

Effects of Seaweed-Based Fertigation and Drip Emitter Configuration on Okra (*Abelmoschus esculentus* L.) Performance and Irrigation Hydraulics

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Abstract

Okra is one of the important warm-season vegetables in the semi-arid region of Iraq, and it is necessary to enhance water productivity under drip irrigation. A field experiment was carried out from March to September 2024 at the Qlyasan Agricultural Research Station (Kurdistan Region, Iraq), conducted in a randomized complete block design (RCBD) with a split-plot arrangement: fertigation (F) in main plots, and irrigation/emitter configuration (P) in subplots. Fertigation treatments comprised 0 (F0; mineral NPK), 2.5 (F1), and 5.0 L ha⁻¹ (F2) seaweed extract (Kelpak®; *Ecklonia maxima*), whereas P combined emitter type (on-line vs in-line) and nominal discharge (2 vs 4 L h⁻¹). Seven plant attributes and five hydraulic/wetting indices were evaluated (Q, DU_{lq}, EU, Dw, and Aw). Efficiency was enhanced with seaweed fertigation: The highest pods per plant (76.62), plant yield (283.24 g plant⁻¹), and total yield (11.33 t ha⁻¹) were achieved with F2, while chlorophyll peaked at F1 (33.62 SPAD). Emitter configuration influenced hydraulic function and wetting: P4 (in-line 4 L h⁻¹) was the highest EU (87.24%) and Aw (0.0803 m² emitter⁻¹); but P3 (on-line 4 L h⁻¹) produced the deepest Dw (38.7 cm) and the highest marginal total yield (10.91 t ha⁻¹). Interaction means confirmed the greatest total yield of F2×P1 (11.84 t ha⁻¹) and the highest EU value of F1×P4 (88.44%). In general, using seaweed fertigation and a suitable emitter configuration in conjunction with the above, in particular 5.0 L ha⁻¹, can be the optimal combination to enhance okra yield within a desirable uniformity/wetting pattern.

Keywords: Okra, seaweed extract, fertigation, drip irrigation, emission uniformity, wetted area, wetting depth, semi-arid agriculture

Introduction

Okra (*Abelmoschus esculentus* L.) is an important and popular vegetable in the

Middle East, more widely acknowledged as a useful vegetable because pods contain dietary fiber, minerals, and bioactive compounds (Rouphael and Colla, 2020;

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Dantas *et al.*, 2021). However, restricting irrigation water and the need to increase the efficiency of both water and nutrients frequently limit okra yield in semi-arid conditions. Because it allows for precise fertigation and delivers water directly to the root zone, drip irrigation is usually encouraged for vegetables. However, crop response is highly dependent on hydraulic performance and soil wetting geometry under a specific emitter type and discharge (Burt *et al.*, 1997). The size of wetted soil and application uniformity can be altered by the emitter discharge rate and emitter type (online and inline), which in turn affects nutrient availability, root activeness, and yield steadiness. Wetting pattern measurements are determined by the combination of soil hydraulic characteristics, irrigation time, and emitter flow rate, according to numerical and experimental investigations (Naglič *et al.*, 2014). Therefore, field-based assessment of hydrological and agronomic characteristics is crucial for developing locally applicable suggestions.

Simultaneously, there is a developing interest in using plant biostimulants, especially seaweed extracts, to supplement mineral fertilization. According to du Jardin (2015), although reactions vary depending on dosage, crop, and application technique, seaweed extracts include a variety of bioactive substances (such as polysaccharides, betaines, and phenolics) that can promote root growth, enhance nutrient uptake, and improve plant performance under stress (Mughunth *et al.*, 2024). Particularly in okra, Swarnam *et al.* (2020) Seaweed-based products may be helpful in situations where climate stress and input expense restrict productivity, as demonstrated by reported enhancement in okra yield and quality after seaweed extract use under field conditions.

Although biostimulant-based nutrition and drip irrigation structure have been researched independently, there is still restricted combined evidence for okra in the agro-ecological conditions of the Kurdistan Region of Iraq. Furthermore, clogging and operating conditions can cause variations in emitter discharge in drip irrigation systems, which could limit the effectiveness of improved nutrient management and decrease irrigation uniformity. Recent research on okra shows that irrigation levels significantly impact water productivity and yield, and biostimulants like seaweed extracts can reduce the effects of water stress (Wakchaure *et al.*, 2023).

