E12D2	-0.075	0.144	-0.520	0.604	-0.362	0.212	°
E13D0	0.150	0.144	1.041	0.302	-0.137	0.437	°
E13D1	-0.025	0.144	-0.173	0.863	-0.312	0.262	°
E13D2	-0.110	0.144	-0.763	0.448	-0.397	0.177	°
E21D0	-0.150	0.144	-1.041	0.302	-0.437	0.137	°
E21D1	-0.110	0.144	-0.763	0.448	-0.397	0.177	°
E21D2	-0.170	0.144	-1.179	0.242	-0.457	0.117	°
E22D0	-0.070	0.144	-0.486	0.629	-0.357	0.217	°
E22D1	-0.150	0.144	-1.041	0.302	-0.437	0.137	°
E22D2	-0.195	0.144	-1.353	0.180	-0.482	0.092	°
E23D0	-0.190	0.144	-1.318	0.192	-0.477	0.097	°
E23D1	-0.135	0.144	-0.936	0.352	-0.422	0.152	°
E23D2	-0.200	0.144	-1.387	0.170	-0.487	0.087	°
T0	0.000	0.000					

Meaning codes: 0 < *** < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1 < ° < 1

Statistical analysis revealed significant differences ($p < 0.05$) for the effects of duration, treatments, and their interactions (Table 7). The ranking analysis indicated the formation of four distinct groups for duration and six groups for treatments, illustrating the variation in final germination responses depending on extract type and dose. Treatments such as E22D2

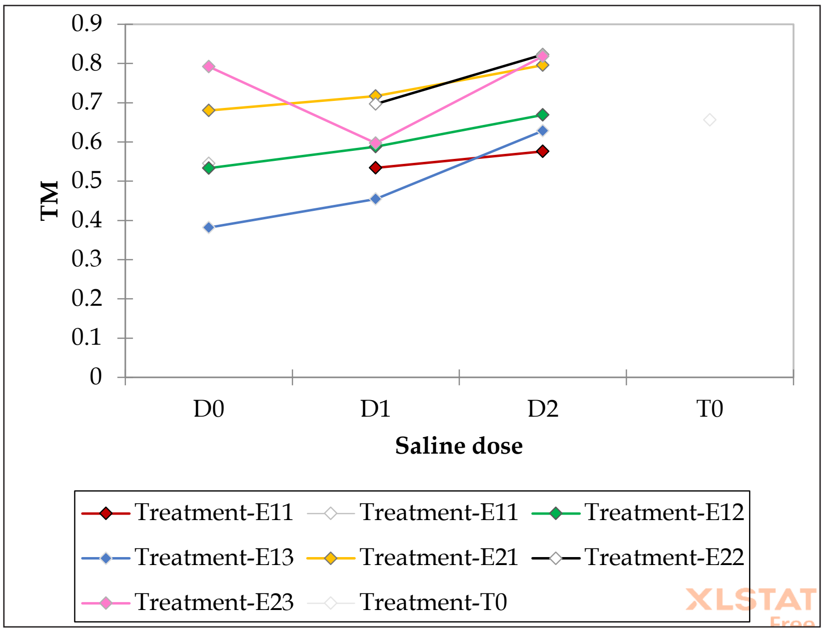

Fig. 7. Average Germination Time (TM) of Simeto seeds under different plant extract treatments and dilutions over six days.

Table 9. Two-way ANOVA results for TM showing the effects of treatment, duration, and their interactions

