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Response to Water Stress in Vicia sp.: Integrated Assessment of Phenological, Physiological, and Agronomic Parameters and Tolerance Indices

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Abstract
This study investigated the effects of water stress on specific phenological, physiological, and agronomic characteristics, as well as the tolerances of fourteen forage ecotypes belonging to the genus Vicia *sp., which include two different species, namely, Narbon vetch (*Vicia narbonensis*) and common vetch (*Vicia sativa *L.), under greenhouse conditions where water stress is applied. The results revealed that water stress induced phenological modifications, such as delays in the vegetative cycle (flowering, pod formation, and full maturity), as well as physiological changes, including reductions in the relative water content and total chlorophyll rate, the accumulation of proline and soluble sugars, and a decrease in yield. These results reveal a diversity of responses among the evaluated varieties, indicating the presence of variability among the ecotypes of both species.*

Keywords: Vicia sativa, Vicia narbonensis, *biomass, yield, grain, water stress.*

1. INTRODUCTION

Legumes, together with grasses, represent the most valuable botanical families for food supply worldwide. Legumes comprise three families (or subfamilies): Fabaceae (or Papilionaceae), Mimosaceae, and Caesalpiniaceae. Among the 17,000 known species, only approximately 3,700 have been identified for their forage qualities (Klein et al., 2014).

In Algeria, grain legumes (chickpea, lentil, broad bean, faba bean, and pea) constitute, alongside cereals, major traditional crops. They are essential both for human nutrition and animal feed.

Forage resources are provided primarily by rangelands (fallow lands, natural pastures, steppe rangelands, and forest rangelands) and by products of cereal cultivation (cereal stubble and straw). Given the poor feeding conditions of livestock, particularly dairy cattle, it is essential to diversify forage crops and conservation methods in suitable regions (the North of the country, irrigated areas, and high plains) (Mebarkia et al., 2007).

In addition to the small area allocated to these crops, the diversity of species is minimal, and vetch-oat, barley, and oat crops intended for hay production are the principal cultivated species. This limitation is due to several factors: the choice of ecotype in terms of pedoclimatic constraints, the absence of seed production, pod shattering, and the lack of expertise among farmers (Mebarkia et al., 2007).

In Algeria, research on vetches (*Vicia* sp.) remains limited, particularly regarding their response to thermal stress. As highlighted by Mebarkia (2011), the effects of late cold spells, which are frequent in high-altitude areas during flowering, and high temperatures at the end of the growth cycle are still insufficiently documented, despite their critical impact on yield.

The predominance of water stress as the primary constraint on plant production systems (Molla, 2001) necessitates an in-depth characterisation of its physiological impacts. A thorough understanding of how it modulates growth dynamics, nutrient assimilation, and water use efficiency in plants is essential for developing strategies to mitigate yield losses.

To overcome water stress, plants employ several adaptive strategies that differ from one species to another and involve a wide combination of morphological, physiological, and biochemical factors (Ludlow & Muchow, 1990).

The genetic improvement of plants for resistance to water stress has long been part of the selection process in most crops that have been or are growing under arid and semiarid conditions (Davoud et al., 2009). Drought tolerance in crops has become one of the main priorities of agronomic research in these regions. Nevertheless, drought tolerance is a complex trait resulting from the contributions of numerous factors (Merah, 2001).

The aim of this study was to select the most efficient vetch ecotype capable of overcoming water shortages that may occur during a critical phase of development. The focus has been primarily on the following:

- ➢ Examining the variability of phenotypic, physiological, and agronomic responses and tolerance among different ecotypes when faced with water stress;
- ➢ Identifying the ecotypes that exhibit the best tolerance to drought.

2. MATERIALS AND METHODS

2.1 Experimental Site

The experiment was conducted in a greenhouse covered with plastic film located at Safa Aures Nursery, Elhammadia Commune, Bordj Bou Arréridj (ERGR Batna), oriented in a north–south direction. The geographical characteristics are as follows: latitude 35° 58 35.2088" North, longitude 04° 44 47" East, and altitude 850 m.

