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Optimizing growth, yield, and quality of soybean varieties using irrigation intervals and nano zinc fertilizer under semi-arid conditions.

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ABSTRACT

Background: Due to the general effect of climate change, a considerable increase in irrigation demand is expected globally to pose a future challenge for agriculture.
Objectives: To study the influence of irrigation interval and nano-zinc chelate fertilization on soybean [(Glycine max (L. Merr.]. Growth, yield, yield components, and oil quality.
Methods: A field experiment conducted at Qlyasan Research Station, University of Sulaimani, Sulaimaniyah, Iraq, during the 2023 growing season, investigated the effects of irrigation intervals and nano-zinc fertilizer on soybean growth and yield. The study employed a split- split plot design with three replications, the treatment (main plot) irrigation intervals (5, 10, and 15 days), three soybean varieties in a subplot (Lee74, Ebba, and Shaimaa), and three nano-zinc fertilizer levels applied as a foliar spray during vegetative growth in the sub-sub plot (0, 200, and 400 µg L-1), using drip irrigation at3.4 L/h. Results: It was revealed that 5-day irrigation intervals significantly improved plant parameters, including plant height, leaf area index, seed weight, and seed oil and protein content. Nano-zinc fertilizer application at 400 µgL -1 enhanced root depth, pod weight, and oil content, while 200 µg L -1 promoted optimal protein synthesis. The Ebba variety achieved the highest seed yield (1823.75 kg ha -1) under 5-day irrigation with 200 µg L -1 nano-zinc fertilizer. The Lee74 variety produced the highest protein percentage (34.97%) with 5-day irrigation and 400 µg L-1 Zinc. Both Lee74 and Ebba varieties reached maximum oil content (24.85%) under 5-day irrigation with 400 µg L-1 zinc application. Conclusions: Maximum plant height, leaf area, pod weight, seed yield, seed oil, and protein content were enhanced by frequent irrigation intervals. High levels of nano-zinc fertilizers also augmented plant resilience against water stress, enhancing growth parameters and elevating yield components.

***Keywords*:** [Glycine max (L.) Merr.], nano zinc-fertilizer, irrigation scheduled, water stress management ,soybean yield and quality.

Introduction

Soybean [(Glycine max (L.) Merr.] is one of the most important oilseed crops in the world. It is the world's leading economic oilseed crop [1]. Soybean accounts for roughly 30% of the global processed crop oil and are also a key component in biodiesel production. Often termed the "Golden Bean" due to its extensive nutritional benefits and versatile uses, soybean seeds contain approximately 20% oil and 40-50% high-quality protein. With its essential amino acids, including glycine, tryptophan, and lysine, soybeans offer a nutritional profile comparable to cow's milk [2]. Irrigation is a critical factor influencing soybean growth, yield, and its components. Exposure of soybean plants to soil moisture stress at any stage of their life cycle can harm growth, yield, and related components. the most critical stages for ensuring adequate water supply to soybean plants are during pod development and seed filling, as water stress during these phases can significantly reduce yield [3]. Moreover, the decrease in crop yield due to this kind of stress has been reported to be between 54% and 82%. The maximum decrease is in abiotic stresses, including drought, salinity, heat, cold, light intensity, inadequate nutrients, and soil acidity [4]. Drought stress is one of the most important limiting factors for the growth and yield of crops, which affects 40 to 60 percent of the world's agricultural lands [5]. The shift toward using modern fertilizers as alternatives to traditional ones has become necessary to supply essential nutrients for plant growth, boost productivity, and maintain soil health and quality [6]. Micronutrient fertilizers can enhance plant tolerance to environmental stresses, drought and salinity. Among these, Zn is an essential element for the activities of several antioxidant enzymes that maintain the membrane lipids, proteins, and nucleic acids in plant cells [7]. Nano-fertilizers are more advantageous to conventional fertilizers because they can triple the effectiveness of the nutrients, reduce the requirement of chemical fertilizers, make the crops drought and disease resistant, and are less hazardous to the environment. They can easily get absorbed by plants due to their high surface area to volume ratio. Zn nanoparticles represent a novel form of plant fertilizer, produced through nanoparticle synthesis technology, and offer numerous benefits, such as increased tolerance to abiotic stress in certain plants [8]. Zinc, though required in small amounts, plays a crucial role in producing the hormone auxin [[9]. Numerous studies have demonstrated that micronutrients help alleviate drought stress in crops [10]. Furthermore, research has confirmed the efficacy of zinc, in the forms of zinc sulfate, zinc chelate, and zinc nanoparticles, in enhancing plant resistance to environmental stress by improving morphological, physiological, and biochemical parameters in various plants [11].

To optimize soybean yield, it is essential to enhance plant nutrition through more efficient fertilization and irrigation techniques. The primary objective of this study was to determine the appropriate irrigation intervals and requirements that balance maximum water savings with minimal yield loss. Additionally, the study aimed to investigate the influence and interaction of Nano zinc fertilizer on plant resistance to water stress, as well as to identify the optimal application level and select a crop variety with inherent drought resistance for achieving this goal.

Materials and Methods

Plant material and soil analysis

A field experiment was carried out during 2023 growing season at Qlyasan Research Station (Latitude: 35° 34′ 17″ N, Longitude: 45° 22′ 00″ E, and altitude of 757 masl), 2 km northwest of Sulaimani city. To study the influence of irrigation interval and zinc Nano- chelate fertilization on soybean varieties [*Glycine max* (L.) Merr.] growth, yield, yield components, and oil quality. The soil for the studied area was also analyzed (Table 1).

Table 1: Soil physical and chemical characteristics.

Physicochemical Properties			
Physical properties	Sand	59.68	
	Silt	619.17	(gk g^{-1})
	Clay	321.15	
	Texture	Silty Clay	
	PH	7.59	
	Ec	490	(µS cm^{-1})
	Bulk Density (0-30 cm)	1.38	Mg/m^3
	F.c	29.93	%
Chemical properties	Available water%	10.87	%
	O.M	22.4	gk g^{-1}
	$Caco_3$	304.3	(g kg^{-1})

Field experimental design

The experiment followed a split-split plot design (3×3×3) involving three factors, arranged in a completely randomized block Design with three replications. The factors were: (A) irrigation intervals (5, 10, and 15 days), assigned to the main plots; (B) three soybean varieties (Lee74, Ebba, and Shaimaa), placed in the sub-plots; and (C) zinc level (0, 200, and 400 µg L^{-1}), applied by spraying at 30 and 60 days after plant emergence and assigned to the sub-sub plots. Each main plot contained 9 subplots, measuring 2×2 m. Each subplot had 4 rows, with 0.5 meters between rows and 0.4 meters between plants within each row.