Additionally, the hydraulic design's nutrient strategy has a major impact on okra growth and yield formation in warm, water-restrictive conditions. The importance of management packages that preserve photosynthesis while boosting water productivity is supported by research on okra deficiency irrigation, which reveals that yield and water productivity are sensitive to the balance between soil moisture availability and plant physiological adjustment throughout flowering and pod set (Wakchaure *et al.*, 2023). Seaweed-based products are increasingly being used as plant biostimulants to increase stress tolerance and nutrient use efficiency through a variety of bioactive components. Studies on horticultural crops show that these products improve root growth, nutrient uptake, and metabolic resilience when timing and dosage are optimized (Craigie, 2011; Calvo *et al.*, 2014; du Jardin, 2015). But, when used during fertigation, preserving emitter function and decreasing clogging risk became particularly important for guaranteeing a constant nutrient supply (Shi *et al.*, 2022). Throughout the growing season, if emitter discharge and water

application uniformity stay within reasonable bounds, drip irrigation systems can only be realized from an agronomic perspective of irrigation engineering. Uneven water distribution can result in localized plant water stress and irregular nutrient delivery through fertigation due to variations in uniformity brought on by pressure fluctuations, installation problems, or gradual emitter clogging (Burt *et al.*, 1997). As a result, even when the total irrigation volume seems adequate, crop yield stability may decrease. Practically speaking, the area of the root zone that actively engages in water and nutrient uptake is determined by the geometry of the wetted soil zone, which is typically characterized by wetted depth and wetted surface area. Emitter flow rate interacts with soil hydraulic properties and irrigation time to affect the size of the wetted zone and the redistribution of moisture in the soil profile, as both numerical models and field studies have shown. Thus, in fine-textured soils, site-specific assessment is especially crucial (Naglič *et al.*, 2014; Šimůnek *et al.*, 2016).

Thus, this study investigated the differences between drip irrigation configuration (online and inline emitters with flow rates of 2 or 4 L h⁻¹) and fertilization strategy (mineral NPK compared with seaweed-based fertigation). In addition to irrigation hydraulic, and wetting traits characteristics, the analysis took into account a number of significant indicators of okra productivity. The particular aims were to evaluate the effects of irrigation structures and fertilization techniques on the growth and yield development of Okra, ascertain the effects of these variables on discharge, homogeneity, and wetting pattern geometry, and while preserving the desired hydraulic, determine a workable treatment mixture that

optimizes yield performance under semi-arid conditions.

Materials and Methods

Site description and soil

The experiment was conducted at Qlyasan Agricultural Research Station, College of Agricultural Engineering Sciences, University of Sulaimani, Kurdistan Region–Iraq, located (Latitude 35° 34' 307"; N, Longitude 45° 21' 992"; E, 765 MASL) during March–September 2024. The soil (0–30 cm) was identified as silty clay (pH 7.13; EC 0.61 dS m⁻¹; organic matter 21.6 g kg⁻¹; CaCO₃ 107 g kg⁻¹).

Experimental design and treatments

The field was carried out in a randomized complete block design (three replicates) arranged as a split plot. The present research evaluates the effects of fertilization strategy and drip irrigation structures. Fertilization treatments were allocated to the main plot: F0 = conventional mineral NPK; F1 = seaweed extract at 2.5 L ha⁻¹; and F2 = seaweed extract at 5.0 L ha⁻¹. The seaweed extract was Kelpak® (*Ecklonia maxima*) used with fertigation in five split applications (at planting and 15, 30, 45, and 60 days after planting/transplanting). While subplots represented irrigation configurations, they were: P1 = online emitters (2 L h⁻¹), P2 = inline (2 L h⁻¹), P3 = online emitters (4 L h⁻¹), and P4 = inline (4 L h⁻¹). Each sub subplot was 2 × 2 m (4 m²) with 16 plants (0.60 m between rows and 0.40 m between plants).