This study focuses on a region classified as having a semiarid bioclimate characterised by cool, wet winters and hot, dry summers. This area experiences variable rainfall, with an average level of 400 mm (Rouabhi et al., 2018), during the period from December to June.

2.2 Plant Material

The experiment involved fourteen vetch populations, ten of which belonged to *Vicia narbonensis* and four to *Vicia sativa*. The code and origin of the plant material used are listed in Table 1.

2.3 Irrigation Management

Irrigation was conducted according to the following method:

2.3.1 SDH treatment: This represents the nonstressed treatment, where soil moisture was maintained at field capacity, ensuring that the plants did not experience water deficit during the growth cycle.

2.3.2 ADH treatment: This represents the stress treatment, where the soil water content was maintained at 45% of field capacity, from the onset of flower bud formation until the end of the cycle.

- ➢ Stress was applied by stopping irrigation until 50% of the available water reserve was depleted.
- ➢ The substrate used retained 32% of its weight at the water holding capacity.
- ➢ Soil desiccation was monitored by weighing the pots daily.

2.4 Experimental Design

The experiment consisted of 112 pots arranged in two blocks, one stressed and the other irrigated, with each block comprising 56 fully randomised pots (Figure 1).

2.5 Sowing

The experiment was carried out in plastic pots with the following dimensions: 17 cm in diameter and 35 cm in height, with homogeneous soil (clay–loam texture) mixed with 10% compost.

Each pot contained a layer of gravel to facilitate water infiltration during drainage and 6 kg of the soil–compost mixture.

Prior to sowing, seeds were selected, and five seeds were sown in each pot at a depth of three (3) cm. Two weeks after planting, four (4) plants were thinned per pot.

2.6 Initiation of stress treatment

To confer a degree of resistance to the plants, water stress was imposed from the onset of flower bud formation until the end of the growth cycle.

2.7 Measurements

At the flowering stage and 15 days after the onset of water deficit treatment, the phenological stages of the ecotypes were monitored (from flowering until complete maturity) to assess the effects of water stress on the progression of these phases.

The following measurements were taken from the harvested plants:

The chlorophyll content was determined according to the methods of Arnon (1949). For the absorption spectra, measurements were performed via the following equations described by Lichtenthaler (1987):

- Chlorophyll a = $[(12.25 \times A663\ nm) - (2.79 \times A645\ nm)] \times V/m$
- Chlorophyll b = $[(21.50 \times A645\ nm) - (5.10 \times A663\ nm)] \times V/m$

The chlorophyll a and b contents are expressed in µg/mg.

The proline content in the dry matter of the leaves was measured following the method described by Troll and Lindesly (1955). The optical density was measured spectrophotometrically at a wavelength of 528 nm. Optical density values were converted into proline concentrations via a standard curve previously established from a series of solutions with known proline concentrations.

The soluble sugars were quantified according to the methods of Fales (1951). The optical density of the mixture was measured at a wavelength of 620 nm and converted into a concentration via a standard curve prepared from glucose solutions.

At the end of the growth cycle, plants from the remaining pots were harvested, and the following parameters were recorded: number of pods per plant, weight of pods, 100-grain weight, and yield.

2.8 Stress tolerance evaluation indices

To quantify the impact of stress and facilitate the identification of resistant ecotypes, several indicators were selected. These indices, which are calculated from the yields of ecotypes under optimal conditions (Ypi) and stressed conditions (Ysi), as well as overall mean yields under irrigated (Yp) and nonirrigated (Ys) conditions, are defined as follows:

- Stress susceptibility index (SSI): $SSI = [1 - (Ysi/Ypi)]/SI$, where SI (stress intensity) represents the average relative reduction: $SI = 1 - (Ys/Yp)$
- Tolerance index (TOL): $TOL = Ypi - Ysi$ (Hossain et al., 1990)
- Mean productivity (MP): $MP = (Ypi + Ysi)/2$ (Rosielle & Hamblin, 1981; Hossain et al., 1990)
- Geometric mean productivity (GMP): $GMP = \sqrt{(Ypi \times Ysi)}$ (Fernandez, 1992)
- Stress tolerance index (STI): $STI = (Ypi \times Ysi)/(Yp)^2$ (Rosielle & Hamblin, 1981; Fernandez, 1992)
- Harmonic mean (HARM): $HARM = [2 \times (Ypi \times Ysi)]/(Ypi + Ysi)$ (Khalili et al., 2004)

2.9 Statistical analysis

The obtained results were analysed via the STATE BOX software versions 6.4 and 7.6, employing an analysis of variance (ANOVA) based on the Newman–Keuls means comparison test at a significance level of 5%.