Agronomic management: In spring 2023, the seeds were sown on May 23, and the length of the growing season was 150 days from emergence on May 29 to maturity on November 10, 2023.

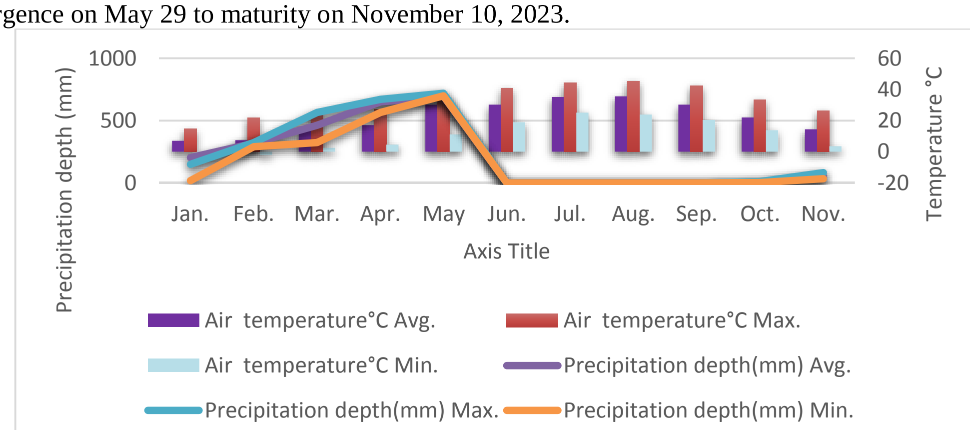

Figure 1: Climatic conditions at the Qlyasan location in 2023.

Experimental parameters:
Plants of 1 m^2 area from each plot were selected, and five plants from each plot were sampled randomly to measure different plant characters: Plant High PH (cm), N. Leaves Plant^{-1} (NLP), N. Branches Plant^{-1} (NBP), Root Depth (RD)(cm), Leaf Area Index (LAI), Root Wight (RW) kg ha^{-1}, Stem Wight(SW) (kg ha^{-1}), No. of Pod plant^{-1} (NPP), Pod Weight (WP) (kg ha^{-1}), Seed Yield (SY) (kg ha^{-1}), 100 Seed Weight (100-SW) (g), Oil Percentage %, and protein Percentage.
Statistical analysis
The Analysis of Variance (ANOVA) was evaluated as a general test of the effects of different irrigation intervals, zinc Nano-fertilizer treatments, and soybean varieties on growth, yield, and yield components. The LSD test ($p \leq 0.05$) was performed for the comparison between mean values. SPSS software was utilized to analyze the data.
Irrigation of soybean:
The drip irrigation system was used to irrigate the soybean crop. The discharge of the dripper was 3.2 L/hr and the volume of water added to each experimental plot was calculated by the following equation [12]

$$V = (d_n * A * \% w) * 1000 \quad \text{.................. (1)}$$

Where:
V = volume of water added for each plot (L);

$$d_n = (FC - WP / 100) (\rho b / \rho w) D \ \% \text{ wetted area} \quad \text{.................. (2)}$$

d_n = depth of water added (m); FC = moisture at field capacity (%); WP = moisture at welting point (%); ρb = soil bulk density (Mg/m^3); ρw = water density (Mg/m^3);
D = depth of soil that must be wetted (m);

$$\% \text{Wetted area} = [(w_d \times w \times n) / a] \times 100 \quad \text{.................. (3)}$$

w_d = wetted diameter of the dripper = 0.40 m; w = the length of land wetted (m)
n = number of planted rows in each plot = 4; a = wetted area, A = area of each plot (4m^2)
Water requirements for soybeans can be calculated by using each of the following approaches:

Water Balance Equation and Actual Evapotranspiration (ET_a):
The water equilibrium equation was used as a direct method to calculate actual water use for the crop, according to this equation [13].

$$(I + P + C) - (ET_a + D + R) = \pm \Delta S \quad \text{.................. (4)}$$

Where:
I = irrigation water added (mm), P = precipitation (mm), C = ground water raising by capillary effect (mm), ET_a = actual evapotranspiration (mm), D = deep percolation (mm), R = surface runoff (mm), ΔS = soil moisture storage at the beginning and end of the season.
For:
R = 0 (because the land is level and runoff is almost zero), C = 0 (because the groundwater table is deep, more than 3 m), D = 0 (because the water was added according to the equation (4) and there
There was no surplus water to go deeper. So, equation (5) will be reduced to:

$$I + P = ET_a \pm \Delta S \quad \text{.................. (5)}$$

Because each term of I, P, and ΔS can be measured easily, ET_a can be computed by using Eq. (5).