Source	Value	Standard Error	t	Pr > |t|	Lower Bound (95%)	Upper Bound (95%)	Significance Codes for p-Values
Constante	0.639	0.027	23.698	**<0,0001**	0.585	0.693	***
E11D0	-0.022	0.035	-0.643	0.522	-0.091	0.047	°
E11D1	-0.024	0.035	-0.704	0.484	-0.093	0.045	°
E11D2	-0.016	0.035	-0.465	0.644	-0.085	0.053	°
E12D0	-0.025	0.035	-0.709	0.480	-0.094	0.044	°
E12D1	-0.014	0.035	-0.396	0.693	-0.083	0.055	°
E12D2	0.003	0.035	0.073	0.942	-0.067	0.072	°
E13D0	-0.055	0.035	-1.585	0.117	-0.124	0.014	°
E13D1	-0.040	0.035	-1.163	0.249	-0.109	0.029	°
E13D2	-0.006	0.035	-0.162	0.872	-0.075	0.063	°
E21D0	0.005	0.035	0.140	0.889	-0.064	0.074	°
E21D1	0.012	0.035	0.349	0.728	-0.057	0.081	°
E21D2	0.028	0.035	0.806	0.423	-0.041	0.097	°
E22D0	-0.017	0.035	-0.495	0.622	-0.086	0.052	°
E22D1	0.008	0.035	0.233	0.817	-0.061	0.077	°
E22D2	0.033	0.035	0.962	0.339	-0.036	0.102	°
E23D0	0.027	0.035	0.782	0.437	-0.042	0.096	°
E23D1	-0.012	0.035	-0.341	0.734	-0.081	0.057	°
E23D2	0.032	0.035	0.936	0.353	-0.037	0.102	°

*Meaning codes: 0 < *** < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1 < ° < 1*

and E23D0 were among the most effective, while certain E1 treatments showed reduced germination percentages.

Germination Index (IG): During the first three days, no germination was observed for Simeto seeds. From the fourth day, the germination index (IG) increased progressively, reaching a maximum value of 2.1 on the sixth day. Among the treatments, E13D0 exhibited the highest IG peak, indicating a slightly enhanced effect on germination progress compared to other treatments (Figure 6). Statistical analysis revealed that the germination index was significantly affected by duration ($p < 0.001$), whereas the type and dose of plant extracts did

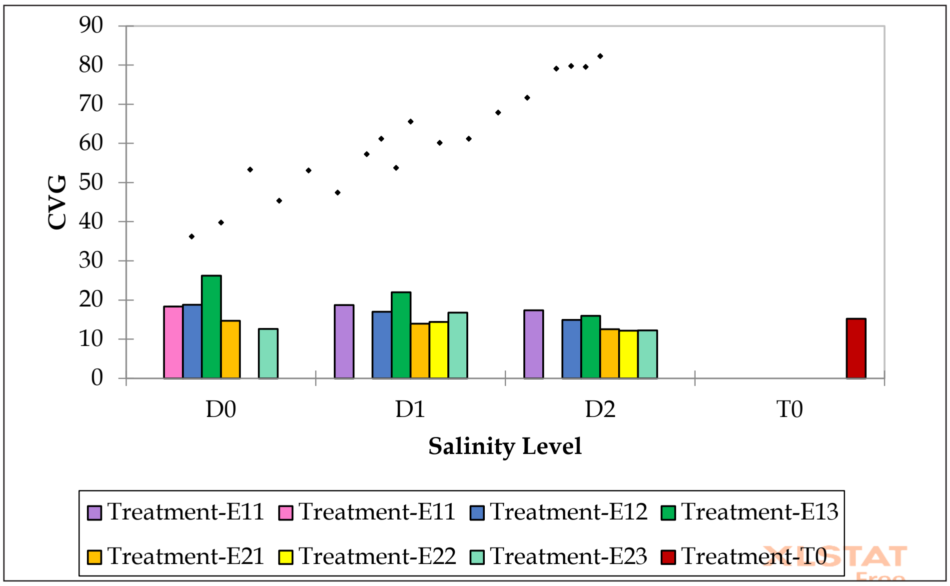

Fig. 8. Germination Speed Coefficient (CVG) of Simeto seeds under different plant extract treatments and dilutions over six days.

