Impact of Combined and Separate Water, Salinity, and Nitrogen Stresses on Morpho-Physiological Traits and Yield Components of Camelina sativa

Mansoureh Bayram[1,*]
[1] PhD of Irrigation and drainage, Tarbiat Modares University, Tehran, Iran

ABSTRACT

Abiotic stresses such as water, salinity, and nitrogen stresses pose significant threats to crop growth and yield, limiting oilseed production in arid and semi-arid regions. A completely randomized factorial design experiment was conducted to evaluate the morpho-physiology, grain yield, and yield components of Camelina under separate stresses (water, salinity, and nitrogen) as well as combined stresses, including: water and salinity, water and nitrogen, salinity and nitrogen, and the simultaneous application of water, salinity, and nitrogen. Treatments consisted of five salinities (1, 2, 4, 6, and 10 dS/m), three irrigation levels (100%, 75%, and 50% of field capacity), and three nitrogen concentrations (100%, 75%, and 50% of the recommended nitrogen dose), each with three replicates. The variance analysis results indicated that separate water and salinity stresses significantly affected grain yield and oil percentage at the 5% significance level. Furthermore, combined stresses-such as water and salinity, water and nitrogen, and the combination of water, salinity, and nitrogen -had a significant effect on oil percentage at the 1% level. The combined effects of water, salinity, and nitrogen also significantly impacted grain yield at the 5% level. Mean comparisons revealed that grain yield increased up to 75% field capacity, after which it decreased. The highest grain yield and oil percentage were recorded at a salinity level of 4 dS/m. Nitrogen deficiency reduced the leaf greenness index, decreased radiation absorption, hindered plant growth, and reduced the leaf area index. Overall, at certain thresholds of salinity, water and nitrogen, an increase in yield and yield components can be observed, suggesting the presence of tolerance levels for these abiotic stresses.

Keywords: *camelina; salinity stress; water stress; grain yield; nitrogen concentration; oil percentage*

1. *INTRODUCTION*

Abiotic stresses, such as salinity and water stress, pose increasingly severe threats to agriculture [1], often leading to substantial reductions in crop yields—sometimes halving the potential harvest of major crops [2]. Furthermore, nitrogen is also a significant limiting factor in agricultural productivity. Arid and semi-arid regions face three main challenges: Water, salinity, and nutrient deficiency. Understanding the morpho-physiological changes is crucial for selecting varieties that can resist and thrive under these conditions [3].

Water stress disrupt several physiological and biochemical processes in crops, including photosynthesis, osmotic potential, and turgor pressure, as well as causing serious damage to the cell membranes, ultimately reducing yields [4]. Additionally, water stress inhibits nitrogen mineralization and limits nitrogen transport to the roots [5]. During such stress, leaf stomata tend to close, restricting nutrient availability. Foliar nutrient applications can be an effective strategy to mitigate the negative effects of water stress [6].

Water stress disrupts several physiological and biochemical processes in crops, including photosynthesis, osmotic potential, and turgor pressure, leading to significant damage to cell membranes and ultimately resulting in reduced yields [4]. Furthermore, water stress inhibits nitrogen mineralization and restricts nitrogen transport to the roots [5]. During periods of water stress, leaf stomata tend to close, which limits nutrient availability. In this context, foliar nutrient applications can serve as an effective strategy to alleviate the adverse effects of water stress [6]. Nitrogen is an essential nutrient for the production of oilseed crops[7], as it plays a crucial role in promoting LAI, enhancing light interception, facilitating protein synthesis, and contributing to dry matter accumulation in reproductive organs. A deficiency in nitrogen significantly impairs these processes, consequently limiting crop productivity[8].

Salinity has been estimated to affect approximately one billion hectares of land [9] across more than 100 countries [10]. In Iran, about 7 million hectares are impacted by soil salinity [11]. The most significant consequences of salinity stress include reduced plant growth and yield, osmotic stress, nutritional imbalances—particularly involving calcium (Ca) and potassium (K)—and direct ion toxicity effects on metabolic processes [12-14]. As salinity levels rise, crop yields decline correspondingly [15-16]. Additionally, soil salinity adversely affects the physiological activities of plants by increasing oxidative damage, reducing turgor pressure, and altering leaf gas exchange [17]. These factors ultimately lead to decreased plant growth, development, and yield [18-19]. Furthermore, nitrogen deficiency is exacerbated under saline conditions compared to non-saline environments for several reasons, including insufficient root development, competition between nitrate (NO_3^-) and chloride (Cl^-) ions for uptake sites, and nitrogen leaching as nitrate below the root zone [12]. In such conditions, foliar spraying of nutrients can be used as a viable management strategy.

Camelina sativa is an important source of oil, comprising 45–50% by volume in mature seeds, and protein, contributing (40% in rapeseed meal) suitable for both human and animal nutrition [20]. Notably, at least 90% of the dry grain weight consists of unsaturated fatty acids [21]. This oilseed exhibits exceptional drought resistance, making it well-suited for cultivation in arid climates. Compared to its "sister crop," rapeseed, Camelina sativa demonstrates greater resilience, requiring fewer inputs and displaying enhanced resistance to abiotic stresses [22]. Additionally, it plays a critical role in producing cuticular wax, which mitigates water loss, facilitates gas exchange, and provides protection against abiotic challenges [23-25]. The oil extracted from Camelina sativa has a diverse range of applications and can be utilized for industrial, food, and pharmaceutical purposes [26]. Its oil and meal are incorporated into diets for animals and ruminants [27], and it has been proposed as a cost-effective feedstock for biodiesel production [28].

2. *INTRODUCTION*

A pot experiment was conducted in a greenhouse using Camelina sativa L. and loam soil. Soil samples were collected from the topsoil (0–30 cm) of the surface horizon in Eyvanekey Garmsar, Semnan, Iran (35.322N, 52.056E). Key physical and chemical properties of the soil are presented in Table 1. Saline water was sourced from the natural saline lake of Howz-e Soltan, Qom, Iran (50.811N, 34.465E), with its original properties outlined in Table 2. To create the saline water treatments, well water (EC = 0.85) was diluted with saline lake water. Pots with dimensions of 18 cm in height and diameter were compacted to a density of 1.32 g/cm³. Ten Camelina seeds were sown per pot, and the experimental treatments were applied after germination.

