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Synergistic Effects of Seaweed Extract Concentrations and Nitrogen Fertilization Levels on Growth and Yield of Wheat (Triticum aestivum L.) under Semi-Arid Conditions

Alham Mohamed Hassan[1*], Hudi Mohammed Omar[2], Wajdi Aissa Mohammed[3]
[1,2,3]Department of Crop Science, Faculty of Agriculture, Omar Al -Mukhtar, Libya

التأثيرات التآزرية لتركيزات مستخلص الطحالب ومستويات التسميد النيتروجيني على نمو وإنتاجية القمح (*Triticum aestivum L*) تحت الظروف شبه الجافة

الهام محمد حسن[1*]، هدى محمد عمر[2]، وجدي عيسى محمد[3]
[1,2,3]قسم المحاصيل، كلية الزراعة، جامعة عمر المختار، البيضاء، ليبيا

*Corresponding author: *elham.hassn@omu.edu.ly*

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Abstract:
Optimizing nitrogen (N) fertilization is critical for wheat productivity, but challenges regarding nutrient use efficiency persist. Biostimulants, such as seaweed extract (SWE), offer a promising strategy to enhance crop performance. This study investigated the synergistic effects of SWE applied as a seed treatment (coating and priming) and varying N levels (0, 60, 120, and 180 kg N/ha) on the growth, yield, and physiological efficiency of wheat under semi-arid conditions. A split-plot field experiment was conducted where main plots were seed treatments and sub-plots were N levels. Results revealed a significant synergistic interaction ($P < 0.05$) between SWE application and N fertilization, enhancing final grain yield by up to 36% in the priming treatment compared to the control. This yield increase was primarily attributed to a significant improvement in key yield components, including the number of spikes per m², grains per spike, and thousand-kernel weight. We conclude that integrating SWE seed priming with optimized N fertilization (120–180 kg N/ha) is a potent strategy to enhance wheat productivity. This synergy appears to be driven by an improvement in the plant's Nitrogen Use Efficiency (NUE) and a favorable modulation of yield component trade-offs.

Keywords: Triticum Aestivum, Biostimulants, Seaweed Extract, Nitrogen Use Efficiency (NUE), Synergistic Effect, Yield Components.

الملخص
يُعتبر تحسين التسميد النيتروجيني *(N)* من العوامل الأساسية لزيادة إنتاجية القمح، إلا أن تحديات كفاءة استخدام العناصر الغذائية ما تزال قائمة. تقدم المنشطات الحيوية مثل مستخلص الأعشاب البحرية*(SWE)* ، حلاً واعدًا لتعزيز أداء المحاصيل. تهدف هذه الدراسة إلى تقييم التأثير التآزري لمعالجة بذور القمح بمستخلص الأعشاب البحرية من خلال طريقتين، هما النقع وتغليف البذور، إلى جانب تطبيق مستويات مختلفة من التسميد النيتروجيني (0، 60، 120، و180 كجم/هكتار)، على نمو وإنتاجية وكفاءة القمح الفسيولوجية تحت الظروف شبه الجافة. أجريت التجربة الحقلية باستخدام تصميم القطاعات المنشقة مرة واحدة، حيث مثلت معالجة البذور القطع الرئيسية ومستويات النيتروجين القطع الفرعية. أظهرت النتائج وجود تفاعل تآزري معنوي *(P < 0.05)* بين تطبيق مستخلص الأعشاب البحرية والتسميد النيتروجيني، ما أدى إلى زيادة في إنتاجية الحبوب تصل إلى 36% في حالة النقع مقارنةً بالمعاملة الضابطة. تعزى هذه الزيادة بشكل رئيسي إلى تحسن ملموس في مكونات المحصول الأساسية، مثل عدد السنابل في المتر المربع، وعدد الحبوب في السنبلة، ووزن الألف حبة. تُخلص الدراسة إلى أن دمج معالجة نقع البذور بمستخلص الأعشاب البحرية مع التسميد النيتروجيني الأمثل (120-180 كجم/هكتار) يمثل استراتيجية فعالة لتعزيز إنتاجية القمح. ويبدو أن هذا التآزر يعود إلى تحسين كفاءة استخدام النيتروجين *(NUE)* في النبات وتعديل إيجابي في التوازن بين مكونات المحصول.

الكلمات المفتاحية: القمح، المنشطات الحيوية، مستخلص الأعشاب البحرية، كفاءة استخدام النيتروجين*(NUE)* ، التأثير التآزري، مكونات المحصول.