Table 10. Two-way ANOVA results for CVG showing the effects of treatment, duration, and their interactions

Source	Value	Standard Error	t	Pr > |t|	Lower Bound (95%)	Upper Bound (95%)	Significance Codes for p-Values
Constante	16.157	0.780	20.721	**<0.0001**	14.603	17.711	***
E11D0	0.623	1.002	0.622	0.536	-1.375	2.621	°
E11D1	0.696	1.002	0.694	0.490	-1.302	2.693	°
E11D2	0.426	1.002	0.425	0.672	-1.572	2.424	°
E12D0	0.702	1.002	0.701	0.486	-1.296	2.700	°
E12D1	0.356	1.002	0.355	0.723	-1.642	2.354	°
E12D2	-0.058	1.002	-0.058	0.954	-2.056	1.940	°
E13D0	2.194	1.002	2.189	**0.032**	0.196	4.192	*
E13D1	1.350	1.002	1.347	0.182	-0.648	3.348	°
E13D2	0.136	1.002	0.136	0.892	-1.862	2.134	°
E21D0	-0.109	1.002	-0.109	0.914	-2.107	1.889	°
E21D1	-0.257	1.002	-0.256	0.798	-2.255	1.741	°
E21D2	-0.535	1.002	-0.533	0.595	-2.533	1.463	°
E22D0	0.458	1.002	0.457	0.649	-1.540	2.456	°
E22D1	-0.176	1.002	-0.176	0.861	-2.174	1.822	°
E22D2	-0.617	1.002	-0.616	0.540	-2.615	1.381	°
E23D0	-0.521	1.002	-0.520	0.605	-2.519	1.477	°
E23D1	0.301	1.002	0.301	0.765	-1.697	2.299	°
E23D2	-0.604	1.002	-0.602	0.549	-2.602	1.394	°
T0	0.000	0.000					

Meaning codes: 0 < *** < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1 < ° < 1

not have a significant impact (Table 8). These results suggest that the temporal factor plays a primary role in IG development, while the treatments applied have only minor or non-significant effects.

Average Germination Time (TM): No germination was observed during the first three days. From the fourth day, the average germination time (TM) increased gradually, reflecting progressive germination. Simeto exhibited moderate TM progression, indicating a relatively early germination pattern (Figure 8). Statistical analysis showed that the duration significantly influenced TM ($p < 0.001$), whereas the type and dose of plant extracts did not produce significant differences (Table 8). These findings suggest that the temporal factor is the primary determinant of germination timing, while treatments have minimal impact on the average germination time (Fig. 7 and Table 9).

Germination Speed Coefficient (CVG) :The germination speed coefficient (CVG) remained low and stable during the first three days. From the fourth day, CVG increased for Simeto, indicating a gradual acceleration of germination. The applied plant extracts influenced the germination rhythm, with certain treatments such as E13D0 showing a noticeable effect (Figure 8). Statistical analysis revealed highly significant differences for the duration, treatments, and their interactions ($p < 0.05$), confirming that both temporal and treatment factors modulate the speed of germination (Table 10).

The germination behavior of durum wheat (*Triticum durum* var. Simeto) under saline stress was markedly influenced by both the type and concentration of plant extracts. Analysis of germination rate (TG) revealed a progressive decrease with increasing NaCl concentrations, highlighting a clear inhibitory effect of salinity. This reduction can be attributed to impaired water uptake during seed imbibition, disruption of enzymatic activity responsible for mobilizing seed reserves, and elevated oxidative stress, consistent with findings in chickpea and rice (Bewley and Black, 1994; Gill and Tuteja, 2010; Kaya and al., 2008; Siti Aishah and al., 2010).

Corrected germination (GC) showed a rapid initial increase followed by stabilization, reflecting the influence of both duration and treatment. Low-dose rosemary extracts (E21), especially the E21D2 treatment, significantly enhanced GC compared with control and other treatments, demonstrating a stimulatory effect on germination under moderate salinity. Similarly, E23D2 and E21D1 also improved GC, suggesting that rosemary extracts can mitigate salt-induced inhibition. This beneficial effect is likely due to the high content of antioxidant compounds in rosemary, including rosmarinic acid, flavonoids, and phenolic diterpenes, which can scavenge reactive oxygen species and protect enzymatic systems involved in germination (Mehmet and al., 2013; Pintore and al., 2002; Bendif and al., 2017; Akinmoladun and al., 2014; Ben Mrid and al., 2021).

