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Research Article

Effect of Irrigation Frequency on Growth, Yield and Nutritional Quality of *Sesamum indicum* in a Semi-Arid Region in Morocco

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Commonly referred to as the "Queen of Oilseeds", *Sesamum indicum* is widely recognized for its nutritional value and health-promoting properties. Currently, water stress is one of the main factors limiting sesame production, particularly in regions experiencing prolonged drought periods, such as semi-arid areas of Morocco. One effective approach to mitigate this constraint is the rational use of irrigation water; therefore, it is necessary to understand plant responses to different irrigation regimes. The objective of this study was to establish an appropriate irrigation schedule to optimize the agronomic performance of sesame under semi-arid conditions. A field experiment was conducted at the National Agency of Medicinal and Aromatic Plants in Taounate using a randomized complete block design with irrigation intervals. Growth parameters (plant height, number of capsules per plant, number of seeds per capsule, capsule length, and 1000-seed weight), yield parameters (seed yield, biological yield, and harvest index), and biochemical traits (oil and protein contents) were evaluated. Analysis of variance revealed that irrigation intervals significantly affected all measured parameters. Irrigation conducted every 3 days resulted in the highest plant height (84.08 cm), number of capsules (38.05), number of seeds per capsule (49.6), capsule length (30.2 mm), and 1000-seed weight (3 g), followed by irrigation intervals of 6, 9, and 15 days. The maximum seed yield (1,222.66 kg ha^{-1}), biological yield (4,241.33 kg ha^{-1}), and harvest index (31.89%) were obtained from plants irrigated every 6 days. Biochemically, the highest oil content (49.83%) was recorded in plants irrigated every 6 days, followed by those irrigated every 3, 9, and 15 days. In contrast, the highest protein content (22.63%) was observed under the 15-day irrigation interval. A negative correlation was found between total seed oil and total protein contents.

Keywords: *Sesamum indicum*, irrigation, plant growth, yield, protein, oil

1 Introduction

Plants are exposed to a wide range of biotic and abiotic stresses, including pathogens, drought, high soil salinity, deforestation, and climate change. Drought tolerance refers to the ability of plants to grow and survive under conditions of water deficit and represents one of the major constraints affecting crop production, particularly in arid and semi-arid regions (Batool et al., 2022). Water plays a fundamental role in plant life, as it is essential for all biochemical reactions and regulates physiological processes that determine both the quality and quantity of plant growth (Parveen et al., 2021). Morphological, physiological, and biochemical responses of plants to drought stress vary depending on the duration and intensity of stress as well as the developmental stage of the plant (Zia et al., 2021).

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Water stress reduces root system development by decreasing the length and proliferation of root hairs, thereby limiting the contact surface between roots and soil and reducing water uptake for plant growth (Kim et al., 2020). As a result, plants experience impairment of various physiological and biochemical functions (Gupta et al., 2020). Optimal irrigation management should therefore aim to reduce water consumption without negatively affecting yield and its components. Water stress has been reported to reduce plant biomass, seed yield, days to maturity, harvest index, and seed weight in crops such as common bean (Gupta et al., 2020), and sunflower (Ashraf & Siddiqi, 2024).

Morocco is projected to face a significant water stress due to reduced precipitation associated with climate change. Annual water withdrawals in Morocco range between 11 and 15 billion cubic meters, of which approximately 75% is allocated to irrigation (Taheripour et al., 2020). This challenge is further exacerbated by the fact that semi-arid areas account for more than 54% of the country's territory. Such conditions pose a serious threat to national food security. Consequently, drought tolerance has become a highly desirable trait in crops of economic and agronomic importance.