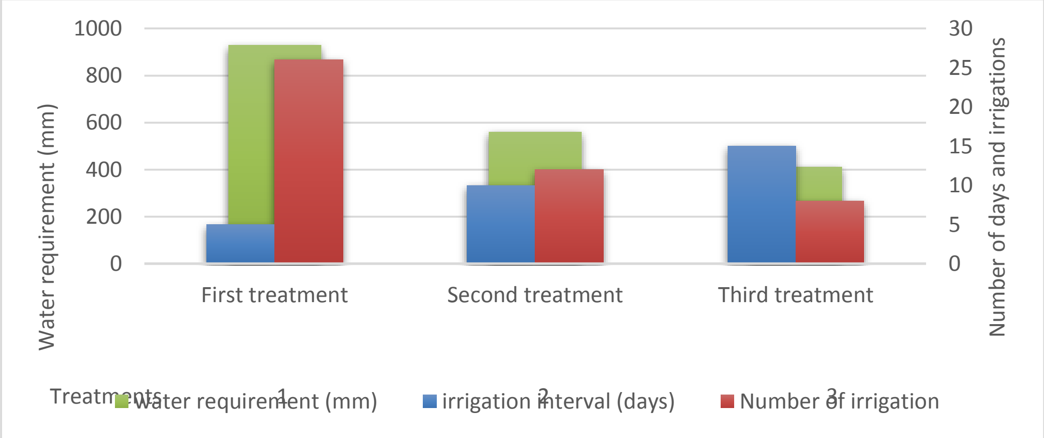

Figure 2: Water requirement for each treatment during the growing season

Results

The effect of individual factors

Vegetative growth trait

Data in Table 2 indicated significant differences at $p \leq 0.05$ among the soybean varieties for most traits. In particular, the highest plant height was associated with the irrigation interval of 5 days, with an average amount of 80.36 cm, which was 20.5 and 39.10% greater than that produced under the irrigation intervals of 10 and 15 days, respectively. The increase in irrigation interval decreased NLP^{-1}, so that the highest NLP^{-1} (53.88 on average) was obtained under the irrigation interval of 5 days, which was 31.41 and 83.76% greater than that under irrigation intervals of 10 and 15 days, respectively. The NBP showed progressive decreases as irrigation intervals lengthened. The 5-day irrigation interval recorded maximum values of (4.63 NBP), representing a 15.2% and 58.0% decrease in branch production when the irrigation interval was further extended to 10 and 15 days, respectively. The RD exhibited a contrasting pattern compared to shooting parameters, with deeper root systems developing under longer irrigation intervals. The 15-day irrigation interval induced the RD at 34.72 cm, while the decreases from 15-day to 5 and 10-day intervals were 52.5 and 21.8%. The LAI exhibited substantial decreases as irrigation intervals extended. The highest value was obtained by the 5-day irrigation interval of 2.53 cm, extending to a 10-day interval, representing a significant 57.2% decrease. When the irrigation interval was further extended to 15 days, LAI increased by 79.4% from the 5-day interval. The RW revealed significant decreases as irrigation intervals shortened. The maximum value observed in the 15-day irrigation interval was 670.38 kg ha^{-1}, reducing to a 10- and 5-day interval, representing a 38.0% and 69.0% decrease, respectively. The 15-day irrigation interval induced the RW at 670.38cm, while the decreases from 15 to 5 and the 10-day interval were RW decreased by 68.59 and 37.96%, respectively. The 5-day irrigation interval demonstrated superior performance, producing an average of 1286.17 kg ha^{-1} SW. In contrast, extending the irrigation interval to 10 and 15 days resulted in a reduction of SW by 31.22% and 56.04% from the 5-day interval.

Table 2 shows differences ($p \leq 0.05$) among the soybean varieties for most traits, except PH. The Shaimaa variety exhibited superior achieving the highest NLP with the amount of 47.88 cm, surpassing Ebba by 8.02% and Lee74 by 49.65%. In terms of NBP, the maximum value was associated with the Ebba variety, with 3.93 branches outperforming Lee74 and Shaimaa by 34.40% and 8.15%, respectively. Shaimaa also displayed the highest RD at 28.00 cm, exceeding Ebba and Lee74 by 8.27% and 14.28%, respectively. However, Lee74 excelled in LAI, with 1.81, surpassing Ebba and Shimaa by 31.59% and a substantial 92.16%. Ebba exhibited the highest RW at 471.72 kg ha^{-1}, outperforming Lee74 and Shaimaa by 29.64% and 2.81%, respectively. Similarly, Ebba dominated in SW with 1202.42 kg ha^{-1}, surpassing Lee74 and Shaimaa by 54.21% and 59.49%, respectively.

Table 2 shows differences ($p \leq 0.05$) among the Nano zinc fertilizers for all traits, especially at the highest level of 400µg L^{-1}, which have shown significant advantages in most of the characteristics measured, at 400 µg L^{-1}, the highest PH was recorded at 71.02 cm, was 6.01% higher than the control treatment. The NLP in 400 µg L^{-1} zinc Nano fertilizer level reached 44. 89 leaves showed a 27.87% increase compared to the control treatment and 26.1% higher than 200 µg L^{-1}, Means comparison for NBP^{-1} at different zinc-nano levels showed 7.60 and 31.75% superiority of the fertilizer level of 400 µg L^{-1} over the fertilizer levels of 200µg L^{-1} and 0 µg L^{-1}, respectively. The depth of the 400µg L^{-1} treatment roots was 28.83 cm, showing a 28.15% increase compared to the control treatment. The LAI is also higher in the 400 µg L^{-1} treatment, showing a 46.35% increase compared to the control treatment. In addition, the application of 400 µg L^{-1} enhanced pod formation to 65.72, showing a 14.80% increase over the control treatment. The highest RW was associated with 200 µg L^{-1} with 442.88 cm which was 8.12 % greater than the control treatment, SW with the same pattern was higher in 200 µg L^{-1} with a maximum value of 977.21 showing an 11.28% increase over the control treatment and indicating an increase of 10.96% than 400 µg L^{-1} treatment.

Table 2: Means comparison effects of irrigation interval, variety, and zinc Nano fertilizer on the growth parameter of soybean.

Treatments	PH (cm)	NLP^{-1}	NBP^{-1}	RD (cm)	LAI	RW (kg ha^{-1})	SW (kg ha^{-1})
Irrigation interval (days)							
5	80.36	53.88	4.63	16.50	2.53	208.13	1286.17
10	66.66	41.00	3.92	27.13	1.08	415.86	884.53
15	57.77	29.33	1.94	34.72	0.52	670.38	565.32
LSD ($p \leq 0.05$)	9.920	1.454	0.210	1.60	0.04	3.29	60.62
Varieties							
Lee74	70.30	32.00	3.63	24.50	1.81	363.86	779.71
Ebba	67.50	44.33	3.93	25.86	1.38	471.72	1202.42
Shaimaa	67.00	47.88	2.94	28.00	0.94	458.80	753.89
LSD ($p \leq 0.05$)	n.s	2.104	0.26	1.20	0.04	11.515	49.647
Zinc Nano fertilizer (µg L^{-1})							
0	67.00	35.11	2.96	22.50	1.11	409.61	878.12
200	66.77	44.22	3.63	27.02	1.40	442.88	977.21
400	71.02	44.88	3.90	28.83	1.62	441.88	880.69
LSD ($p \leq 0.05$)	1.84	1.14	0.20	0.79	0.05	15.00	57.68

Yield and its component

Table (3) shows that the increase in irrigation interval decreased the NPP 25.44 average obtained under the irrigation interval of 15 days, which was 71.85 and 19.85% lower than the 5 and 10 irrigation intervals. The highest seed yield was recorded with the 5days irrigation interval, producing 1449.52 kg ha^{-1}. Extending the irrigation interval to 10 days resulted in a 35.8% reduction in yield, while the 15days interval led to a dramatic 68.4% decrease. The 100 SW was associated with the irrigation interval of 5 days, with an average amount of 10.68, which was 2.90 and 41.74% greater than that produced under the irrigation intervals of 10 and 15 days, respectively. Both oil and protein percentages increased with the decrease in irrigation interval oil percentage recorded the highest value in 5 days with 24.46 which was 4.95 and 9.28% greater than that produced under the irrigation intervals of 10 and 15 days and protein percentage obtained a maximum value in 5 days irrigation interval with 34.51 which was 8.39 and 17.50% greater than that produced under the irrigation intervals of 10 and 15 days.