Drip system and irrigation management

Water was delivered from a 20,000 L storage tank, a 120 mesh screen filter, and a centrifugal pump with around 3.5 horsepower. A pressure of around 1.8 bar

was maintained during operation. In order to match plant spacing, emitters were placed 0.40 m apart. Except for emitter type and nominal discharge, irrigation was planned twice a week, and its duration was modified in accordance with measured discharge to obtain similar irrigation management.

Measured traits and sampling procedures

Seven plant traits were selected for the extracted depend on based on their agronomic relevance and responsiveness to fertilization and irrigation configuration: plant height (cm), leaf number (plant^{-1}), total leaf area ($\text{dm}^2 \text{ plant}^{-1}$), leaf chlorophyll content (SPAD), number of pods per plant^{-1} , plant yield (g plant^{-1}), and total yield (t ha^{-1}). Eight representative plants per plot (excluding borders) were tagged for repeated measurements. Chlorophyll was measured using a SPAD meter on fully expanded mid-canopy leaves (5 readings per plot). Leaf area was estimated using image-based analysis software (Digimizer®); the mean leaf area \times leaf number was used to compute leaf area per plant. Total yield was calculated from plot yield using: $\text{TY} (\text{t ha}^{-1}) = [\text{Plot yield (kg)} / \text{Plot area (m}^2)] \times 10,000$

Five irrigation traits were evaluated: measured discharge ($Q, \text{L h}^{-1}$), distribution uniformity of the low quarter (DULq, %), emission uniformity (EU, %), wetting depth (D_w , cm), and wetted area ($A_w, \text{m}^2 \text{ emitter}^{-1}$).

Emitter discharge was measured volumetrically:

$q (\text{L h}^{-1}) = V / t$,
where q is emitter discharge, V is collected water volume (L), and t is collection time (h).

DULq was computed as:
 $\text{DULq} (\%) = (Q_{25} / Q) \times 100$
where Q_{25} is the mean discharge of the lowest 25% of emitters, and Q is the overall mean discharge (Burt *et al.*, 1997).

The emission uniformity (EU) was calculated following standard micro-irrigation practice:
 $\text{EU} (\%) = 100 \times (1 - 1.27 \times \text{CV}_q / \sqrt{e}) \times (Q_{25} / Q)$,
where CV_q is the coefficient of variation of discharge and e is the number of emitters per plant (≈ 1).

Wetting depth (D_w) was measured by carefully excavating near emitters after irrigation to locate the wetting front.

Wetted area (A_w) was approximated using the wetted diameter at the soil surface (W_w):

$$A_w = \pi \times (W_w / 2)^2.$$

Statistical analysis

The OPSTAT program was used to analyze the variance of ANOVA data in this investigation, appropriate for the split-split plot RCBD. Treatment means were compared using Duncan's multiple range test at $P \leq 0.05$. Additionally, Pearson correlation analysis was performed across the 12 F \times P interaction means to examine associations between total yield and hydraulic/wetting indicators (Q , EU, DULq, D_w , and A_w).

Results and Discussion

Plant traits

When compared to mineral fertilization, seaweed fertigation enhanced okra growth and yield (Table 1). In comparison to NPK (F0), the higher seaweed rate (F2) resulted in elevated the height of plants (117.05 cm), increased leaves (67.13 plant^{-1}), a larger

total leaf area ($11.80 \text{ dm}^2 \text{ plant}^{-1}$), and a higher yield ($283.24 \text{ g plant}^{-1}$; 11.33 t ha^{-1}). These reactions align with seaweed extracts' documented ability to improve physiological activity and nutrient uptake, which supports biomass accumulation and yield formation (du Jardin, 2015; Mughunth *et al.*, 2024). The intermediate seaweed dose (F1; 33.62 SPAD) caused the leaf chlorophyll content to peak, indicating a dose-based physiological response.

Growth and yield were also impacted by the irrigation structure. While inline emitters at

4 L h^{-1} (P4) obtained the highest chlorophyll readings (33.24 SPAD), inline emitters at 4 L h^{-1} (P3) produced the highest total leaf area ($11.12 \text{ dm}^2 \text{ plant}^{-1}$) and total yield (10.91 t ha^{-1}). Larger and deeper wetted size that sustain steady root zone water availability during hot spells are likely responsible for the better performance of higher discharge treatments, as research has frequently indicated on the drip irrigation in wetting patterns (Naglič *et al.*, 2014).