Sesamum indicum is one of the oldest and most important oilseed crops worldwide. It is an annual plant commonly cultivated in arid and semi-arid regions. Sesame seeds are considered a highly nutritious food, as they are rich in oil (44–58%) and protein (17–32%) (El Hanafi et al., 2023). In addition to its nutritional value, *Sesamum indicum* exhibits several biological activities, including antihypertensive effects (Wichitsranoi et al., 2011), antihyperglycemic action (GhoreiShi et al., 2022), and reduces plasma cholesterol (Shankar et al., 2005). Sesame is also regarded as a powerful antioxidant due to its high content of bioactive compounds such as sesamol, sesamolin, and sesamin (Sallam et al., 2021).

Sesame originated in East Africa and India (Mehra, 1970). Currently, Asia is the largest producer of sesame, accounting for approximately 70% of global production, followed by Africa and Latin America with 26% and 4%, respectively (El Harfi et al., 2021). In Morocco, the sesame sector contributes significantly to agricultural production, with an annual value ranging between 15 and 25 million dirhams. Production in the Tadla region, which represents more than 90% of the national cultivated area, ranged from 3.7 to 6.6 tons per year during the period 2018–2022. However, during the 2021–2022 agricultural season, production declined markedly due to limited water availability (Ormvat Adla, 2023). Despite the agronomic importance of sesame, scientific information on the effects of drought on sesame growth, yield, and quality under Moroccan conditions remains limited. Therefore, the present study was conducted to determine the most appropriate irrigation interval for optimizing both quantitative and qualitative traits of *Sesamum indicum* under the climatic conditions of Morocco.

2 Material and Methods

The experiment was conducted at the National Agency of Medicinal and Aromatic Plants in Taounate, Morocco, located at approximately 34.535831° N latitude and -4.640000° W longitude. The study area is characterized by a semi-arid climate, and the meteorological data recorded during the experimental period are presented in Table 1. The physical properties of the soil are shown in Table 2, while its mineral composition was determined using inductively coupled plasma atomic emission spectrometry (ICP-AES) according to the method described by (Pohl et al., 2018) and the results are presented in Table 3.

Sesame seeds were obtained from the Tadla-Azilal region, and botanical identification was carried out at the Scientific Institute of Rabat. The experiment was arranged in a randomized complete block design with four irrigation intervals: 3, 6, 9, and 15 days. Seeds were hand-sown at a depth of 3–4 cm, and all plots were irrigated immediately after sowing. The application of the different irrigation treatments began one month after sowing. Standard agronomic practices for sesame cultivation were followed as recommended; no herbicides, pesticides, chemical fertilizers, or organic fertilizers were applied. Plots were harvested manually in October when leaf color changed from green to yellow. Mature plants were stacked in an upright position and allowed to sun-dried.

Table 1 Meteorological data of the experimental site during the experimental period

	June	July	August	September	October
Temperature (°C)	22.8	26.2	26.2	22.5	17.2
Precipitation (mm)	8	16.3	4.3	16.9	39.6
Air relative humidity	48	41	43	53	63

Table 2 Physical properties of the soil

Physical Properties (%)	
Clay	17
Fine silt	34
Coarse silt	13
Fine sand	22
Coarse sand	14

Table 3 Mineral composition of the soil

Element	**Rate (mg kg^{-1})**
Ca	> 1,000
Na	78.31
K	189.37
Fe	106.56
Mg	74.01
P	4.14
Zn	3.98
N	0.17

2.1 Data Collection

Growth parameters:

- Plant height (cm): at maturity, plant height was measured from the base to the tip of the plant and averaged.
- Number of capsules per plant: capsules were counted on ten randomly selected plants from each plot.
- Number of seeds per capsule: for each sampled plant, seeds from ten capsules were counted.
- Thousand-seed weight (g): one thousand seeds from each plot were counted and weighed.
- Capsule length (mm): capsule length was measured at maturity.