Table (3) shows that the Ebba variety obtained the highest (NPP) at 67.61 outperforming Lee74 and Shaimaa variety by 4.14% and 24.62%, respectively. Ebba Variety repeatedly proved superior. It exhibited the highest PW at 1831.78 kg ha^{-1}, surpassing Lee74 and Shaimaa varieties by 1.25% and 39.88%, respectively. Similarly, Ebba variety proceeded in SY with 1110.8 kg ha^{-1}, outperforming Lee74 and Shaimaa varieties by 18.01% and 41.31%, respectively. While Ebba variety dominated in yield-related traits, it demonstrated outstanding performance in seed quality traits, achieving the highest 100-SW at 10.1 g, exceeding Ebba variety by 6.74% and Shaimaa by 11.75%. Additionally, Lee74 variety demonstrated superior performance in seed quality parameters, leading in both oil and protein content. Concerning oil content, Lee74 achieved 23.47%, displaying a superiority of 0.81%, exceeding Ebba and 0.33% surpassing Shaimaa. Similarly, for protein content, Lee74 reached 32.21%, surpassing Ebba by 1.60% and Shaimaa by 1.24%, further establishing its dominance in seed quality traits.

Table (3) shows that the 400 µg L^{-1} treatment achieved an NPP of 65.72, representing a 14.79% increase compared to the control treatment. 400 µg L^{-1} treatments resulted in a PW of 1702.33 kg ha^{-1}, surpassing the control treatment by 7.22%. SY with the value of 1021.38 in 400 µg L^{-1} treatments showed a substantial enhancement of 16.03% from the control treatment. The 100-SW displayed a modest improvement of 3.09% compared with the control treatment, the Oil% increased by 2.42% compared with the control, and Protein in 400 µg recorded the highest value32.384 surpassed by 3.62% over the control treatment.

Table (3): Means comparison effects of irrigation interval, variety, and zinc Nano fertilizer for yield and yield components of soybean.

Treatments	NPP^{-1}	PW (kg ha^{-1})	SY (kg ha^{-1})	100-SW (g)	Oil (%)	Protein (%)
			Irrigation interval (days)			
5	89.55	2278.55	1449.52	10.68	24.46	34.51
10	71.77	1775.84	930.472	10.38	23.30	31.84
15	25.44	895.48	457.583	7.53	22.38	29.37
LSD (p≤0.05)	1.639	84.24	14.049	0.407	0.153	0.143
			Varieties			
Lee74	64.91	1809.16	941.27	10.09	23.47	32.21
Ebba	67.61	1831.78	1110.80	9.461	23.28	31.70
Shaimaa	54.25	1308.92	785.50	9.037	23.39	31.81
LSD (p≤0.05)	0.962	88.84	24.471	0.33	0.088	0.175
			Zinc Nano fertilizer (µg L^{-1})			
0	57.25	1587.64	880.27	9.40	22.88	31.36
200	63.80	1659.89	935.91	9.50	23.54	31.98
400	65.72	1702.33	1021.38	9.69	23.72	32.38
LSD (p≤0.05)	1.060	69.041	18.471	0.148	0.114	0.173

The effect of bilateral interactions

Vegetative Growth Traits

Table 4 shows differences among the interaction of irrigation interval and soybean varieties for most traits at p≤0.05. Ebba varieties showed the greatest plant height, recording 84.16cm, followed by Shaimaa at 82.75 cm and Lee74 at 74.16cm. The Ebba variety demonstrated exceptional performance, achieving its peak NLP of 64.83 under a 5-day irrigation interval. In contrast, the Lee74 variety experienced the lowest NLP of 24.00 and acquired a 15-day irrigation interval. The Ebba variety excelled in NBP, reaching its peak of 5.22 during a 5days irrigation interval. In contrast, the Shaimaa variety displayed minimal NLP 1.27 observed induced by a 15days irrigation interval. When exposed to a 15-day irrigation interval, the Shaimaa variety exhibited exceptional RD, reaching 38.33 cm. Conversely, the Lee74 cultivar displayed the most restricted root development, with a minimal RD of 14.66 cm under a 5-day irrigation interval. The largest LAI 3.56 was obtained in 5 days of irrigation for the Lee74 variety, while the lowest 0.38 was in 15 days of irrigation for the Ebba variety. As far as RW is concerned, the highest average of 668.33kg ha^{-1} was obtained in the 15day interval of the Shaimaa variety, while the lowest average of 157.25 kg ha^{-1} was recorded in the 5day interval of the Ebba variety, the highest SW 1711.88 kg ha^{-1} occurred during the 5-day interval in the Ebba variety, and the lowest weight in the 15-day interval in the Shaimaa 541.17 kg ha^{-1}.

Table (4) shows differences among the interaction of irrigation interval and Nano zinc fertilizers level for most traits at p≤0.05, except RW and SW. During the 5-day irrigation interval, the fertilizer 200 µg L^{-1} of Nano zinc had the highest PH at 81.83cm and the lowest height at 54.50 cm in the 15 days. In the 5-day irrigation with 200 µg L^{-1} Nano zinc, the maximum NLP 59.00 was recorded, while the lowest NLP 24.16 was observed in the 15days irrigation with no-fertilizer level. For the NBP, the highest NBP of 5.22 was seen in the 5days interval on the level 400 µg L^{-1} Nano zinc, and the lowest number, 1.77, was observed in the 15days irrigation on the same fertilizer level. In 15days irrigation, RD was the highest at 35.16 cm in 15days irrigation intervals with 200 µg mL^{-1} and 400µg mL^{-1} Nano zinc fertilizer. The lowest 11.83 cm was noted in control treatments during the 5days irrigation. The LAI reached a maximum of 2.78 in the 5days irrigation with 400 µg mL^{-1}, and in the 15days irrigation interval, it reached 0.40 with 200 µg mL^{-1}.

The data in Table 4 indicate significant differences at (p≤0.05) in most examined traits, except the NBP. Regarding PH, the Ebba variety exhibited the most substantial growth compared to the control treatment, measuring 69.33 cm; the Shaimaa variety, under the same control treatment, recorded the least height at 64.33 cm. Regarding NLP^{-1} Shaima variety, subjected to the maximum fertilizer level of 400 µg L^{-1}, the highest number at 51.50, while the Lee74 variety attained the lows NLP^{-1} with the control treatment, quantified at 25.83, RD was maximized in the Shaimaa variety treated with 400 µg L^{-1} of fertilizer, reaching 30.66 cm, while the Lee74 variety under the control treatment, demonstrated the least RD at 19.33 cm. The highest LAI was observed in the Lee74 variety treated with 400 µg L^{-1} of nano zinc fertilizer, measuring 2.23, whereas the least was recorded in the Shaimaa variety under the control treatment at 0.77 cm, RW is concerned, the highest average of 502.08kg ha^{-1} was obtained in the Ebba variety interval of the 200mgL^{-1}, while the lowest average of 333.83kg ha^{-1} was recorded in the Lee variety of the no fertilizer treatment, the highest SW 1306.1kg ha^{-1} occurred during the Ebba in the 200mgL^{-1}, and the lowest weight 679.66 kg ha^{-1}.in the in the Shaimaa variety with no fertilizer treatment.