Table 1. Some physical and chemical properties of the experimental saline soil

Texture	θ_{FC}	pH	EC (dS/m)	$CaCO_3$ (%)	OC (%)	Cl^-	Na^+	Ca^{2+}	SO_4^{2-}	K^+ (mg/kg)	Mg^{2+} (mg/kg)
						(g/kg)					
loamy	0.329	7.5	5	11	0.3	0.789	1.29	0.262	2.51	30	65.43

Table 2. Some chemical properties of the natural saline water before dilution

EC (dS/m)	pH	HCO_3^-	Cl^-	K^+	Na^+	Mg^{2+}	Ca^{2+}	SO_4^{2-} (mg/l)	B (mg/l)
		(g/l)							
144	8.15	2.06	38.64	0.66	27.6	5.37	0.288	81.96	13.15

The experimental treatments comprised five salinity levels (1, 2, 4, 6, and 10 dS/m), three irrigation regimes (100%, 75%, and 50% of field capacity), and three nitrogen concentrations (100%, 75%, and 50% of the recommended nitrogen levels), each with three replications. Nitrogen treatments ($S_0W_0N_i$) were administered by applying NPK fertilizer in liquid form during three growth stages: tillering, stem elongation, and flowering. After each irrigation, the volume of drainage water and its electrical conductivity were measured. Evapotranspiration was calculated using soil water balance and by weighing the pots daily. Control pots (without plants) were placed alongside the experimental pots to measure evaporation, allowing for the separation of transpiration from total evapotranspiration. At the flowering stage, one plant from each pot was harvested to assess physiological and morphological traits, including leaf area. Two remaining plants in each pot were grown to the yield stage, after which they were harvested, and seed yield and its components were evaluated. Following harvest, the plants were washed three times with tap water, twice with distilled water, and dried in an oven at 70 °C for 48 hours. The dry matter content was then measured. The seeds were ground, placed into filter paper, and the oil content was determined using the Soxhlet extraction method with standard hexane solvent[29].

Growth traits such as plant height and leaf length were measured daily using a ruler. Leaf area was determined with a Delta-T area meter (Delta-T Devices LTD, Burwell, Cambridge, England). The leaves were dried at 70°C for 24 hours, and specific leaf area was calculated by dividing leaf surface area by dry mass. The leaf area index was obtained by dividing leaf surface area by the ground surface area. Leaf greenness was measured using a Chlorophyll Meter (SPAD-502 Plus, Osaka, Japan). Photosynthetic parameters, including stomatal conductance and photosynthetic rate, were measured using a portable photosynthesis system (LI-COR 6400, Lincoln, USA). The relative water content (RWC) and water saturation deficit (WSD) were calculated according to the method outlined by Garg [30] using the following equation:

$$RWC=\frac{WF-WD}{WT-WD} \quad (1)$$

$$WSD=\frac{WT-WF}{WT-WD} \quad (2)$$

where W_F is fresh weight, W_D is dry weight, and W_T is turgid weight of leaf samples.

All data analyses, including variance analysis and mean comparisons, were conducted using the LSD method with SAS statistical software (Version 9.4; SAS Institute Inc., Cary, NC, USA). Prior to performing statistical analyses, the normality of the data was verified based on the distribution of residuals.

3. Results and Discussion

3.1 Variance analysis of yield and yield components, morpho-physiological traits

3.1.1 Variance Analysis of yield and yield components

The variance analysis results for yield and yield components are presented in Table 3. The analysis revealed that water stress had a significant impact on grain yield, while both water and salinity stresses individually affected oil percentage, seed number per plant, and pod number per plant, all at the 1% significance level. Additionally, the combined stress of water and salinity significantly affected both fresh biological yield and oil percentage at the 1% level. The dual stress of water and nitrogen significantly influenced oil percentage, and the triple stress of water, salinity, and nitrogen significantly impacted dry matter yield, oil percentage, seed weight per plant, and seed number per plant, also at the 1% level. The effect of water stress on TSW was significant at the 5% level, as was the effect of salinity stress on grain yield, dry matter yield, and fresh biological yield. The dual stress of water and salinity significantly affected seed yield and seed number per plant, while the triple stress of water, salinity, and nitrogen significantly influenced seed yield, fresh biological yield, and pod number, all at the 5% significance level. However, the separate stress of nitrogen, as well as the dual stresses of water and nitrogen and salinity and nitrogen, had no discernible impact on yield or yield components.

Table 3. Variance Analysis (mean squares) of effects of separate stresses of water, salinity, and nitrogen, as well as dual stresses of water and salinity, water and nitrogen, salinity and nitrogen, and triple stress of water, salinity, and nitrogen on yield and yield components

Treatments	DF	Yield			Percentage oil	TSW	Seed Weight /Plant	Seed NO./ plant	Pod NO./ plant	Seed NO./ pod
		Grain	Dry matter	Fresh biological						
Rep	2	5819.6 *	3.43**	3.01^{ns}	0.002^{ns}	0.13^{ns}	0.18**	121827.43**	784.36*	9.39^{ns}
Water stress	2	85958.19**	5.83**	25.71**	0.08**	0.49*	0.38**	284401.16**	1145.99**	96.92**
salinity stress	4	34733.79*	1.39*	6.24*	0.065**	0.17^{ns}	0.13**	93257.36**	1180.25**	2.64^{ns}
Nitrogen stress	2	1772.17^{ns}	0.93^{ns}	2.49^{ns}	0.0000181^{ns}	0.02^{ns}	0.006^{ns}	14937.1^{ns}	231.3^{ns}	1.65^{ns}
Water *salinity stresses	8	19820.34*	0.48^{ns}	6.27**	0.024**	0.17^{ns}	0.06^{ns}	56379.16*	384.39^{ns}	14.33^{ns}
Water * Nitrogen stresses	4	1285^{ns}	0.74^{ns}	0.27^{ns}	0.027**	0.05^{ns}	0.009^{ns}	24513.75^{ns}	66.92^{ns}	23.72^{ns}
salinity * Nitrogen stresses	8	1473.26^{ns}	0.85^{ns}	2.27^{ns}	0.005^{ns}	0.12^{ns}	0.013^{ns}	6841.65^{ns}	167.06^{ns}	5.48^{ns}
Water *salinity* Nitrogen stresses	16	20478.89*	1.15**	4.15*	0.009**	0.12^{ns}	0.08**	67188.92**	447.78*	14.39^{ns}
Error variance	-	10303.4	0.496	2.21	0.004	0.126	0.033	24509.2	209.6	10.89
CV	-	56.18	41.37	51.5	16.3	32.2	46.8	45.9	39.9	36.7