Yield parameters:

- Seed yield (kg ha^{-1}): sesame plants from each plot were harvested at maturity. Seed yield was calculated using the following formula and then converted to kg ha^{-1}:

$$\text{seed yield (kg m}^{-2}\text{)} = (\text{seed yield (kg)}/\text{plot area (m}^2\text{)}) \times 10{,}000$$

- Biological yield (kg ha^{-1}): biological yield was determined by weighing the total aboveground biomass harvested from each plot.
- Harvest index (%): harvest index was calculated using the following equation:

$$\text{harvest index (\%)} = \text{seed yield (kg ha}^{-1}\text{)}/\text{biological yield (kg ha}^{-1}\text{)}$$

Biochemical parameters:

- Seed oil content (%): sesame seeds (10 g) were extracted with 200 mL of n-hexane for 12 h. The oil was recovered by evaporating the solvent using a rotary vacuum evaporator, and oil content was expressed as a percentage.
- Seed protein content (%): protein content of ground seed samples was determined using the Kjeldahl distillation method as described by (Khalid et al., 2003). Nitrogen content (%) was multiplied by 6.25 to calculate protein content:

$$\text{protein (\%)} = \text{nitrogen (\%)} \times 6.25$$

2.2 Statistical analysis

All analyses were performed in triplicate, and results were expressed as means ± standard deviation. Statistical analysis was conducted using one-way analysis of variance (ANOVA). Mean comparisons were performed using Tukey's test at the 5% significance level. Correlation analysis was carried out using Pearson's correlation coefficient, with significance levels set at $p < 0.05$ or $p < 0.01$. All statistical analyses were performed using SPSS statistical software (version 20; IBM SPSS Statistics, New York, NY, USA).

3 Results and Discussion

3.1 Growth Parameters

Results presented in Table 4 show that growth parameters were significantly affected by different irrigation intervals. Irrigation of sesame plants every 3 days resulted in the highest values of plant height (84.08 cm), number of capsules per plant (38.05), number of seeds per capsule (49.6), capsule length (30.46 mm), and 1,000-seed weight (0.3 g), followed by irrigation intervals of 6, 9, and 15 days. Relationships among growth parameters under different irrigation intervals were also examined, and several parameters were positively correlated with one another, exhibiting high correlation coefficients (Table 7).

In general, drought is one of the main factors limiting crop productivity worldwide (Yemata and Bekele, 2024). In the present experiment, all growth parameters were markedly affected under reduced water availability, a finding supported by previous studies. Ozkan and Kulak (2013) reported that sesame plant height was reduced by 43.30% under water stress compared with the control treatment. Similarly, Karaaslan et al. (2007) observed in the Harran region of Turkey that sesame plants subjected to higher irrigation regimes (6- and 12-day intervals) produced a greater number of capsules than those exposed to less frequent irrigation regimes (18- and 24-day intervals). In the Jiroft region of Iran,

Table 4 Effect of levels irrigation days on plant height, capsules number plant^{-1}, seed number capsules, seed weight, capsule length

	Plant height (cm)			Capsules number plant^{-1}			Seed number capsules^{-1}			Seed weight 1,000 (g)			Capsule length (mm)		
	mean	ES	CV%	mean	ES	CV%	mean	ES	CV%	mean	ES	CV%	mean	ES	CV%
3 day	84.08^{a}	15.75	18.26	38.05^{a}	5.73	14.12	49.6^{a}	1.7	4.15	0.3^{a}	0.005	1.9%	30.46^{a}	2.45	8.05
6 day	69.73^{a}	18.36	26.33	33.24^{a}	5.35	16.1	49.96^{a}	3.85	8.36	0.29^{ab}	0.01	3.93	25.8^{a}	8.13	31.53
9 day	67.56^{b}	10.81	16.01	29,91^{b}	5.23	17.50	46.14^{b}	5.04	10.1	0.29^{ab}	0	0	25.5^{a}	2.24	9.9
15 day	52.24^{b}	8.83	16.90	26.2^{bc}	5.27	20.14	40.9^{b}	8.6	17.35	0.28^{bc}	0.005	2.03	22.5^{b}	2.3	9.47
Level of significance		***			***			**			*			*	