Table 1. Marginal means of selected plant traits as affected by fertilization strategy (F) and irrigation configuration (P).

Trait	F0	F1	F2	P1	P2	P3	P4
Plant height (cm)	98.22 c	108.12 b	117.05 a	100.75 c	107.17 b	112.22 a	111.03 a
No.of leaves .plant ⁻¹	54.11 c	60.64 b	67.13 a	58.48 c	59.76 bc	62.86 a	61.41 ab
Total leaf area (dm ² plant ⁻¹)	9.17 c	10.29 b	11.80 a	9.68 b	10.08 b	11.12 a	10.81 a
Leaf chlorophyll (SPAD)	28.07 c	33.62 a	32.32 b	29.35 c	31.23 b	31.52 b	33.24 a
No.of Pods .plant ⁻¹	71.34 c	74.54 b	76.62 a	73.46 b	72.94 b	76.32 a	73.96 b
Plant yield (g plant ⁻¹)	244.71 c	258.22 b	283.24 a	266.26 b	255.24 c	272.62 a	254.11 c
Total yield (t ha ⁻¹)	9.79 c	10.32 b	11.33 a	10.65 b	10.21 c	10.91 a	10.16 c

Different letters indicate there is a significant difference between the means according to Duncan's multiple range test ($P \leq 0.05$)

Irrigation hydraulic and wetting traits

Different emitter structures had different hydraulic indicators (Table 2). As anticipated, the 4 L h^{-1} treatments (P3 and P4) had higher measured discharge, and P3 had the deepest wetting pattern ($D_w = 38.7$

cm). With the highest wetted area ($A_w = 0.0803 \text{ m}^2 \text{ emitter}^{-1}$) and application uniformity ($EU = 87.24\%$; $DUI_q = 93.36\%$), Inline 4 L h^{-1} (P4) demonstrated a more stable discharge distribution along laterals. These variations in uniformity are significant because uneven use can result in

variations in the delivery of water and nutrients within the field, which in turn affects crop performance (Burt *et al.*, 1997).

The impact of the biostimulant strategy on irrigation traits were less significant but still detectable. When organic components take part in partial clogging, the higher seaweed

rate (F2) slightly decreased mean discharge and wetted area ($Q = 2.62 \text{ L h}^{-1}$; $A_w = 0.0647 \text{ m}^2 \text{ emitter}^{-1}$). This may indicate a greater susceptibility to discharge reduction under fertigation (Shi *et al.*, 2022). However, uniformity indices across treatments stayed within reasonable bounds.

Table 2. Marginal means of selected irrigation hydraulic and wetting traits as affected by fertilization strategy (F) and irrigation configuration (P).

Trait	F0	F1	F2	P1	P2	P3	P4
Measured discharge, $Q \text{ (L h}^{-1}\text{)}$	2.72 a	2.69 a	2.62 b	1.78 c	1.73 d	3.64 a	3.55 b
Distribution uniformity, DUlq (\%)	92.57 a	92.42 a	91.54 b	91.61 c	91.41 d	92.32 b	93.36 a
Emission uniformity, EU (\%)	85.82 a	85.27 a	83.94 a	83.83 b	83.69 b	85.28 b	87.24 a
Wetting depth, $D_w \text{ (cm)}$	34.20 a	34.70 a	34.80 a	31.90 c	30.30 d	38.70 a	37.40 b
Wetted area, $A_w \text{ (m}^2 \text{ emitter}^{-1}\text{)}$	0.0673 a	0.0662 a	0.0647 b	0.0529 d	0.0570 c	0.0740 b	0.0803 a

Different letters indicate there is a significant difference between the means according to Duncan's multiple range test ($P \leq 0.05$)

Interaction effects (F × P) on plant traits

This interaction demonstrates that biostimulant-driven increases in nutrient-use efficiency are most fully expressed when irrigation maintains favorable wetting and minimizes transient stress. It also suggests that the size of the seaweed advantages may rely on emitter structures (Mughunth *et al.*, 2024; Surendran *et al.*, 2022). The fertilization × irrigation interaction (F × P) for each of the seven plant traits are shown in Table 3.