Table (4) means a comparison of the treatments' bilateral interactions.

Treatments		PH (cm)	NLP^{-1}	NBP^{-1}	RD (cm)	LAI	RW (kg ha^{-1})	SW (kg ha^{-1})
Irrigation interval (days) × varieties								
	Lee74	74.16	42.00	4.77	14.66	3.56	217.66	1211.2
5	Ebba	84.16	64.83	5.22	16.33	2.30	157.25	1711.8
	Shaima	82.75	54.83	3.88	18.50	1.73	249.50	935.33
	Lee74	67.41	30.00	3.11	28.83	1.09	386.91	666.72
10	Ebba	67.50	35.50	5.00	25.41	1.45	402.08	1201.72
	Shaimaa	65.08	57.50	3.66	27.16	0.70	458.58	785.17
15	Lee74	69.33	24.00	3.00	30.00	0.79	487.00	461.13
	Ebba	50.83	32.66	1.55	35.83	0.38	855.83	693.66
	Shaima	53.16	31.33	1.27	38.33	0.39	668.33	541.17
LSD (p≤0.05)		10.37	3.64	0.49	2.085	0.071	19.945	85.991
Irrigation interval (days)× zinc Nano fertilizer (µg L^{-1})								
5	0	79.16	46.66	3.88	11.83	2.10	185.91	1247.75
	200	81.83	59.00	4.77	14.66	2.72	231.75	1329.50
	400	80.08	56.00	5.22	23.00	2.77	206.75	1281.26
	0	66.41	34.50	3.22	21.83	0.77	382.83	804.77
10	200	64.00	41.50	4.11	31.25	1.08	425.41	960.17
	400	69.58	47.00	4.44	28.33	1.40	439.33	888.66
	0	55.41	24.16	1.77	33.83	0.45	660.08	581.83
15	200	54.50	32.16	2.00	35.16	0.40	671.50	641.97
	400	63.41	31.66	2.05	35.16	0.70	679.58	472.16
LSD (p≤0.05)		3.18	1.98	0.34	1.38	0.08	n.s	n.s
varieties × zinc Nano fertilizer (µg L^{-1})								
	0	67.33	25.83	2.88	19.33	1.51	333.83	872.05
Lee74	200	67.33	36.83	3.77	25.00	1.70	351.91	775.97
	400	76.25	33.33	4.22	29.16	2.23	405.83	691.12
	0	69.33	36.83	3.55	22.66	1.04	486.58	1082.6
Ebba	200	65.16	46.33	4.00	28.25	1.50	502.08	1306.1
	400	68.00	49.83	4.22	26.66	1.59	426.50	1218.4
Shaima	0	64.33	42.66	2.44	25.50	0.77	408.41	679.66
	200	67.83	49.50	3.11	27.83	1.00	474.67	849.50
	400	68.83	51.50	3.27	30.66	1.06	493.33	732.50
LSD (p≤0.05)		3.183	1.982	n.s	1.38	0.08	25.98	99.91

Yield and Yield component traits

Table (5) indicates that NPP was highest in 5 days of irrigation in Ebba variety 94.83 and lowest in 15 days of irrigation in Shaimaa variety 23.16, the highest PW was also observed in the 5days interval of the Ebba variety 2690.25 kg ha^{-1}, while the lowest was observed in the 15days interval of the Shaimaa variety 823.66 kg ha^{-1}. The SY realized this during 5 days of irrigation, and the Ebba variety was 1794.66 kg ha^{-1}, the lowest was during 15 days, and the Shaimaa variety was 382.25 kg ha^{-1}. The highest 100-SW 12.53g was observed at Lee74 for 5 days and the lowest weight was 6.33g in the same variety for 15 days. The Oil percentage was the highest on 5 days, 24.56% in the Shaimaa variety, and the lowest value was 21.51% in the same variety under a 15days irrigation interval. Finally, the protein percentage reached the highest value in the 5days irrigation interval, 34.8% for the Lee74 variety, followed by the lowest in the 15days interval for the same variety, 29.41.

Table(5) revealed that applying nano zinc fertilizer at a level of 200 µg L^{-1} in combination with a 5days irrigation interval resulted the highest NPP^{-1} 92.92, whereas the lowest number 21.83 was observed under a 15days irrigation interval with the control treatment. In terms of PW, the highest value (2288.67) kg ha^{-1} was achieved with 5 days of irrigation and 400 µg L^{-1} of fertilizer, while the lowest 835.61 kg ha^{-1} occurred under the control treatment with 15 days of irrigation. Similarly, SY was maximized 1589.50 kg ha^{-1} under the same 5days irrigation with 400 µg L^{-1}, contrasting sharply with the SY 407.33 kg ha^{-1} recorded under the 15days with control treatment. Furthermore, the greatest 100-SW 10.93 g was obtained with 5 days of irrigation and 200 µg L^{-1} of nano zinc fertilizer, while the lowest 100-SW 7.40 was associated with the 15-day irrigation under the same fertilizer level. Regarding seed composition, the highest oil content 24.75% and protein content 34.51% were recorded under the 5days irrigation with 400 µg L^{-1} fertilizers, whereas the lowest values for both parameters 22.15% for oil and 29.18% for protein were found under the control treatment with a 15days irrigation interval.

Table 5 shows that the Ebba variety under 400 µg L^{-1} fertilizers exhibited the highest NPP at 72.00, in contrast to the Shaimaa variety with the control treatment, which demonstrated the lowest NPP at 50.91. When subjected to 400 µg L^{-1} fertilizer, the Ebba variety also produced the heaviest pods, weighing 1914.50 kg ha^{-1}, while the Shaimaa variety under the control treatment recorded the lightest PW at 1179.33 kg ha^{-1}. Furthermore, the Ebba variety with 400 µg mL^{-1} fertilizers demonstrated the highest SY at 1118.2 kg ha^{-1}, in contrast to the Shaimaa variety treated with no fertilizer, which exhibited the lowest SY at 723.08kg ha^{-1}. Additionally, the Lee74 variety treated with 400 µg L^{-1} fertilizer produced the greatest 100SW at 11.080, whereas the Shaimaa variety receiving 200 µg L^{-1} fertilizers had the least number of seeds at 8.628%. The maximum oil content was observed in the Lee74 variety subjected to a treatment of 400µg L^{-1} of fertilizer at 23.86%, whereas the minimum was found in the Ebba variety under the comparison treatment at 22.71%. Finally, the Lee74 variety treated with 400µg L^{-1} fertilizer exhibited the highest protein content 32.81%, in contrast to the Shaimaa variety under the comparison treatment, which recorded the lowest value (31.49%).