Introduction

Wheat (Triticum aestivum L.) is central to food security across North Africa and is a cornerstone of the daily diet in Libya. However, domestic wheat production faces persistent and formidable challenges. Declining rainfall, soil degradation, and socio-economic instability have led to a sharp reduction in both cultivated area and total output. According to recent [1], the area planted with wheat in Libya has contracted to less than 100,000 hectares, with production plummeting to approximately 90,000 tonnes, far below national demand. With per capita wheat consumption steadily rising, the country now imports over 90% of its needs, leaving it highly vulnerable to global market volatility and supply chain disruptions.

Similar patterns are evident throughout North Africa, where Morocco, Algeria, Tunisia, and Egypt collectively sow nearly 5.5 million hectares of wheat [2]. Yet, much of this land remains rainfed, resulting in low and inconsistent yields, often below 2 tonnes per hectare, except in irrigated systems such as those in Egypt, where production can exceed 5 tonnes per hectare [3]. As the impacts of climate change intensify, the regional wheat deficit continues to widen, making the pursuit of sustainable agricultural solutions increasingly urgent.

In recent years, applying biostimulants as seed treatments has emerged as a highly efficient strategy to enhance early crop establishment and resilience. Research consistently demonstrates that seed priming or coating with seaweed extracts can significantly improve germination rates, promote a more robust root architecture, and enhance seedling vigor, which are critical for stand establishment under stressful semi-arid conditions [4].

Furthermore, the integrated use of seaweed biostimulants with nitrogen fertilizers has shown considerable promise in improving nutrient use efficiency (NUE), a key goal for sustainable agriculture. For instance, recent studies on cereals have experimentally confirmed this synergy, demonstrating that seaweed-based biostimulants can significantly increase NUE, allowing for reduced fertilizer inputs while maintaining high productivity [5]. This synergy may arise from SWE-induced enhancement of root architecture, which increases the soil volume explored for nutrient uptake, or by upregulating the activity of nitrogen-metabolizing enzymes within the plant.

Despite these advances, a significant research gap exists regarding the performance of such integrated practices under the specific agro-environmental conditions of Libya's semi-arid regions. Understanding the interactive effects of SWE seed treatments and nitrogen fertilization on wheat performance is essential for developing adaptive management strategies suitable for local farmers.
Therefore, this study aims to:

- Evaluate the efficacy of different seaweed extract application methods (seed coating vs. seed priming) on wheat growth, yield, and yield components.
- Quantify the interactive response of wheat to integrated management of seaweed extract seed treatments and varying nitrogen levels.
- Elucidate the underlying physiological mechanisms, such as resource partitioning efficiency (e.g., Harvest Index), that contribute to improved productivity.

The outcomes are expected to provide valuable insights for enhancing wheat production systems in Libya and similar regions, helping to bridge the gap between current outputs and food security needs.

Material and methods

Experimental Site and Soil Characteristics

A field experiment was conducted during the 2024/2025 winter season in Al-Wasita, a location situated in the northern part of Al Jabal Al Akhdar (32°47' E, 21°39 N '), at an altitude of approximately 185 meters above sea level. Composite soil samples (0–30 cm) were analyzed prior to the experiment as shown in Table 1.

Table 1: Main physicochemical properties of the experimental soil (double-column format).

Property 1	Value	Unit	Property 2	Value	Unit
Sand	13.20	%	Silt	68.15	%
Clay	18.75	%	pH	7.8	-
EC	0.40	ds/m	OM	1.85	%
Total N	0.09	%	Texture	-	Silty Clay Loam

Experimental Design and Treatments

Measured approximately 12 m² (3 m × 4 m), providing sufficient area for accurate measurements and minimizing edge effects. Within each plot, a central 1 m² area was harvested for yield assessment. The main plots were assigned to seed bio-priming treatments: (1) Seed Coating with Acadian® extract (3 ml/kg), (2) Seed Priming by soaking seeds in an Acadian® solution (3 ml/L) for 12 hours, and (3) an untreated Control. The sub-plots were assigned to four nitrogen levels: 0, 60, 120, and 180 kg N/ha, applied as urea.

Crop Husbandry

Wheat (Triticum aestivum L.) was sown in November 2024 using manual dibbling at a seed rate of 40 kg/ha. Standard cultural practices for the region were followed.

Data Collection and Trait Measurement

All measurements were taken from five randomly tagged plants per plot, unless otherwise specified.

Plant Height (cm): Measured from the soil surface to the tip of the main spike, excluding the awns.