Table 1

Code and Origin of the 14 Ecotypes Studied

Population	Ecotype	Code	Origin
	01	N-2380	Lebanon
	02	N-2383	
	03	N-2390	
	04	N-2392	
	05	N-2393	Syria

Vicia narbonensis	06	N-2461	Turkey
	07	N-2464	
	08	N-2466	
	09	N-2468	Lebanon
	10	N-2561	Syria
Vicia sativa	11	S-BBA	Algeria (BBA)
	12	S-SETIF	Algeria (SETIF)
	13	S-CHELEF	Algeria (ITGC)
	14	S-174	

Figure 1 *Experimental Layout*

NON-STRESSED BLOCK

R_2	**R_1**	**R_3**	**R_4**
N ECO 3	S-VAR174	N ECO 10	N ECO 8
N ECO 9	N ECO 8	N ECO 8	S-174
N ECO 8	N ECO 2	N ECO 4	N ECO 6
N ECO 6	N ECO 4	N ECO 6	S-BBA
N ECO 1	N ECO 9	N ECO 2	N ECO 1
N ECO 5	S-CHELEF	N ECO 5	N ECO 10
N ECO 4	N ECO 3	N ECO 1	S-CHELEF
S-BBA	N ECO 10	S-SETIF	N ECO 2
N ECO 7	N ECO 5	N ECO 3	N ECO 4
S-174	N ECO 1	S-174	N ECO 9
N ECO 10	N ECO 6	S-BBA	S-SETIF
S-CHELEF	S-SETIF	S-CHELEF	N ECO 3
S-SETIF	S-BBA	N ECO 9	N ECO 7
N ECO 2	N ECO 7	N ECO 7	N ECO 5

STRESSED BLOCK

R_8	**R_6**	**R_5**	**R_7**
N ECO 2	N ECO 7	N ECO 4	N ECO 3
N ECO 6	N ECO 1	N ECO 9	N ECO 10
N ECO 10	N ECO 8	S-BBA	N ECO 8
N ECO 1	N ECO 9	N ECO 7	N ECO 5
N ECO 9	S-CHELEF	N ECO 1	N ECO 4
N ECO 3	S-SETIF	N ECO 3	N ECO 2
N ECO 4	N ECO 6	S-CHELEF	S-BBA
N ECO 5	N ECO 10	N ECO 5	S-SETIF
N ECO 8	S-174	N ECO 2	N ECO 6
N ECO 7	N ECO 4	N ECO 10	N ECO 7
S-SETIF	N ECO 5	S-SETIF	N ECO 1
S-Var 174	S-BBA	N ECO 6	N ECO 9
S-CHELEF	N ECO 2	N ECO 8	S-174
S-BBA	N ECO 3	S-Var 174	S-CHELEF

3. RESULTS AND DISCUSSION

3.1 Effects of water stress on phenological stages

3.1.1 Onset of Flowering (OF)

In the vegetative–reproductive transition phase, water stress significantly delayed the onset of flowering ($p = 0.0025$). Compared with those under stress, irrigated plants under stress initiated flowering at 72.41 days, indicating an additional delay of 0.63 days (+0.87%) (Table 2).

Differences among ecotypes were highly significant ($p < .001$), with the Newman–Keuls test identifying seven homogeneous groups (Figure 2) (S.Var174 being the latest at 81.63 days; N.Eco 2 the earliest at 66.25 days).