Table (5) means a comparison of the treatments' bilateral interactions

Treatments		NPP^{-1}	PW (kg ha^{-1})	SY (kg ha^{-1})	100-SW (g)	Oil (%)	Protein (%)
Irrigation interval (days) × varieties							
5	Lee74	87.25	2292.33	1250.58	10.36	24.53	34.80
	Ebba	94.83	2690.25	1794.66	9.15	24.28	34.18
	Shaimaa	86.58	1853.08	1303.33	12.53	24.56	34.55
10	Lee74	81.16	2187.25	1063.66	11.49	23.11	32.53
	Ebba	81.16	1890.25	1056.83	11.10	23.33	31.51
	Shaimaa	53.00	1250.02	670.91	8.54	23.46	31.47
15	Lee74	26.33	947.91	509.58	8.44	22.76	29.29
	Ebba	26.83	914.86	480.91	8.13	22.23	29.40
	Shaimaa	23.16	823.66	382.25	6.03	22.15	29.42
LSD (p≤0.05)		1.66	153.88	42.386	0.56	0.153	0.303
Irrigation interval (days)× zinc Nano fertilizer (µg L^{-1})							
5	0	83.41	2143.70	1368.75	10.51	24.01	33.83
	200	92.92	2288.67	1390.25	10.93	24.61	34.26
	400	92.33	2403.20	1589.58	10.61	24.75	34.51
10	0	66.50	1783.53	864.750	10.21	22.48	31.43
	200	73.17	1699.11	959.917	10.17	23.61	31.76
	400	75.66	1844.83	966.750	10.74	23.81	32.11
15	0	21.83	835.611	407.333	7.48	22.15	29.18
	200	25.33	991.917	457.583	7.40	22.40	29.50
	400	29.17	858.916	507.833	7.71	22.60	29.85
LSD (p≤0.05)		1.84	119.582	31.993	0.25	0.197	n.s
Varieties × zinc Nano fertilizer (µg L^{-1})							
	0	57.50	1912.66	802.33	9.52	22.86	31.60

Lee74	200	66.41	1741.67	1022.1	9.69	23.68	32.22
	400	70.83	1773.16	999.33	11.08	23.86	32.18
	0	63.33	1670.94	1115.4	8.83	22.71	30.98
Ebba	200	67.50	1909.91	1098.7	10.19	23.40	31.77
	400	72.00	1914.50	1118.2	9.36	23.73	32.34
	0	50.91	1179.33	723.08	9.84	23.06	31.49
Shaimaa	200	57.50	1328.11	686.83	8.62	23.55	31.95
	400	54.33	1419.33	946.58	8.63	23.56	31.98
LSD ($p\leq0.05$)		1.84	119.58	31.99	0.257	0.197	.030

The effect of triple interactions
Vegetative Growth Traits

Table 6 shows differences among the interaction of irrigation interval, soybean varieties, and application of Nano zinc fertilizer level for all traits at $p\leq0.05$, The Ebba variety demonstrated its most impressive vertical growth, reaching a peak height of 85.00 cm when cultivated under a 5-day irrigation interval and supplemented with 200 µg L^{-1} of Nano zinc fertilizer. In contrast, the same Ebba variety exhibited significantly impaired growth, measuring only 47.00 cm when acquired to a 15day irrigation interval without zinc fertilizer treatment, in terms of NLP^{-1}, the integration of a 5-day irrigation interval, the Ebba variety, and a fertilizer concentration of 400µg L^{-1} resulted in the maximum NLP^{-1} 72.00. Conversely, the minimum NLP^{-1} of 18.00 was recorded during the 15-day irrigation interval with the Lee74 variety under the control treatment of zinc fertilizer levels. For the NBP, the 5-day irrigation and the Ebba variety with the 400 µg L^{-1} Nano zinc fertilizer level achieved the highest number, 6.00, while the lowest value of 1.00 was seen in the 15days irrigation with the Lee74 variety at the control treatment of zinc fertilizer. In terms of RD, the 15-day irrigation with the Ebba variety and the 200 µg L^{-1} fertilizer level recorded the highest RD at 37.50 cm, while the 5days irrigation with the Lee74 variety at the control treatment of zinc fertilizer had the lowest 10.00 cm. The LAI was maximized in the 5days irrigation with the Lee74 variety and the 200 µg L^{-1} fertilizer level, measuring 3.70, whereas the lowest area of 0.240 was observed in the 15days irrigation interval with the Ebba variety and the 400 µg L^{-1} fertilizer level. The RW was observed to be at its zenith during the 15days irrigation interval for the Ebba variety under the control treatment of zinc fertilizer, attaining a measurement of 965.50 kg ha^{-1}; conversely, the 5-day irrigation interval associated with the Ebba variety under the same control treatment exhibited the minimum weight at 141.00 kg ha^{-1}. In terms of SW, the optimal combination of the 5days irrigation interval accompanied by Ebba variety with the 200µg L^{-1} of Nano zinc fertilizer yielded the maximum weight of 1815.50 kg ha^{-1}, whereas the minimal weight of 336.00 kg ha^{-1} was documented during the 15days irrigation interval with the Shaimma variety at a level of 400µg L^{-1}.

Table (6) Means comparison of the triplicate interaction.

Treatments			PH (cm)	NLP^{-1}	NBP^{-1}	RD (cm)	LAI	RW (kg ha^{-1})	SW (kg ha^{-1})
		0	70.00	35.50	4.00	10.00	3.310	162.75	1375.25
	Lee74	200	77.50	47.50	5.00	13.00	3.690	227.00	1233.00
		400	75.00	43.00	5.33	21.00	3.65	263.25	1025.62
		0	84.00	53.50	4.33	11.00	1.49	141.00	1519.50
	Ebba	200	85.00	69.00	5.33	15.00	2.78	188.25	1815.50
5		400	83.50	72.00	6.00	23.00	2.63	142.50	1800.66
		0	83.50	51.00	3.33	14.50	1.50	254.00	848.50
	Shaimaa	200	83.00	60.50	4.00	16.00	1.69	280.00	940.01
		400	81.75	53.00	4.33	25.00	2.00	214.50	1017.50
		0	59.75	24.00	2.33	22.50	0.73	368.50	743.16
	Lee74	200	60.50	33.50	3.00	30.00	0.93	342.75	683.50
		400	82.00	32.50	4.00	34.00	1.60	449.50	573.50
		0	77.00	30.00	4.33	23.00	1.05	362.25	1047.17
	Ebba	200	61.50	36.00	5.33	32.25	1.41	412.50	1309.50
10		400	64.00	40.50	5.33	21.00	1.90	431.50	1248.50
		0	62.50	49.50	3.00	20.00	0.53	417.75	624.00
	Shaimaa	200	70.00	55.00	4.00	31.50	0.89	521.00	887.52
		400	62.75	68.00	4.00	30.00	0.69	437.00	844.00
		0	72.25	18.00	2.33	25.50	0.50	470.25	497.75
	Lee74	200	64.00	29.50	3.33	32.00	0.49	486.00	411.41
		400	71.75	24.50	3.33	32.50	1.38	504.75	474.25
		0	47.00	27.00	2.00	34.00	0.59	956.50	681.25
15	Ebba	200	49.00	34.00	1.33	37.50	0.32	905.50	793.50
		400	56.50	37.00	1.33	36.00	0.24	705.50	606.25