Plant Dry Weight (g): Above-ground biomass was harvested, washed with distilled water to remove debris, and oven-dried at 70°C until a constant weight was achieved.

Leaf Area Index (LAI): Estimated non-destructively using a standard correction factor for cereals, where Leaf Area = Length × Maximum Width × 0.75.

Yield and Yield Components: At maturity, a central 1 m² area was harvested to determine grain and straw yields.

Thousand-Kernel Weight (TKW, g): This trait was measured as a primary indicator of grain filling and quality [6] For each plot, three representative subsamples of cleaned grain were taken. From each, 100 kernels were manually counted and weighed. This weight was then multiplied by 10 to estimate the thousand-kernel weight. The final value was adjusted to a standard 13% moisture content.

Harvest Index (HI): Calculated as the ratio of grain yield to total above-ground biomass (grain + straw yield).

Growth Analysis

Absolute Growth Rate for Height (AGR_h): Calculated to quantify the rate of stem elongation over a specific time interval using the formula:

$$AGR_h = (H2 - H1) / (t2 - t1)$$

Where, H1 and H2 are the plant heights (cm) at times t1 and t2, respectively.

Relative Growth Rate for Dry Weight (RGR_w): Calculated to assess the efficiency of biomass accumulation over time using the classical formula proposed by [7]:

$$RGR_w = (\ln(W2) - \ln(W1)) / (t2 - t1)$$

Where W1 and W2 are the plant dry weights (g) at times t1 and t2, respectively

Statistical Analysis

All statistical analyses were performed using R software [8]. The data were analyzed according to a split-plot design, with seed treatments as the main plot factor and nitrogen levels as the sub-plot factor. An analysis of variance (ANOVA) was conducted to assess the main effects and their interaction. Prior to ANOVA, the assumptions of normality of residuals and homogeneity of variance were verified using the Shapiro-Wilk test and Levene's test, respectively [9,10]. For significant effects, mean comparisons were performed using Tukey's Honestly Significant Difference (HSD) test at a significance level of $P < 0.05$ [11]. Data manipulation and preparation were carried out using the dplyr [12], tidyr [13], readxl, and janitor [14] packages. The emmeans package was utilized for post-hoc analyses, and figures were generated using the ggplot2 package [15].

Results and discussion

Results

Data on vegetative growth rates, such as Relative Growth Rate (RGR) and Absolute Growth Rate (AGR), were also collected. While nitrogen fertilization influenced these parameters as expected, no significant interaction between seaweed extract and nitrogen levels was observed.

Interactive Effects on Vegetative Growth and Spike Density

The analysis of variance revealed a significant interaction ($P < 0.05$) between seaweed extract application (S) and nitrogen fertilization levels (N) for key vegetative and reproductive traits, including plant height at harvest (PHH), tiller number, and spike density (spikes per m²). This indicates that the biostimulant's effectiveness was not uniform across nitrogen levels but rather depended on the plant's nitrogen status.

This synergistic interaction is clearly illustrated in Figure 1, which displays the non-parallel response lines for the seaweed treatments across nitrogen levels, a hallmark of true interaction. Specifically, the priming treatment (S2) maintained a consistently high spike density across all nitrogen levels, while the control (S0) and coating treatment (S1) showed a stronger incremental response as nitrogen levels increased. This suggests that priming with seaweed extract enhances the plant's capacity to efficiently convert nitrogen inputs into productive tillers and spikes.

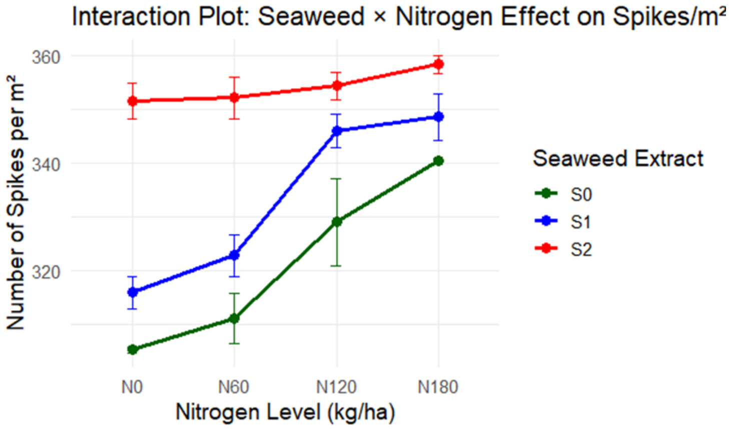

Figure 1. Interactive effect of seaweed extract and nitrogen fertilization on spike density (Spikes/m²). The non-parallel lines confirm a true synergistic interaction. S2 treatment consistently maintained higher spike density across all nitrogen levels, while S0 and S1 treatments showed greater nitrogen dependency.