The interaction was not significant ($p = .99$): all the ecotypes responded uniformly to stress, suggesting a conserved physiological mechanism among legumes, as observed in *Lupinus angustifolius* (Berger et al., 2021).

3.1.2 Full Flowering (FF)

At the peak of reproduction, water stress significantly prolonged full flowering ($p < 0.001$). Compared with 91.04 days under stress, complete flowering occurred at 85.75 days under irrigation, indicating a critical delay of 5.29 days (+6.2%) (Table 2).

Ecotypes highly significantly differed ($p < .001$), resulting in 8 homogeneous groups (Figure 2) (S.Var174 being the latest at 106.25 days; N.Eco 9 the earliest at 76.63 days).

The interaction was very significant ($p = .00038$): S.Var174 showed an exacerbated delay of 10 days (101.25 → 111.25 days, +9.9%), reflecting its vulnerability, similar to *Vicia faba* under arid conditions (Maqbool et al., 2022). In contrast, N.Eco 9 had a limited delay of 4.25 days (74.5 → 78.75 days, +5.7%), demonstrating resilience comparable to that of *Trifolium subterraneum* (Smith et al., 2023).

3.1.3 Onset of Pod Formation (OPF)

During fruiting, water stress significantly delayed pod initiation ($p < 0.001$). This critical stage occurred at 97.84 days under irrigation compared with 102.75 days under stress, resulting in a delay of 4.91 days (+5%) (Table 2).

Ecotypes exhibited highly significant differences ($p < .001$) and were grouped into nine homogeneous categories, with S.Var174 being the latest at 123.75 days and N.Eco 2 the earliest at 86.88 days (Figure 2).

The interaction was significant ($p = .009$): S.Var174 presented a marked delay of 7 days (120.25 → 127.25 days, +5.8%), which is consistent with observations in *Pisum sativum* under severe stress (Sánchez-Virosta et al., 2023). Conversely, N.Eco 9 presented a minimal delay of 2.5 days (84 → 86.5 days, +3.0%), reminiscent of the tolerance reported for *Medicago truncatula* (Kamphuis et al., 2021).

3.1.4 Full Maturity (FM)

At the end of the growth cycle, water stress significantly prolonged maturation ($p < 0.001$). Maturity was reached at 146.66 days under irrigation compared with 151.96 days under stress, representing an extension of 5.30 days (+3.6%) (Table 2).

Ecotypes highly significantly varied ($p < .001$), forming nine homogeneous groups (Figure 2), with S.Var174 being the latest at 164.75 days and N.Eco 9 the earliest at 136.88 days.

The interaction was not significant ($p = .95$): the delay was consistent across all ecotypes, a phenomenon similar to that reported in *Cicer arietinum* (Devasirvatham et al., 2020), suggesting a generalised metabolic slowdown.

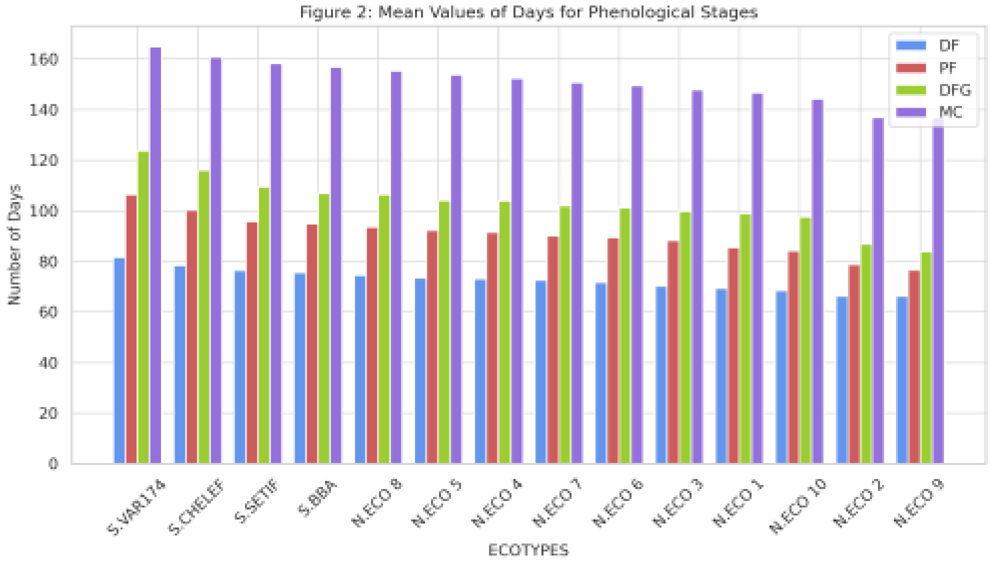
Table 2 *Statistical results of the studied parameters.*