	0	47.00	27.50	1.00	42.00	0.28	553.50	566.50
Shaimaa	200	50.50	33.00	1.33	36.00	0.41	623.00	721.00
	400	62.00	33.50	1.50	37.00	0.48	828.50	336.00
LSD ($p \leq 0.05$)		5.513	3.432	0.596	2.381	0.145	45.004	173.043

Yield and Yield component trait

Table (6) shows Regarding the NPP^{-1}, the 5-day irrigation interval combined with the Ebba variety at the concentration of 200 and 400µg L^{-1} of Nano zinc fertilizer reported the highest NPP of 96.00, in contrast to the 15-day irrigation interval with the Lee74 variety, which under the control treatment of the zinc Nano fertilizer level registered the lowest value 21.50. with admiration to PW, the 5-day irrigation interval with the Ebba variety at the concentration of 400µg L^{-1} of Nano zinc fertilizer recorded the highest weight of 2833.50 kg ha^{-1}, while the 15-day irrigation interval with the Ebba variety under the control treatment of zinc exhibited the lowest weight of 583.33 kg ha^{-1}; additionally, SY reached its maximum in the 5days irrigation interval with the Ebba variety at the 200µg L^{-1} fertilizer level 1823.75 kg ha^{-1}, while the minimum was observed during the 15days irrigation interval with the Shaimaa variety under the control treatment of zinc, yielding a weight of 355.25 g. The greatest weight for the 100-SW was recorded at 12.96 g in the 5days irrigation interval with the Shaimaa variety under the control treatment of zinc, whereas the minimum weight of 4.27 g was noted in the 15-day irrigation interval with the Shaimaa variety at the 400µg L^{-1} level of Nano zinc fertilizer. The oil percentage was maximized at 24.85% during the 5dasy irrigation interval for both the Lee74 and Ebba varieties at the 400µg L^{-1} level of Nano zinc fertilizer, while the lowest oil percentage of 21.75% was observed in the 15days irrigation interval with the Shaimaa variety under the control treatment of zinc. Lastly, the protein percentage exhibited an increase to 34.97% during the 5days irrigation interval with the Lee74 variety at the 400µg L^{-1} level of Nano zinc, while the minimum protein percentage of 28.750% was recorded during the 15days irrigation interval with the Ebba variety under the control treatment of nano zinc fertilizer.

Table (7) Means comparison of the triplicate interaction.

Treatments			NPP^{-1}	PW (kg ha^{-1})	SY (kg ha^{-1})	100-SW (g)	Oil (%)	Protein (%)
5	Lee74	0	78.50	2324.75	1019.50	8.94	24.15	34.30
		200	89.75	2320.25	1282.00	10.37	24.60	35.14
		400	93.50	2232.00	1450.25	11.77	24.85	34.97
	Ebba	0	92.50	2517.75	1750.75	9.610	23.55	33.05
		200	96.00	2719.50	1823.75	10.20	24.45	34.28
		400	96.00	2833.50	1809.50	7.64	24.85	35.23
	Shaimaa	0	79.25	1588.75	1336.00	12.96	24.35	34.15
		200	93.00	1826.25	1065.00	12.22	24.80	34.60
		400	87.50	2144.25	1509.00	12.42	24.55	34.90
10	Lee74	0	72.50	2379.75	938.75	11.17	21.80	31.45
		200	86.00	2025.25	1310.00	11.53	23.70	32.45
		400	85.00	2156.75	942.25	11.77	23.85	33.70
	Ebba	0	74.00	1911.75	1177.50	10.89	22.55	31.15
		200	80.50	1832.75	951.75	11.16	23.60	31.55
		400	89.00	1926.25	1041.25	11.26	23.85	31.85
	Shaimaa	0	53.00	1059.25	478.00	8.58	23.10	31.47
		200	53.00	1239.33	618.00	7.84	23.55	31.70
		400	53.00	1451.50	916.75	9.21	23.75	31.24
15	Lee74	0	21.50	1033.50	448.75	8.45	22.65	29.05
		200	23.50	879.50	474.50	7.185	22.75	29.08
		400	34.00	930.75	605.50	9.695	22.90	29.75
	Ebba	0	23.50	583.33	418.00	6.00	22.05	28.75
		200	26.00	1177.50	520.75	9.21	22.15	29.50
		400	31.00	983.75	504.00	9.18	22.50	29.95
	Shaimaa	0	20.50	890.00	355.25	8.00	21.75	28.87
		200	26.50	918.75	377.50	5.82	22.30	29.55
		400	22.50	662.25	414.00	4.27	22.40	29.85
LSD ($p \leq 0.05$)			3.18	207.12	55.41	0.44	0.342	0.518