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; CV – coefficient of variation; ES – standard error; means followed by the same letter (s) in a column are not statistically different at 5% level of probability

irrigation intervals of 5 and 7 days resulted in a higher number of seeds per capsule compared with longer intervals of 8 and 10 days (Asaeidi et al., 2012). Drought stress has also been reported to adversely affect plant height in other crops, such as maize (Hussain et al., 2019). Although sesame is often described as a drought-tolerant crop (Golestani and Pakniyat, 2015), limited water availability restricts plant growth and flowering, ultimately reducing capsule and seed formation (Yadav et al., 2022). Bhargava and Sawant (2013) demonstrated that water stress reduces cell division and differentiation in sesame, leading to a smaller leaf area that is closely linked to water availability. In addition, Hassen (2022) explained that soil water deficiency can restrict nutrient uptake, thereby limiting plant growth and resulting in shorter plants.

3.2 Yield Parameters

As shown in Table 5, irrigation interval had a significant effect on yield parameters. Seed yield, biological yield, and harvest index were all significantly influenced by irrigation frequency. The highest seed yield and harvest index were obtained from plants irrigated every 6 days, reaching 1,222.66 kg.ha^{-1} and 31.89%, respectively. In contrast, the highest biological yield (4,241.33 kg.ha^{-1}) was recorded under the 3-day irrigation interval. The lowest values of all yield parameters were observed at irrigation intervals of 9 and 15 days. Correlation analysis among yield-related traits across irrigation intervals showed that seed yield, biological yield, and harvest index were positively correlated (Table 7).

In general, crop yield is strongly influenced by drought conditions (Mourad et al., 2025). Water stress has been reported to significantly affect sesame yield parameters, leading to a yield reduction of up to 28% under drought conditions (Hussain et al., 2019). In agreement with these findings, the present study showed that prolonged irrigation intervals, particularly the 15-day interval, resulted in the lowest yield values. These results are consistent with those reported by Eskandari et al. (2009), who observed that biological and grain yields per unit area declined with reduced water availability. Similarly, Jamshidi Zinab et al. (2023) reported that drought stress reduced seed yield across all studied varieties of oilseed rape. Comparable responses have been documented in other oilseed crops, where water stress reduced seed yield in sunflower and safflower by 16.3% and 9.4%, respectively (Ebrahimian et al., 2019). Dehkhoda et al. (2013) explained that under water stress conditions, photosynthetic activity declines, limiting assimilate availability to reproductive organs and consequently reducing seed yield, biological yield, and harvest index.

Table 5 Effect of day irrigation intervals on yield seed, biological yield and harvest index %

	Yield seed (kg ha^{-1})			Biological yield (kg ha^{-1})			Harvest index (%)		
	mean	ES	CV%	mean	ES	CV%	mean	ES	CV%
3 days	1,009.33^{a}	148.19	14.68	4,241.33^{a}	258.47	6.86	27.25^{ab}	4.02	14.77
6 days	1,222.66^{a}	45.38	3.71	4,060.66^{ab}	245.87	6.41	31.89^{a}	0.88	2.78
9 days	934.16^{b}	69.07	7.39	3,833.33^{ab}	114	2.82	23.00^{b}	1.09	4.77
15 days	897.16^{b}	67.50	7.52	3,703.73^{bc}	41.7	0.98	21.15^{b}	1.4	6.63
Level of significance		**			**			*	

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; CV – coefficient of variation; ES – standard error; means followed by the same letter (s) in a column are not statistically different at 5% level of probability

Table 6 Effect of levels irrigation days on oil percent, protein percent

	Oil percent (%)			Protein percent (%)		
	mean	ES	CV%	mean	ES	CV%
3 day	48.83ab	0.39	1.92	20.59c	0.28	0.59
6 day	49.83a	0.14	0.66	20.98c	0.76	1.02
9 day	48.66ab	0.45	2.12	21.48b	0.65	1.33
15 day	47.66b	0.36	1.61	22.63a	0.55	1.17
Level of significance	*			***		