NS=not significantly difference, ** and * significantly difference at the 0.01 and 0.05 levels

3.1.2 Variance analysis of physiological traits

Table 4 presents the variance analysis of physiological traits. The findings indicate that the separate stresses of water and salinity significantly affected the chlorophyll index at both the beginning and end of flowering (SPAD-First and SPAD-End) as well as the C_i/C_a *,ratio, with significance observed at the 1% level. Additionally, the combined stress of water and nitrogen on the chlorophyll index at the end of flowering was also significant at the 1% level. Salinity stress significantly impacted relative leaf water content, while the combined stress of water and salinity significantly affected relative leaf water content, photosynthetic rate (Photo.), and stomatal conductance (Cs), all at the 5% significance level. The dual stress of salinity and nitrogen significantly influenced the chlorophyll index at the end of flowering, and the triple stress of water, salinity, and nitrogen had a significant effect on relative leaf water content, also at the 5% level. However, nitrogen deficiency, as well as the combined stresses of water and nitrogen, and stresses of salinity and nitrogen, did not exhibit a significant impact on physiological traits.*

The greenness index is pivotal in light absorption and is regarded as essential for the photosynthesis process. However, the variance analysis results indicate that the greenness index exerted a more substantial influence on physiological traits than on photosynthesis itself. This phenomenon can be attributed to the stabilization of photosynthesis through an increase in the greenness index. Furthermore, these findings align with the conclusions drawn by Pan [31] and Anand et al. [32].

Table 4. Variance Analysis (mean squares) of effects of separate stresses of water, salinity, and nitrogen, as well as dual stresses of water and salinity, water and nitrogen, salinity and nitrogen, and triple stress of water, salinity, and nitrogen on physiological traits

Treatment	DF	SPAD-First	SPAD-End	RWC	WSC	Photo.	Cs	Ci	C_i/C_a
Rep	2	92.57^{ns}	1492.97^{**}	0.323^{**}	0.15^{*}	22.73^{**}	0.0024^{ns}	23611.47^{**}	92.57^{ns}
Water stress	2	426.06^{**}	1370.18^{**}	0.0003^{ns}	0.08^{ns}	5.94^{ns}	0.0003^{ns}	3054.68^{ns}	426.06^{**}
salinity stress	4	153.89^{**}	828.87^{**}	0.061^{*}	0.04^{ns}	2.56^{ns}	0.0008^{ns}	2961.81^{ns}	153.89^{**}
Nitrogen stress	2	23.04^{ns}	95.05^{**}	0.054^{ns}	0.01^{ns}	0.92^{ns}	0.0011^{ns}	2893.13^{ns}	23.04^{ns}
Water *salinity stresses	8	79.49^{ns}	629.97^{ns}	0.056^{*}	0.04^{ns}	8.55^{*}	0.0029*	2428.04^{ns}	79.49^{ns}
Water * Nitrogen stresses	4	40.96^{ns}	145.09^{**}	0.006^{ns}	0.09^{ns}	4.21^{ns}	0.0028^{ns}	1282.74^{ns}	40.96^{ns}
salinity * Nitrogen stresses	8	56.27^{ns}	265.9^{*}	0.031^{ns}	0.05^{ns}	4.85^{ns}	0.0008^{ns}	2576.93^{ns}	56.27^{ns}
Water *salinity* Nitrogen stresses	16	21.46^{ns}	181.02^{ns}	0.041^{*}	0.05^{ns}	1.75^{ns}	0.0013^{ns}	2307.63^{ns}	21.46^{ns}
Error variance	-	42.58	127.9	0.023	0.04	3.98	0.0014	2192	42.57
CV	-	15.5	20.9	42.4	33.05	28.6	43	22.9	15.5

NS=not significantly difference, ** and * significantly difference at the 0.01 and 0.05 levels

3.1.3 Variance analysis of morphological traits

The results of the variance analysis of morphological traits, presented in Table 5, indicate that water stress significantly affected leaf length, total leaf count, number of sub-branches, and specific leaf area at the 1% significance level. Similarly, salinity stress had a significant impact on plant height, total leaf count, number of yellow and dry leaves, number of sub-branches, and specific leaf area, also at the 1% level. Nitrogen deficiency significantly influenced specific leaf area and leaf area index at the 1% level, while the combined stress of water and salinity significantly affected leaf length, total leaf count, leaf area index, and specific leaf area. The dual stress of salinity and nitrogen, as well as the triple stress of water, salinity, and nitrogen, significantly impacted specific leaf area at the 1% level. Additionally, water stress significantly affected height, leaf width, and W_a *at the 5% level. The effects of salinity stress on* W_a *and nitrogen deficiency on leaf area index were also significant at the 5% level. Combined water and salinity stress significantly impacted the number of yellow and dried leaves at the 5% significance level, while the combined water and nitrogen stress significantly influenced total leaf count and the number of sub-branches at the 5% level. Except for specific leaf area, neither the dual stress of salinity and nitrogen nor the triple stress of water, salinity, and nitrogen had a significant effect on any morphological traits.*

Table 5. Variance Analysis (mean squares) of effects of separate stresses of water, salinity, and nitrogen, as well as dual stresses of water and salinity, water and nitrogen, salinity and nitrogen, and triple stress of water, salinity, and nitrogen on morphological traits