The detailed mean values for these traits are presented in Table 2 and Table 3. The combination of S2 × N180 produced the highest number of spikes (358.33 m^{-2}), while the S0 × N0 treatment resulted in the lowest spike density (305.28 m^{-2}).

Table 2: Interaction effect of seaweed extract and nitrogen fertilization on key vegetative growth traits of wheat.

Treatment	Plant Height at Harvest (cm)	Tillers/m² (90 Days)	Productive Tillers/m²
S0(Control)			
N0	99.43 ± 1.25 b	346.57 ± 4.13 c	88.14 ± 2.35 c
N60	99.98 ± 1.17 b	356.62 ± 3.98 bc	87.36 ± 2.41 c
N120	100.73 ± 1.08 ab	358.72 ± 4.07 bc	91.86 ± 2.12 b
N180	100.82 ± 1.05 ab	360.67 ± 3.91 bc	94.45 ± 2.05 b
S1 (Coating)			
N0	99.75 ± 1.22 b	354.17 ± 4.09 bc	89.21 ± 2.28 c
N60	100.56 ± 1.14 b	360.40 ± 3.85 bc	89.59 ± 2.19 c
N120	101.37 ± 1.10 ab	362.13 ± 3.92 bc	95.51 ± 2.04 b
N180	103.02 ± 1.07 a	360.00 ± 3.89 bc	96.83 ± 1.98 b
S2 (Priming)			
N0	98.99 ± 1.28 b	358.56 ± 4.11 bc	98.04 ± 2.15 a
N60	100.34 ± 1.15 b	368.67 ± 3.95 b	95.52 ± 2.12 b
N120	102.14 ± 1.09 ab	383.33 ± 4.23 a	92.46 ± 2.27 b
N180	101.40 ± 1.08 ab	382.83 ± 4.18 a	93.71 ± 2.19 b

Different letters within a column indicate significant differences at $P < 0.05$ according to Tukey's HSD test.

Table 3: Interaction effect of seaweed extract and nitrogen levels on the number of spikes per m².

Seaweed Treatment	N0	N60	N120	N180
S0 (Control)	305.28 ± 5.18 d	311.17 ± 4.96 d	329.00 ± 5.02 c	340.50 ± 4.85 b
S1 (Coating)	315.94 ± 5.12 cd	322.83 ± 5.01 cd	345.89 ± 5.14 b	348.59 ± 5.08 b
S2(Priming)	351.54 ± 5.07 a	352.06 ± 4.89 a	354.27 ± 5.11 a	358.33 ± 4.97 a

Different letters indicate significant differences among treatments at $P < 0.05$.

Main Effects on Grain Yield and Yield Components

For traits where no significant S × N interaction was observed, the main effects of each factor were evaluated separately (Tables 4 and 5). Application of seaweed extract significantly enhanced grain yield (GY), straw yield (SY), grains per spike, and thousand-kernel weight (TW). Again, seed priming (S2) consistently outperformed other treatments.

Similarly, increasing nitrogen fertilization from N0 to N180 resulted in a progressive and significant increase in yield and its components. The harvest index (HI) remained unaffected, indicating a proportional increase in both grain and straw biomass.

Table 4. Main effects of seaweed extract and nitrogen levels on grains per spike and thousand-kernel weight.

Treatment Level	Grains/Spike	Thousand-Kernel Weight (g)
Seaweed Extract (S)		
S0 (Control)	46.62 ± 1.02 c	37.17 ± 0.88 c
S1 (Coating)	48.83 ± 1.09 b	38.56 ± 0.91 b
S2 (Priming)	52.44 ± 1.12 a	39.58 ± 0.93 a
Nitrogen Level (N)		
N0	48.10 ± 1.05 d	37.79 ± 0.89 d
N60	48.73 ± 1.07 c	38.26 ± 0.90 c
N120	49.78 ± 1.09 b	38.62 ± 0.91 b
0N180	50.57 ± 1.11 a	39.07 ± 0.92 a

Different letters indicate significant differences at $P < 0.05$.

Table 5: Main effects of seaweed extract and nitrogen levels on final yield and harvest index.