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; CV – coefficient of variation; ES – standard error; means followed by the same letter (s) in a column are not statistically different at 5% level of probability

Table 7 Matrix of simple correlation coefficient among different parameters

	PH	CN	SN	SW	CL	YS	BY	HI	O%	P%
PH	1	.977*	.997**	.998**	-.791	-.595	-.810	-,324	-.835	.962*
CP	.977*	1	.961*	.988*	-.692	-.502	-.670	-.277	-.788	.884
SN	.997**	.961*	1	.992**	-.783	-.655	-.831	-.387	-.871	.969*
SW	.998**	.988*	.992**	1	-.750	-.593	-.767	-.342	-.842	.940
CL	-.791	-.692	-.783	-.750	1	.266	.932	-.121	.453	-.901
SY	-.595	-.502	-.655	-.593	.266	1	.573	.923	.927	-.606
BY	-.810	-.670	-.831	-.767	.932	.573	1	.215	.663	-.939
HI	-.324	-.277	-.387	-.342	-.121	.923	.215	1	.791	-.279
O%	-.835	-.788	-.871	-.842	.453	.927	.663	.791	1	-.791
P%	.962*	.884	.969*	.940	-.901	-.606	-.939	-.279	-.791	1

PL – plant height; CN – capsule number; SN – seed number; SW – 1,000-seed weight; YS – yield seed; BY – biological yield; O % – oil %; P % – protein %; * correlation is significant at the 0.05 level; ** correlation is significant at the 0.01 level

Furthermore, reductions in yield attributes under drought stress may also result from decreased nutrient uptake due to osmotic stress in the soil (Ebrahimian et al., 2019).

3.3 *Biochemical parameters*

According to Table 6, irrigation interval had a significant effect on oil content. The highest oil percentages, 49.83% and 48.83%, were obtained from plants irrigated every 6 and 3 days, respectively, followed by irrigation intervals of 9 and 15 days, which resulted in oil contents of 48.66% and 47.66%. A negative correlation was observed between total oil and total protein content (r = -0.79) (Table 7).

Numerous studies have demonstrated the impact of drought stress on the biochemical composition of oilseed crops, highlighting the sensitivity of oil quality to water availability. In flax, seed oil content was significantly reduced under water-limited conditions (Zare et al., 2023), while in sunflower, drought stress altered fatty acid composition (Ghaffari et al., 2023), under limited water availability. Gu et al. (2020) explained that drought-induced reductions in the activity of enzymes involved in fatty acid biosynthesis, such as 1,3-ketoacyl-CoA synthase and acetyl-CoA carboxylase, may lead to decreased oil accumulation under water stress conditions. With respect to protein content, the present study showed an increase in protein percentage with increasing water limitation. The highest protein contents, 22.63% and 21.48%, were recorded under irrigation intervals of 15 and 9 days, respectively, followed by the 6-day and 3-day intervals, with values of 20.98% and 20.59%. Similar trends were reported by Zare et al. (2023), who observed increased protein concentration and amino acid content under water stress conditions.

Tavares et al. (2022) also reported improvements in protein quantity and quality under drought stress in other oilseed crops, including soybean. Under stress conditions, plants tend to accumulate amino acids and proteins, which play key roles in regulating enzyme activity, biosynthetic pathways, gene expression, and redox homeostasis, thereby enhancing plant tolerance to both abiotic and biotic stresses (Kaur et al., 2021).

4 Conclusions

In conclusion, the findings of this study demonstrated that the morphological traits and yield-related parameters of sesame were markedly and negatively affected by increasing levels of water stress. It by contrast, from a biochemical perspective, key quality attributes, including oil and protein contents, showed relative resilience, suggesting that sesame is able to maintain its nutritional and functional quality even under drought conditions.

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