Treatment	DF	Leaf					Branch NO.	W_a	LAI	SLA
		Height	Length	Width	NO.	Yellow and dry				
Rep	2	58.42^{ns}	0.8^{ns}	0.017^{ns}	264.97^{ns}	12.17^{ns}	16.47^{ns}	0.48^{ns}	0.0003^{ns}	15.86^{ns}
Water stress	2	1244.72^{*}	14.25^{**}	0.742^{*}	6712.51^{**}	16.33^{ns}	88.82^{**}	6.13^{*}	0.0102^{ns}	2580.89^{**}
salinity stress	4	5988.89^{**}	4.24^{ns}	0.187^{ns}	1748.45^{**}	213.41**	52.72^{**}	3.97^{*}	0.0077^{ns}	3084.87^{**}
Nitrogen stress	2	332.04^{ns}	0.93^{ns}	0.109^{ns}	591.16^{ns}	20.96^{ns}	17.42^{ns}	1.47^{ns}	0.0194^{*}	1336.69^{**}
Water *salinity stresses	8	450.42^{ns}	6.55^{**}	0.376^{ns}	898.8^{**}	53.66*	20.6^{ns}	1.54^{ns}	0.0287^{**}	1307.37^{**}
Water * Nitrogen stresses	4	113.87^{ns}	0.51^{ns}	0.022^{ns}	587.49^{*}	14.02^{ns}	37.01^{*}	2.7^{ns}	0.0073^{ns}	273.4^{ns}
salinity * Nitrogen stresses	8	236.65^{ns}	1.19^{ns}	0.085^{ns}	205.86^{ns}	9.71^{ns}	3.7^{ns}	1.61^{ns}	0.0025^{ns}	384.61^{**}
Water *salinity* Nitrogen stresses	16	372.75^{ns}	3.4^{ns}	0.196^{ns}	304.84^{ns}	31.27^{ns}	16.18^{ns}	1.87^{ns}	0.0061^{ns}	272.9^{**}
Error variance	-	393.5	0.2	2.1	458.2	22.02	14.9	1.43	0.004	113.5
CV	-	36.7	42	38.6	58.4	43.9	102	23.2	53.3	31.5

NS=not significantly difference, ** and * significantly difference at the 0.01 and 0.05 levels

3.2 Means comparison of the effects of water, salinity, and nitrogen on yield and yield components, as well as physiological and morphological traits

3.2.1 Means comparison of the effects of water stress on yield and yield components

A comparison of means regarding the effect of water stress on yield and yield components is presented in Table 6. The results indicate that the highest yield and yield components were observed at 75% FC. Conversely, the lowest seed yield, seed weight per plant, seed number per plant, and seed number per pod under water stress occurred at both 50% and 100% FC. Additionally, the lowest dry matter yield, fresh biological yield, and pod numbers were recorded at 50% FC, along with the lowest oil percentage and TSW in the same treatment. Angadi et al. [33] indicated that the primary factor contributing to reduced grain yield under water stress is a decrease in the number of pods per plant. Furthermore, some researchers have reported that the number of pods per plant has the most significant direct and indirect effects on grain yield, followed by TSW and the number of seeds per pod [34]. Given that the mean comparison results for seed yield, seed weight, seed number per plant, and pod count are similar, it is evident that seed yield is closely dependent on its yield components.

The data presented in Table 6 indicate that the number of seeds per pod, seed weight, and number of pods per plant (or per unit area) are the primary determinants of camelina seed production. The number of pods per plant, including their green husks, conducts photosynthesis and contributes to the accumulation of materials necessary for seed development. Grain yield initially increased under 75% FC water deficit and subsequently decreased, aligning with the findings of Bronson et al. [35]. In their study, Bronson et al. [35] illustrated the relationship between grain yield and water consumption across various fertilizer levels. Their results indicated that the highest yield was achieved at an irrigation fraction of 0.65 to 0.75 (272-303 mm). In the research conducted by Angelini et al. [36], TSW and the number of pods under optimal conditions for various cultivars were reported to range from 0.94 to 1.17 and 6.9 to 10.2, respectively. Ahmed et al. [37] reported TSW under different levels of water deficit to range from 1.7 to 0.92, while the results of this study ranged from 1.17 to 0.98.

Table 6. Mean comparison of effect of water stress on yield and yield components

Water stress (%FC)	Yield			Percentage oil	TSW	Seed Weight /Plant	Seed NO./ plant	Pod NO./ plant	Seed NO./ pod
	Grain	Dry matter	Fresh biological						
	(kg ha^{-1})	(g)	(g)	(%)	(g)	(g)	-	-	-
100	155.72b	1.86a	3.14a	33.7c	0.98b	0.34b	307.42b	36.089ab	7.53b
75	231.16a	1.96a	3.48a	41.9a	1.18a	0.49a	431.24a	41.378a	10.47a
50	155.18b	1.29b	2.03b	36.2b	1.14a	0.33b	282.96b	31.289b	8.91b

3.2.2 Means comparison of the effects of salinity on yield and yield components

The mean comparison of salinity's effects on yield and yield components is presented in Table 7. The data indicate that a salinity level of 4 dS/m exerted the most pronounced impact on seed yield, dry matter yield, biological yield, oil percentage, seed weight per plant, number of seeds per plant, and number of pods. Notably, with the exception of the 10 dS/m treatment, no significant differences were observed in dry matter yield, seed weight per plant, or the number of seeds per plant across the various salinity levels. Conversely, the lowest values for yield and yield components were recorded at 10 dS/m.