Discussion

Indicators of soybean vegetative growth and productivity in tables 2-7 reveal that better performance under frequent irrigation is achieved by reducing water pressure, allowing plants to focus on growth and yield above the ground. In the meantime, less frequent irrigation promotes deeper root systems, but plants invest more in survival mechanisms to cope with water shortages, which results in a reduction in the parameters of stems and yields this result is agreement with [9], who noted that well-watered plants exhibited greater height and produced a higher number of leaves compared to those subjected to drought stress. Similarly, [14] documented an increased number of pods and seeds per pod associated with higher irrigation frequencies, while [15] substantiated the correlation between irrigation frequency and biomass production, highlighting significant enhancements in seed quality associated with irrigation intervals of 5 to 7 days, the quality of seeds, especially protein content, is favorably influenced by the frequency of irrigation. Furthermore, five-day irrigation intervals promote crop height, yield, and nutritional quality by optimizing moisture management, improving nutrients, and minimizing water stress. Water stress resulted in decreased photosynthesis, reduced transpiration and cell expansion, and consequently reduced total top dry weight and yield components [14], [15]. Substantiating the correlation between irrigation frequency and biomass production, highlighting significant enhancements in seed quality associated with irrigation intervals of 5 to 7 days. Reduction of crop yields[16] highlighted enhanced biomass and seed quality with (5–7) days of irrigation intervals. The varying responses of soybean varieties to Nano zinc fertilizer levels can be attributed to several pivotal factors. Primarily, genetic differences among varieties influence their ability to absorb, translocation, and utilize zinc efficiently. The preeminence of the Ebba variety in yield-related characteristics, including elevated shoot weight, pod weight, and seed yield, can be ascribed to its proficient biomass accumulation and superior allocation of resources towards reproductive structures. The variety's increased number of pods per plant and elevated 100-seed weight underscore its robust reproductive efficiency and enhanced seed-filling capacity. Concurrently, Lee74's proficiency in the leaf area index indicates augmented photosynthetic efficiency and light interception capabilities, while its superior oil and protein content suggest distinct genetic determinants influencing seed composition and quality traits the superiority of the shaimaa variety (NLP^{-1} to NBP^{-1} and RD) likely arises from its genetic predisposition towards enhanced vegetative growth and root system development, which are typically the result of adaptations aimed at optimizing nutrient and water absorption. The utilization of Nano zinc fertilizer markedly enhances the growth and yield of soybeans, particularly at a level of 400 µg L^{-1}. This benefit can be attributed to the essential function of zinc in plant physiological processes, the enhancement of nutrient uptake, and the augmentation of stress resistance. Nevertheless nan zinc fertilizer at 400 µg L^{-1} significantly boosts growth and yield b enhancing nutrient uptake, stress resistance, and physiological processes [17], demonstrating its importance in optimizing soybean productivity, the effectiveness of 200 µg L^{-1} in fostering certain attributes highlights the necessity of employing a balanced fertilizer regimen to maximize both growth and nutritional quality in soybeans..

The findings of this study align with those of [20], who reported that high yielding varieties markedly surpassed others when optimal fertilizer application was employed, demonstrating that genetic potential can be fully realized through appropriate management practices, as well as agreement with [21], who similarly identified significant variations in oil and protein content across different soybean genotypes and [22], the result corroborates the conclusions of [23], who posited that the foliar application of Zn nanoparticles was more effective in boosting crop yields compared to traditional soil applications. Furthermore, foliar spraying has been shown to enhance crop quality; [24] Nano fertilizers are rapidly absorbed by plants, addressing food scarcity issues while promoting plant growth[17], [18] observed up to a 25% improvement in water use efficiency with zinc supplementation under moderate water stress, [19] concluded that the foliar application of ZnO nanoparticles led to improve the quality of crop, improved crop yields quality in terms of protein, carbohydrate, These findings emphasize the importance of zinc, genetic adaptability, and environmental conditions in improving soybean productivity under varying cultivation conditions.

Conclusions

The study found that the more frequent irrigation intervals (every 5 days) resulted in the maximal plant height, leaf area, pod weight, seed yield, oil and protein content, illustrating the critical role of consistent moisture availability in maximizing agricultural productivity. Applying zinc Nano-fertilizers, particularly at a level of 400 µg L^{-1}, further augmented plant resilience against water stress, enhancing growth parameters and elevating yield components. The interplay between irrigation frequency and zinc Nano-fertilizer application accentuates the necessity of harmonizing water management with nutrient supplementation to optimize soybean productivity. These findings provide critical insights for enhancing water use efficiency and nutrient management practices in soybean cultivation, especially in environments characterized by water scarcity.

Conflict of interest
None

Author Contribution
S. A. Mahmood: Suggested the proposal, analyzed the data, and wrote the manuscript.
Fieldwork and data presentation.

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تحسين النمو وانتاجية وجودة الاصناف فول الصويا باستخدام فترات الري وسماد الزنك النانوي في ظل ضروف شبه قاحلة.

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الخلاصة

الخلفية: بسبب التأثير العام لتغير المناخ، من المتوقع أن يؤدي الزيادة الكبيرة في طلبات الري عالميًا إلى تحديات مستقبلية في الزراعة.

الأهداف: دراسة تأثير فترة الري واستخدام سماد الزنك النانوي على نمو فول الصويا(*Glycine max L.*) [، والمحصول، ومكونات المحصول، وجودة الزيت.

المنهجية: أجريت تجربة ميدانية في محطة قلياسان، جامعة السليمانية، السليمانية، العراق، في ربيع 2023، لدراسة تأثير فترات الري وسماد الزنك النانوي على نموو حاصل وفول الصويا. باستخدم تصميم التجربة القطع المنشقة المقسمة وبثلاث مكررات، حيث كانت فترات الري (5 و 10 و 15 يومًا) في الالواح الرئيسية، ثلاث أصناف من فول الصويا(لي 74، إبا، وشيماء) في الالواح الفرعية ، وثلاثة مستويات من سماد الزنك النانوي في اللوحة الفرعية الفرعية (0 و 200 و 400 ميكروغرام / لتر)، باستخدام الري بالتنقيط بمعدل 3.4 لتر / ساعة.

النتائج: اظهرت نتائج التجربة أن فترات الري كل 5 ادت الى معايي تحسينات ملحوظة في نمو النبات مثل الارتفاع، ومساحة الأوراق، ووزن البذور، ومحتوى الزيت والبروتين. ساعد تطبيق سماد الزنك النانوي بتركيز 400 ميكروغرام / لتر في تحسين عمق الجذور ووزن القرون ومحتوى الزيت، بينما ادى تطبيق 200 ميكروغرام / لتر من السماد الزنك النانوى الى زيادة إنتاج البروتين بشكل مثالي. حقق صنف إيبا أعلى محصول بذور (1823.75 كغم / هكتار) تحت ري كل 5 أيام مع 200 ميكروغرام / لتر من سماد الزنك النانوي. أنتج صنف لي 74 أعلى نسبة بروتين (34.973%) مع ري كل 5 أيام و 400 ملي غرام / لتر من الزنك. وصل كل من صنفي لي 74 وإباء إلى أعلى محتوى من الزيت (24.85%) تحت ري كل 5 أيام مع 400 ملي غرام / لتر من سماد الزنك النانوي.

الاستنتاجات: ساهمت فترات الري القصيرة في تحسين نمو وانتاجيةفول الصويا،كما عززت المستويات العاليةمن سماد الزنك النانوي من قدرة النبات على مقاومة الاجهاد المائي،مما ادى الى تحسين الصفات الفسيولوجية والانتاجية.

الكلمات المفتاحية: [*Glycine max (L.) Merr*].، الأسمدة النانوية،،جدولة الري ، إدارة إجهاد المياه،.