Practically speaking, Table 3 shows where the expansion or moistening of the wetting environment provides the benefits of seaweed. For instance, plant yield varied from 237.77 under F0×P2 to 296.08 under F2×P1, and total yield varied from 9.51 under F0×P2 to 11.84 under F2×P1. Canopy physiological response also varied: total leaf area ranged from 7.76 (F0×P1) to 12.82 (F2×P3), and SPAD ranged from 25.56 (F0×P1) to 35.57 (F1×P2). These maxima under particular F × P combinations imply that when irrigation configuration

decreases transient stress during reproductive growth and supplies a favorable wetted soil size, better biostimulant-driven nutrient uptake and canopy function are most fully shown (Surendran *et al.*, 2022; Wakchaure *et al.*, 2023).

Additional interaction patterns were also evident for the remaining growth and reproductive traits. Plant height ranged from 88.53 under F0×P1 to 121.17 under F2×P3, and leaf number ranged from 50.83 (F0×P1)

to 70.07 (F2×P3). Pods per plant ranged from 69.31 (F0×P2) to 77.85 (F1×P3), indicating that the reproductive sink responded to specific F × P combinations. These responses can be explained by improved canopy vigor and nutrient acquisition under seaweed-based biostimulants, combined with irrigation configurations that sustain a stable wetted soil volume during flowering and pod set (Mughunth *et al.*, 2024; Surendran *et al.*, 2022; Wakchaure *et al.*, 2023).

Table 3. Interaction means (F × P) for the seven plant traits

F	P	Plant height (cm)	No. of leaves .plant ⁻¹	Total leaf area (dm ² plant ⁻¹)	Leaf chlorophyll (SPAD)	No.of Pods. Plant ⁻¹	Plant yield (g plant ⁻¹)	Total yield (t ha ⁻¹)
F0	P1	88.53 e	50.83 f	7.76 h	25.56 e	70.21 de	241.33 g	9.65 g
	P2	98.93 d	54.03 e	8.22 gh	26.67 de	69.31 e	237.77 g	9.51 g
	P3	103.43 cd	56.07 de	8.67 fg	28.91 cd	74.23 b	257.42 de	10.30 de
	P4	101.97 cd	55.50 de	8.51 fg	31.13 bc	71.62 cd	242.33 g	9.69 g
F1	P1	99.17 d	57.53 d	8.98 ef	30.97 bc	73.79 b	261.37 cd	10.45 cd
	P2	105.90 c	61.00 c	9.43 de	35.57 a	72.85 bc	251.83 f	10.07 f
	P3	112.07 b	62.43 c	10.28 c	34.33 a	77.85 a	265.00 c	10.60 c
	P4	115.33 b	61.60 c	9.96 cd	33.63 ab	73.67 b	254.69 ef	10.18 ef
F2	P1	114.57 b	67.07 ab	11.02 b	31.53 bc	76.37 a	296.08 a	11.84 a
	P2	116.67	64.27	10.35 c	31.45 bc	76.64 a	276.12	11.04 b

		ab	bc				b	
	P3	121.17 a	70.07 a	12.82 a	31.33 bc	76.87 a	295.45 a	11.82 a
	P4	115.80 b	67.13 ab	12.34 a	34.96 a	76.60 a	265.31 c	10.61 c

Different letters indicate there is a significant difference between the means according to Duncan's multiple range test ($P \leq 0.05$)

Interaction effects (F × P) on irrigation traits

Lower measured discharge (Q), distribution uniformity (DUIq), and emission uniformity (EU) in specific combinations may be a sign of increased vulnerability to discharge variability (such as partial clogging), which could decrease the homogeneity of nutrient and water delivery (Burt *et al.*, 1997; Shi *et al.*, 2022). The interaction means (F × P) for irrigation hydraulic and wetting characteristics are shown in Table 4.