Table 7. Mean comparison of effect of salinity on yield and yield components

Salinity stress	Yield			Percentage Oil	Seed Weight /Plant	Seed NO./ plant	Pod NO./ plant
	Grain	Dry matter	Fresh biological				
(dS m^{-1})	(kg ha^{-1})	(g)	(g)	(%)	(g)	(g)	-
1	87.198ab	1.73a	3.21ab	0.401a	0.42a	384.56a	41.407ab
2	59.182abc	1.7ab	2.69bc	0.4a	0.39a	334.67a	36.333ab
4	224.68a	1.96a	3.52a	0.416a	0.46a	394.67a	43.037a
6	168.93bc	1.79a	2.71bc	0.349b	0.4a	342.67a	34.111bc
10	128.4c	1.34b	2.29c	0.298c	0.27b	246.15b	26.37c

3.2.3 Means comparison of the effects of water stress on physiological traits

The mean comparison of the effects of water stress on physiological traits is presented in Table 8. The results indicate that water stress significantly influences certain physiological traits, including chlorophyll content, WSD, and C_i/C_a*. Notably, water stress had the most pronounced effect on these physiological traits at 75% FC and the least effect at 100% FC.*

Pan [31] reported an increase in chlorophyll content from 51 to 61 under high water deficit, while in this study, chlorophyll levels ranged from 47 to 58. Chlorophyll serves as a reliable indicator of a crop's resilience to water stress [38]. The increased chlorophyll index under water stress suggests camelina's resistance to such conditions. In these plants, photosynthesis is sustained by an elevation in chlorophyll levels [39]. This enhancement in chlorophyll, in response to water stress, stimulates cortical photosynthesis, which refers to the process where the greenness index converts CO_2 from the transpiration of underlying tissues into carbon [40]. This adaptation mitigates the risk of anaerobic conditions and enhances water use efficiency [41].

Ahmed et al. [37] conducted research on the physical-biochemical responses and yield of camelina under water stress, reporting a WSD range of 32% to 83.32%. In this study, the results shown in Table 8 indicate a WSD range of 56% to 64%.

Table 8. Mean comparison of effect of water stress on physiological traits

Water stress (%FC)	SPAD-First (mmol m^{-2})	SPAD-End (mmol m^{-2})	WSD	C_i/C_a
100	38.54b	47.62b	0.56b	38.54b
75	43.36a	56.09a	0.64a	43.36a
50	44.26a	57.97a	0.6ab	44.26a

3.2.4 Means comparison of the effects of salinity on physiological traits

Table 9 presents a mean comparison of the physiological traits affected by salinity stress. The results indicate that maximum chlorophyll content, measured at the onset of flowering, and C_i/C_a *were observed at a salinity level of 1 dS/m. Conversely, the highest chlorophyll levels at the conclusion of flowering were recorded at 10 dS/m. The maximum RWC occurred at salinity levels ranging from 1 to 4 dS/m. Additionally, the highest intracellular CO_2 concentration was found at 1 dS/m; however, this concentration was not significantly different from the values observed at salinity levels between 2 and 6 dS/m.*

Furthermore, chlorophyll content at both the beginning and end of flowering, C_i/C_a*, RWC, and intracellular CO_2 concentration were all at their lowest in high salinity conditions. Pan [31] reported an intracellular CO_2 concentration of 238 µmol m^{-2} s^{-1} for the control treatment, which aligns closely with our*

findings. The decline in intracellular CO_2 concentration at 10 dS/m can be attributed to stomatal closure and reduced gas exchange.

Interestingly, RWC increased at a salinity level of 4 dS/m, aiding in moisture retention within the leaf and indicating that the plant had adjusted its osmotic pressure to cope with salinity. When turgor is maintained during osmotic regulation, stomatal conductance tends to remain relatively stable. However, at higher salinities, both gas exchange and RWC were diminished. In the study by Heydarian et al. [42], chlorophyll levels ranged from 18 to 35 mmol m^{-2} at salinities of 0 to 15 dS/m, whereas in our research, chlorophyll content ranged from 45 to 61 mmol m^{-2} at the beginning and end of flowering across salinity levels of 1 to 10 dS/m.

Table 9. Mean comparison of effect of salinity on physiological traits

Salinity stress	SPAD-First	SPAD-End	RWC	C_i	C_i/C_a
(dS m^{-1})	(mmol m^{-2})	(mmol m^{-2})		(µmol CO^2 mol^{-1})	
1	45.05a	56.88ab	0.38a	220.72a	45.05a
2	42.02abc	54.38bc	0.35ab	206.89ab	42.02abc
4	43.28ab	50.19cd	0.41a	202.24ab	43.28ab
6	38.63c	46.94d	0.34ab	201.59ab	38.63c
10	41.3bc	61.08a	0.29b	191.99b	41.3bc

3.2.5 Means comparison of the effects of water stress on morphological traits

Table 10 presents a comparative analysis of the impact of water stress on various morphological traits. The data indicate that, with the exception of SLA, all morphological traits exhibited significant sensitivity to water stress, particularly at 75% FC. The lowest measurements for leaf height, leaf length, leaf width, total leaf count, and number of sub-branches were recorded under 50% FC conditions. Moreover, the minimum total shoot weight, leaf area index, and SLA were also observed at this lower FC level.

In the study conducted by Tribouillois et al. [43], an SLA of 44.9 was documented at a nitrogen application rate of 12 g/ha. In contrast, this study found an SLA of 42.55 under optimal conditions, characterized by the absence of salt and at 100% FC. Additionally, plant height increased from 49.79 cm under optimal conditions to 59.9 cm when subjected to 75% FC stress.

Table 10. Mean comparison of effect of water stress on morphological traits

Water stress (%FC)	Leaf				Branche NO.	W_a	LAI	SLA
	Height	Length	Width	NO.				
	(cm)	(cm)	(cm)	-	-	(g)	-	(cm^2 g^{-1})
100	49.791b	3.15b	0.95b	42.53b	3.53b	5.13ab	0.113ab	42.55a
75	59.902a	4.26a	1.2a	54.56a	5.29a	5.52a	0.136a	29.15b
50	52.336ab	3.86a	1.03ab	45.02ab	2.51b	4.78b	0.108b	29.74b

3.2.6 Means comparison of the effects of salinity on morphological traits

Table 11 presents a comparative analysis of the effects of salinity stress on various morphological traits. Salinity exerted a significant impact on all morphological traits—excluding specific leaf area—across salinity levels ranging from 1 to 4 dS/m, with the lowest values recorded at a salinity level of 10 dS/m. The maximum and minimum effects on specific leaf surface area were observed at salinities of 10 dS/m and 4 dS/m, respectively.