Percentage of reducing germination (PRG) and daily average germination (MJG) indicated a gradual decline over time under salinity, reflecting delayed and slower germination. However, treatments with rosemary maintained higher PRG and MJG values, suggesting that these extracts support sustained germination activity and reduce stress-induced delays. In contrast, high-dose white sagebrush (E13), particularly E13D0, exhibited inhibitory effects, likely due to phytotoxic compounds such as phenolics and sesquiterpene lactones, which are known to disrupt cellular division and elongation (Zeiger, 2002; Bora and Sharma, 2011; Araniti and al., 2013).

Final germination percentage (%GF) analysis confirmed that salinity reduces maximum germination potential, with values below 100% across all treatments. Nevertheless, low-dose rosemary treatments (E21D2, E23D2) recorded the highest %GF, reinforcing the role of antioxidants in alleviating salinity stress. Treatments with high concentrations of white sagebrush caused lower %GF, underlining the importance of careful dosage.

Germination index (IG) and germination speed coefficient (CVG) further revealed the dynamic effect of extracts over time. While no significant differences were observed for IG with treatment, the peak values observed in E13D0 suggest complex interactions between extract type and germination timing. The CVG showed an increase from the fourth day under rosemary treatments, highlighting an acceleration in germination rate compared to control or high-dose sagebrush treatments.

Average time of germination (TM) indicated that germination onset was moderately early for Simeto, with significant differences between days but no notable effects of treatments on TM, suggesting that extracts primarily modulate the rate and vigor rather than the initiation time.

Overall, statistical analyses demonstrated highly significant effects of both treatment and duration on germination parameters. Low-dose rosemary extracts consistently improved germination rate, vigor, and speed under saline stress, whereas high-dose white sagebrush exerted inhibitory effects. These results emphasize the potential of controlled application of plant extracts as a natural, cost-effective, and sustainable strategy to enhance durum wheat germination in saline conditions typical of arid and semi-arid environments (Ashraf and Foolad, 2007; Munns and Tester, 2008).

Conclusion

This study evaluated the effects of *Artemisia herba-alba* (white sagebrush) and *Rosmarinus officinalis* (rosemary) extracts on the germination performance of durum wheat (*Triticum durum*, Simeto variety) under saline stress, a critical limitation in arid and semi-arid regions of Algeria. The findings revealed that rosemary extracts, particularly at low concentrations, significantly improved both germination rate and seed vigor. This beneficial effect is likely linked to the high antioxidant content of rosemary, which enhances the scavenging of reactive oxygen species and supports the activity of enzymes involved in seed reserve mobilization during germination.

Conversely, high concentrations of white sagebrush extracts inhibited germination, indicating potential phytotoxic effects due to elevated levels of phenolic compounds and sesquiterpene lactones. These results emphasize the necessity of carefully controlling extract dosages to maximize positive outcomes while minimizing inhibitory effects.

Overall, the controlled application of plant extracts offers a natural, cost-effective, and sustainable strategy to mitigate salinity-induced stress in durum wheat. Further studies are required to optimize extract concentrations, elucidate underlying physiological mechanisms, and develop practical agronomic guidelines for improving cereal crop performance in high-salinity environments.

Acknowledgments:

The authors

Author Contributions

Conceptualization and supervision were carried out by Siham Zaaboubi. Methodology and experimental work were performed by Imene Brahim, Abdelghani Djerah, Hiba Bouzid, and Manar Agoudjil. Data analysis and interpretation were conducted by Imene Brahim and Abdelghani Djerah. Writing of the original draft was carried out by Imene Brahim and Hiba Bouzid, while review and editing were performed by Siham Zaaboubi and Manar Agoudjil. All authors have read and approved the final version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest related to the content of this article.

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Ethics Approval

Not applicable. The study did not involve human participants, animals, or sensitive data requiring ethical approval.

Consent to Participate

Not applicable.

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