Table 4 shows how hydraulic performance varies across fertilization × irrigation combinations from the standpoint of system diagnosis. While DUIq varied from 90.56 (F2×P1) to 94.03 (F1×P4), emission uniformity (EU) varied from 82.05 under F2×P1 to 88.44 under F1×P4. The wetting indicators ranged from Dw = 30.2 (F0×P2) to Dw = 39.2 (F2×P3) and Aw = 0.0511 (F2×P1) to Aw = 0.0805 (F2×P4), while the measured discharge varied from 1.69 (F2×P2) to 3.69 (F0×P3). Lower EU/DUIq continuity under specific fertigation combinations may indicate increased vulnerability to discharge variability (such

as partial clogging), compromising consistent nutrient delivery and raising root-zone water status variability within plots (Shi *et al.*, 2022; Burt *et al.*, 1997).

To quantify the linkage between root-zone hydrodynamics and productivity, Pearson correlations were computed between total yield and hydraulic/wetting indicators across the 12 F×P combinations (Tables 3–4). Total yield showed a moderate negative association with uniformity indices (EU: $r = -0.44$, $P = 0.15$; DUIq: $r = -0.44$, $P = 0.15$), and a weak positive association with wetting depth (Dw: $r = 0.19$, $P = 0.55$). Relationships with measured discharge (Q) and wetted area (Aw) were weak ($|r| \leq 0.12$; $P \geq 0.71$). Although not statistically significant due to the small number of treatment means ($n = 12$), these patterns suggest that the highest-yielding packages were driven more by a favorable wetted volume/depth than by maximizing uniformity alone, highlighting a potential trade-off between wetting geometry and discharge uniformity under field conditions.

Table 4. Interaction means (F × P) for irrigation hydraulic and wetting traits

F	P	Measured discharge, Q (L h ⁻¹)	DUIq (%)	EU (%)	Wetting depth, Dw (cm)	Wetted area, Aw (m ² emitter ⁻¹)
F0	P1	1.82 e	91.92 b	84.66 b	31.8 c	0.0553 d
	P2	1.76 f	91.55 b	84.13 b	30.2 d	0.0575 d
	P3	3.69 a	93.39 a	87.21 a	37.6 b	0.0762 b
	P4	3.61 b	93.40 a	87.29 a	37.1 b	0.0800 a
F1	P1	1.81 e	92.35 a	84.76 b	31.9 c	0.0523 e
	P2	1.73 f	90.71 b	82.13 b	30.3 d	0.0579 d
	P3	3.66 a	92.59 a	85.74 a	39.1 a	0.0742 b
	P4	3.56 c	94.03 a	88.44 a	37.4 b	0.0803 a
F2	P1	1.72 f	90.56 b	82.05 b	31.9 c	0.0511 e
	P2	1.69 g	91.97 b	84.82 b	30.3 d	0.0557 d
	P3	3.57 b	90.98 b	82.89 b	39.2 a	0.0715 c
	P4	3.49 d	92.63 a	86.00 a	37.8 b	0.0805 a

Different letters indicate there is a significant difference between the means according to Duncan's multiple range test ($P \leq 0.05$)

Conclusions

- Compared with mineral NPK (F0), seaweed fertigation improved okra growth and yield, with the best overall performance at 5.0 L ha⁻¹ (F2).
- Emitter configuration influenced both wetting and productivity: in-line 4 L h⁻¹ (P4) achieved the highest wetted area and uniformity, whereas on-line 4 L h⁻¹ (P3) produced the deepest wetting depth and the highest marginal yield, indicating a trade-off between maximizing uniformity and expanding wetted volume. Consistent with the Results and Discussion, correlations across F×P means suggested that higher yield aligned more with wetting depth than with uniformity indices, although relationships were not statistically significant due to the small number of treatment means (n = 12).
- Interaction effects highlighted that the best-performing packages depend on matching

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- Practically, improving okra performance under semi-arid conditions can be supported by selecting emitter configurations that maintain an adequate wetting depth/area while sustaining acceptable uniformity, together with seaweed fertigation at 5.0 L ha⁻¹ (F2). Mechanistic explanations related to nutrient uptake are inferential because leaf/soil nutrient concentrations and root traits were not measured in this study.

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