According to the findings of Heydarian et al. [42], plant height in the treatment without salinity decreased from 55 cm to 25 cm under a salinity treatment of 15 dS/m. In contrast, the current study measured plant height across various salinity levels, ranging from 34 to 65 cm. The total weight of the aerial parts in this study ranged from 4.6 to 5.52 g. This slight discrepancy compared to other studies may be attributed to the use of NaCl by different researchers and the various cultivars employed.

Stavridou et al. [44] reported between 19 and 42 leaves per camelina plant, and the highest leaf count in the absence of salt stress observed in this study aligns with their findings. Specifically, the plants exhibited 40 healthy leaves without salinity and 27 healthy leaves at a salinity level of 6 dS/m. In western Nebraska, Pavlista et al. [45] irrigated camelina at three levels: 10, 20, and 30 cm. Their findings indicated that applying an average water consumption of 20 cm resulted in maximum plant height, whereas the greatest height recorded in this study was 65.69 cm under a salinity treatment of 1 dS/m.

Table 11. Mean comparison of effect of salinity on morphological traits

Salinity stress	Leaf	Branch NO.	W_a	LAI	SLA

	Height	Length	Yellow and dry	NO.				
dS m^{-1}	cm)	cm	cm	-	-	g	-	cm^2 g^{-1}
1	65.69a	4.1a	13.19a	53.37a	4.67a	5.37ab	0.135a	25.63cd
2	64.54a	3.6ab	13.33a	50.63a	4.63a	5.35ab	0.12ab	30.42c
4	64.07a	3.97a	11.37a	54.52a	5.07a	5.52a	0.111ab	24.02d
6	40.91b	3.13b	7.78b	35.26b	2.22b	4.88bc	0.095b	39.26b
10	34.84b	3.08b	7.82b	43.07ab	2.3b	4.61c	0.135a	49.72a

3.2.7 Means comparison of the effects of nitrogen levels on physiological and morphological traits

The mean comparison of the effects of nitrogen levels on physiological and morphological traits is presented in Table 12. According to the results, the highest leaf area index (LAI) and specific leaf area (SLA) were observed at 100% N, while the lowest values were recorded at 50% N. The data indicate that 100% N yields the highest LAI and SLA, whereas 50% N results in the lowest.

Although the maximum RWC was found at 50% N and the minimum at 100% N, the RWC at 75% N did not differ significantly from the highest nitrogen treatment values. The findings reveal that nitrogen deficiency primarily impacted the leaf area index, specific leaf area, and leaf mass, as these traits are highly dependent on nitrogen concentration. Serrano et al. [46] noted that leaf area is significantly influenced by varying nitrogen application levels, and Wang et al. [47] identified N as a key factor in reducing both LAI and SLA.

According to Wang et al. [48], increasing nitrogen concentrations correspond with a decrease in RWC, leading to fewer plant cells and slower growth rates. Additionally, reduced nitrogen levels result in decreased chlorophyll content, diminished radiation absorption, and stunted growth. Conversely, higher nitrogen availability correlates with increased LAI. The findings demonstrate that LAI declines significantly as nitrogen concentrations decrease[49]. Given that maximum RWC and leaf area were observed at 75% N, this nitrogen concentration will play a crucial role in enhancing yield. Growth analysis is primarily employed to describe how plants respond to environmental stress.

Table 12. Mean comparison of effect of N on physiological and morphological traits

Nitrogen (%)	LAI	SLA (cm^2 g^{-1})	RWC
100	0.137a	38.51a	0.32b
75	0.124a	35.09a	0.35ab
50	0.096b	27.84b	0.39a

4. Conclusion

This study's analysis of variance and comparison of physiological and morphological traits under varying levels of water, salinity, and nitrogen stresses underscore the critical need to manage these stress factors to sustain and enhance plant health and performance. The results revealed that optimal seed yield under water stress was achieved at 75% FC, whereas salinity stress yielded the highest seed production and oil content at a salinity level of 4 dS/m. Nitrogen application levels, on the other hand, resulted in diminished chlorophyll content, reduced light absorption, stunted growth, and a subsequent decrease in LAI.

In general, moderate water and salinity stress levels can positively influence plant growth, physiology, and performance, while excessive stress adversely affects these factors. The findings highlight the essential role of physiological traits, such as chlorophyll content and photosynthesis, in mitigating environmental stressors' effects. A deeper understanding of plant responses to such stress conditions can guide improved management strategies and enhance crop productivity.

REFERENCES

[1] *La Pena, R. D., Hughes, J. (2007). Improving vegetable productivity in a variable and changing climate.*

[2] *Wu, C., Wang, Q., Xie, B., Wang, Z., Cui, J., Hu, T. (2011). Effects of drought and salt stress on seed germination of three leguminous species. African Journal of Biotechnology, vol. 10, no. 78, p. 17954-17961. DOI:10.5897/AJB11.2018.*

[3] *Nam, N. H., Martinez, A., et al. (2007). Morpho-physiological parameters used in selecting*

drought-tolerant cowpea varieties using drought index. International Scholars Journals.