Treatment Level	Grain Yield (t/ha)	Straw Yield (t/ha)	Harvest Index (%)
Seaweed Extract (S)			
S0 (Control)	4.79 ± 0.12 c	7.61 ± 0.21 c	38.65 ± 0.84
S1 (Coating)	5.70 ± 0.15 b	9.20 ± 0.25 b	38.30 ± 0.81
S2 (Priming)	6.53 ± 0.17 a	10.35 ± 0.28 a	38.67 ± 0.79
Nitrogen Level (N)			
N0	5.27 ± 0.13 d	8.51 ± 0.23 d	38.29 ± 0.82
N60	5.51 ± 0.14 c	8.86 ± 0.24 c	38.39 ± 0.81
N120	5.80 ± 0.15 b	9.07 ± 0.24 b	39.06 ± 0.80
N180	6.12 ± 0.16 a	9.79 ± 0.26 a	38.42 ± 0.82

Discussion

Synergistic Enhancement of Nitrogen Use Efficiency

The most salient outcome of this study is the significant synergistic interaction between seaweed extract application and nitrogen fertilization, particularly concerning spike density. This finding transcends simple additive effects and strongly implies that seaweed biostimulants enhance the plant's Nitrogen Use Efficiency (NUE), a conclusion supported by a growing body of recent evidence confirming the capacity of biostimulants to allow for optimized fertilizer inputs while maintaining or increasing productivity [16,17].

Mechanistically, seaweed extracts are well-documented for stimulating root system development, primarily through auxin-like compounds [18]. This leads to a modified root architecture with more extensive growth, which enhances the soil volume explored by the plant and improves nutrient uptake efficiency. It is plausible that plants treated with seaweed extract in our study developed more robust root systems, improving nitrogen scavenging from the soil and translating this enhanced uptake into a higher number of productive tillers and spikes. This mechanism is directly supported by recent experimental work showing that combining biostimulants with nitrogen can double root growth in wheat [19], and is further validated by studies under similar local conditions [20].

Resource Allocation and Physiological Trade-offs

An interesting physiological observation was the trend towards a higher Relative Growth Rate (RGR) in plants under low nitrogen (N0) conditions. This can be interpreted as a stress-avoidance strategy, where plants may accelerate early growth to complete their life cycle before nutrient scarcity becomes severely limiting. Such developmental adjustments are recognized as natural coping mechanisms in wheat against environmental stressors, often involving complex hormonal pathways [21].

Additionally, the negative correlation observed between plant height and spike density suggests a classic yield component compensation, a well-known trade-off in wheat. Our results suggest that seaweed treatments, particularly priming, modulate this trade-off to favor reproductive growth over excessive vegetative growth. Recent research confirms that such trade-offs are complex and genetically controlled, with their temporal determination being a key factor [22]. Overcoming them is a primary objective in modern wheat breeding [23]

Independent Effects on Grain Filling

For yield components where no interaction was detected, such as grains per spike and thousand-kernel weight, both seaweed extract and nitrogen independently enhanced performance. The positive effect of nitrogen is consistent with its fundamental role in photosynthesis and protein synthesis during the grain-filling period. The independent effect of seaweed extract can be attributed to its role in improving sink strength and delaying leaf senescence. This extends the duration of photosynthesis, increasing the availability of assimilates for grain filling and ultimately leading to heavier and more numerous kernels, a mechanism directly supported by recent studies linking seaweed extracts to improved photosynthetic efficiency in wheat [24].

Conclusion

This study conclusively demonstrates the significant synergistic interaction between seaweed extract (SWE) seed treatments and nitrogen fertilization for enhancing wheat productivity in semi-arid environments. The key finding is that seed priming with SWE, when integrated with optimal nitrogen levels (120–180 kg/ha), boosts final grain yield by up to 36%. This improvement is not merely an additive effect but is driven by an enhanced Nitrogen Use Efficiency (NUE), which translates into a greater number of spikes per unit area, the primary determinant of yield.

Furthermore, the research highlights that different application methods of SWE have distinct effects. Seed priming consistently proved superior to seed coating, suggesting that the initial physiological stimulus during germination is critical for establishing a productive crop stand capable of responding efficiently to nutrient inputs.

Based on these findings, we recommend the adoption of SWE seed priming as a viable and potent agronomic practice for wheat farmers in Libya and similar semi-arid regions. Future research should focus on validating these results across multiple locations and seasons and should incorporate direct measurements of root system architecture and isotopic analysis (e.g., ^{15}N) to further elucidate the precise physiological mechanisms underlying this synergy.

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