[4] *Miao, Y., Zhu, Z., Guo, Q., Ma, H., Zhu, L. (2015). Alternate wetting and drying irrigation-mediated changes in the growth, photosynthesis and yield of the medicinal plant Tulipa edulis. Industrial Crops and Products, vol. 66, p. 81-88. https://doi.org/10.1016/j.indcrop.2014.12.002.*

[5] *Rathke, G. W., Behrens, T., Diepenbrock, W. (2006). Integrated nitrogen management strategies to improve seed yield, oil content and nitrogen efficiency of winter oilseed rape (Brassica napus L.): a review. Agriculture, Ecosystems & Environment, vol. 117, no. 2-3, p. 80-108. https://doi.org/10.1016/j.agee.2006.04.006.*

[6] *Sabagh, A. E., Hossain, A., Barutçular, C., Islam, M. S., Ratnasekera, D., Kumar, N., et al. (2019). Drought and salinity stress management for higher and sustainable canola (Brassica napus L.) production: A critical review. Australian Journal of Crop Science, vol. 13, no. 1, p. 88-96.*

[7] *Urbaniak, S. D., Caldwell, C. D., Zheljazkov, V. D., Lada, R., Luan, L. (2008). The effect of cultivar and applied nitrogen on the performance of Camelina sativa L. in the Maritime Provinces of Canada. Canadian Journal of Plant Science, vol. 88, no. 1, p. 111-119. https://doi.org/10.4141/CJPS07115.*

[8] *Jones, J. P., Tucker, T. C. (1968). Effect of nitrogen fertilizer on yield, nitrogen content, and yield components of safflower.*

[9] *Dustnazarova, S., Khasanov, A., Khafizova, Z., Davronov, K. (2021). The threat of saline lands, for example, in the Republic of Uzbekistan. E3S Web of Conferences, vol. 284, p. 02002.*

[10] *Wang, S. J., Chen, Q., Li, Y., Zhuo, Y. Q., Xu, L. Z. (2017). Research on saline-alkali soil amelioration with FGD gypsum. Resources, Conservation and Recycling, vol. 121, p. 82-92. https://doi.org/10.1016/j.resconrec.2016.04.005.*

[11] *Werner, J. (2019). Market Overview of the Water-Energy-Food Nexus in Iran. Embassy of the Kingdom of the Netherlands in the Islamic Republic of Iran.*

[12] *Homaee, M. (1999). Root water uptake under non-uniform transient salinity and water stress. Wageningen University and Research.*

[13] *Munns, R. (2002). Comparative physiology of salt and water stress. Plant, Cell & Environment, vol. 25, no. 2, p. 239-250. https://doi.org/10.1046/j.0016-8025.2001.00808.x.*

[14] *Katerji, N., Van Hoorn, J. W., Hamdy, A., Bouzid, N., Mahrous, S. E. S., Mastrorilli, M. (1992). Effect of salinity on water stress, growth and yield of broadbeans. Agricultural Water Management, vol. 21, no. 1-2, p. 107-117.*

[15] *Maas, E. V., Hoffman, G. J. (1977). Crop salt tolerance-current assessment. Journal of the Irrigation and Drainage Division, vol. 103, no. 2, p. 115-134. https://doi.org/10.1061/JRCEA4.000113.*

[16] *Maas, E. V. (1986). Salt tolerance of plants. Applied Agricultural Research, vol. 1, no. 1, p. 12-25.*

[17] *Hussain, M., Farooq, S., Hasan, W., Ul-Allah, S., Tanveer, M., Farooq, M., Nawaz, A. (2018). Drought stress in sunflower: Physiological effects and its management through breeding and agronomic alternatives. Agricultural Water Management, vol. 201, p. 152-166. https://doi.org/10.1016/j.agwat.2018.01.028.*

[18] *Roy, S. J., Negrão, S., Tester, M. (2014). Salt resistant crop plants. Current Opinion in Biotechnology, vol. 26, p. 115-124.*

[19] *Hussain, M. I., Lyra, D. A., Farooq, M., Nikoloudakis, N., Khalid, N. (2016). Salt and drought stresses in safflower: a review. Agronomy for Sustainable Development, vol. 36, p. 1-31.*

[20] *Negawoldes, T. Y. (2018). Review on nutritional limitations and opportunities of using rapeseed meal and other rape seed by-products in animal feeding. J Nutr Health Food Eng, vol. 8, no. 1, p. 43-48.*

[21] *Kang, J., Snapp, A. R., Lu, C. (2011). Identification of three genes encoding microsomal oleate desaturases (FAD2) from the oilseed crop Camelina sativa. Plant Physiology and Biochemistry, vol. 49, no. 2, p. 223-229. https://doi.org/10.1016/j.plaphy.2010.12.004.*

[22] *George, N., Thompson, S. E., Hollingsworth, J., Orloff, S., Kaffka, S. (2018). Measurement and simulation of water-use by canola and camelina under cool-season conditions in California. Agricultural Water Management, vol. 196, p. 15-23. https://doi.org/10.1016/j.agwat.2017.09.015.*

[23] *Kunst, L., Samuels, L. (2009). Plant cuticles shine: advances in wax biosynthesis and export. Current Opinion in Plant Biology, vol. 12, no. 6, p. 721-727.*

https://doi.org/10.1016/j.pbi.2009.09.009.

[24] *Li-Beisson, Y., Shorrosh, B., Beisson, F., Andersson, M. X., Arondel, V., Bates, P. D., Baud, S., Bird, D., DeBono, A., Durrett, T. P., Franke, R. B. (2013). Acyl-lipid metabolism. The Arabidopsis Book/American Society of Plant Biologists, vol. 11.*

[25] *Yeats, T. H., Rose, J. K. (2013). The formation and function of plant cuticles. Plant Physiology, vol. 163, no. 1, p. 5-20. https://doi.org/10.1104/pp.113.222737.*

[26] *Bakhshi, B., Rostami-Ahmadvandi, H., Fanaei, H. R. (2021). Camelina, an adaptable oilseed crop for the warm and dried regions of Iran. Central Asian Journal of Plant Science Innovation, vol. 1, no. 1, p. 39-45.*

[27] *McVay, K. A., Lamb, P. F. (2008). Camelina Production in Montana. Montana State University Extension, Field Crops, D-16.*

[28] *Bernardo, A., Howard-Hildige, R., O'Connell, A., Nichol, R., Ryan, J., Rice, B., et al. (2003). Camelina oil as a fuel for diesel transport engines. Industrial Crops and Products, vol. 17, no. 3, p. 191-197. https://doi.org/10.1016/S0926-6690(02)00098-5.*

[29] *Keneni, Y. G., Bahiru, L. A., Marchetti, J. M. (2021). Effects of different extraction solvents on oil extracted from jatropha seeds and the potential of seed residues as a heat provider. BioEnergy Research, vol. 14, p. 1207-1222. https://doi.org/10.1007/s12155-020-10217-5.*

[30] *Garg, B. K. (2012). Plant analysis: comprehensive methods and protocols. Scientific Publishers.*

[31] *Pan, X. (2010). A two year agronomic evaluation of Camelina sativa and Brassica carinata in NS, PEI and SK.*

[32] *Anand, A., Suresh, K., Nair, T. V. R. (2007). Photosynthetic variation and photosynthetic nitrogen use efficiency in Brassica species with different genetic constitution of ribulose-1,5-bisphosphate carboxylase. Photosynthetica, vol. 45, p. 147-152. https://doi.org/10.1007/s11099-007-0024-2.*

[33] *Angadi, S. V., Cutforth, H., McConkey, B. G. (2001). Yield adjustment by canola under different plant populations in the semiarid prairie. In Soils and Crops Workshop, February 2001.*

[34] *Tuncturk, M., Ciftci, V. (2007). Relationships between yield and some yield components in rapeseed (Brassica napus ssp. oleifera L.) cultivars by using correlation and path analysis. Pakistan Journal of Botany, vol. 39, no. 1, p. 81.*

[35] *Bronson, K. F., Hunsaker, D. J., Thorp, K. R. (2019). Nitrogen fertilizer and irrigation effects on seed yield and oil in camelina. Agronomy Journal, vol. 111, no. 4, p. 1712-1719. https://doi.org/10.2134/agronj2018.10.0644.*

[36] *Angelini, L. G., Abou Chehade, L., Foschi, L., Tavarini, S. (2020). Performance and potentiality of camelina (Camelina sativa L. Crantz) genotypes in response to sowing date under Mediterranean environment. Agronomy, vol. 10, no. 12, p. 1929. https://doi.org/10.3390/agronomy10121929.*

[37] *Ahmed, Z., Liu, J., Waraich, E. A., Yan, Y., Qi, Z., Gui, D., et al. (2020). Differential physio-biochemical and yield responses of Camelina sativa L. under varying irrigation water regimes in semi-arid climatic conditions. PLoS One, vol. 15, no. 12, e0242441. https://doi.org/10.1371/journal.pone.0242441.*

[38] *Arunyanark, A., Jogloy, S., Akkasaeng, C., Vorasoot, N., Kesmala, T., Nageswara Rao, R. C., et al. (2008). Chlorophyll stability is an indicator of drought tolerance in peanut. Journal of Agronomy and Crop Science, vol. 194, no. 2, p. 113-125. https://doi.org/10.1111/j.1439-037X.2008.00299.x.*

[39] *Rao, S. C., Northup, B. K. (2012). Pigeon pea potential for summer grazing in the southern Great Plains. Agronomy Journal, vol. 104, no. 1, p. 199-203. https://doi.org/10.2134/agronj2011.0260.*

[40] *Aschan, G., Pfanz, H. (2003). Non-foliar photosynthesis-a strategy of additional carbon acquisition. Flora - Morphology, Distribution, Functional Ecology of Plants, vol. 198, no. 2, p. 81-97. https://doi.org/10.1078/0367-2530-00080.*

[41] *Cernusak, L. A., Cheesman, A. W. (2015). The benefits of recycling: how photosynthetic bark can increase drought tolerance. New Phytologist, vol. 208, no. 4, p. 995-997. https://doi.org/10.1111/nph.13723.*

[42] *Heydarian, Z., Yu, M., Gruber, M., Coutu, C., Robinson, S. J., Hegedus, D. D. (2018). Changes in gene expression in Camelina sativa roots and vegetative tissues in response to salinity stress. Scientific Reports, vol. 8, no. 1, p. 9804.*

[43] *Tribouillois, H., Fort, F., Cruz, P., Charles, R., Flores, O., Garnier, E., et al. (2015). A functional characterisation of a wide range of cover crop species: Growth and nitrogen acquisition rates,*

leaf traits and ecological strategies. PLoS ONE, vol. 10, no. 3, e0122156. https://doi.org/10.1371/journal.pone.0122156.

[44] *Stavridou, E., Hastings, A., Webster, R. J., Robson, P. R. (2017). The impact of soil salinity on the yield, composition and physiology of the bioenergy grass Miscanthus×giganteus. GCB Bioenergy, vol. 9, no. 1, p. 92-104. https://doi.org/10.1111/gcbb.12351.*

[45] *Pavlista, A. D., Hergert, G. W., Margheim, J. M., Isbell, T. A. (2016). Growth of spring camelina (Camelina sativa) under deficit irrigation in Western Nebraska. Industrial Crops and Products, vol. 83, p. 118-123. https://doi.org/10.1016/j.indcrop.2015.12.017.*

[46] *Serrano, R., Mulet, J. M., Rios, G., Marquez, J. A., De Larrinoa, I. F., Leube, M. P., et al. (1999). A glimpse of the mechanisms of ion homeostasis during salt stress. Journal of Experimental Botany, p. 1023-1036.*

[47] *Wang, X., Zhang, Y., Huang, M., Chen, J. (2012). Effects of nitrogen fertilization on leaf area index, specific leaf area, and biomass production of crop plants. Field Crops Research, vol. 130, p. 94-102.*

[48] *Wang, Y., Huang, Y., Fu, W., Guo, W., Ren, N., Zhao, Y., Ye, Y. (2020). Efficient physiological and nutrient use efficiency responses of maize leaves to drought stress under different field nitrogen conditions. Agronomy, vol. 10, no. 4, p. 523. https://doi.org/10.3390/agronomy10040523.*

[49] *Waraich, E. A., Ahmed, Z., Ahmad, R., Saifullah, Shahbaz, M., Ehsanullah. (2017). Modulation in growth, development, and yield of Camelina sativa by nitrogen application under water stress conditions. Journal of Plant Nutrition, vol. 40, no. 5, p. 726-735. https://doi.org/10.1080/01904167.2016.1262404.*