Parameter	Treatment	Mean ± Standard Deviation	Effect	CV (%)
Onset of Flowering (days)	Irrigated	72.411B ± 0.772	p = .0025 (***), THS	1.45
	Stressed	73.036A ± 1.053		

Full Flowering (days)	Irrigated	85.75B ± 1.168	p < .001 (***), THS	1.60
	Stressed	91.036A ± 1.300		
Onset of Pod Formation (days)	Irrigated	97.839B ± 1.170		1.39
	Stressed	102.75A ± 1.268		
Full Maturity (days)	Irrigated	146.661B ± 1.472		1.33
	Stressed	151.964A ± 1.966		
Relative Water Content (%)	Irrigated	80.879A ± 1.701		1.74
	Stressed	48.148B ± 1.300		
Chlorophyll a Content (µg/mg)	Irrigated	41.182A ± 0.544		2.71
	Stressed	29.065B ± 0.526		
Chlorophyll b Content (µg/mg)	Irrigated	29.535A ± 0.617		5.47
	Stressed	18.307B ± 0.510		
Proline Content (µg/mg)	Irrigated	58.579B ± 4.169		4.28
	Stressed	105.177A ± 3.635		
Total Soluble Sugars (µg/mg)	Irrigated	52.422B ± 3.255		2.69
	Stressed	94.848A ± 2.142		
Pods per Plant	Irrigated	13.607A ± 2.300	p = .00002 (***), THS 22.14	
	Stressed	5.464B ± 1.232		
Pod Weight (g)	Irrigated	0.776A ± 0.135	p < .001 (***), THS 16.59	
	Stressed	0.568B ± 0.026		
100-Seed Weight (g)	Irrigated	18.719A ± 0.460	3.22	
	Stressed	16.048B ± 0.516		
Seeds per Pod	Irrigated	4.696A ± 0.556	p = .00037 (***), THS 13.96	
	Stressed	4.25B ± 0.516		
Grain Yield (quintals/ha)	Irrigated	24.638A ± 0.539	p < .001 (***), THS 2.87	
	Stressed	14.180B ± 0.026		

Note. *p* = probability; **THS** = very highly significant; **CV** = coefficient of variation.
Significance levels: (***) p < .001.
Means followed by different letters (A, B) differ significantly.

Figure 2 *Mean values of days for phenological stages*



3.2 Impact of water stress on physiological parameters

Physiological analysis revealed different response mechanisms to water deficit through five major indicators.

3.2.1 Relative water content (RWC)

A severe reduction of 40.5% ($p < .001$) was recorded under stress conditions, dropping from 80.88% in the control to 48.15% (Table 2). A significant stratification of ecotypes (7 homogeneous groups, Newman–Keuls; Figure 3) was observed, with a pronounced ecotype × stress interaction ($p < .001$), distinguishing resistant phenotypes (e.g., *N. Eco 9*: 34.1% decrease) from sensitive genotypes (*S. Chelef*: 49.5% decline).

This variability aligns with observations in other legumes: −29% in *Arachis hypogaea* (Babu & Rao, 1983), −25.7% to −31% in *Vigna unguiculata* (Lobato et al., 2008, 2009), and −55% in *Cicer arietinum* (Matos et al., 2010).

Resilience is further enhanced by specific rhizobial symbioses (e.g., *Tonga-Ouest/SA3*), which induce osmoregulatory genes such as *OsLEA* and *P5CS*, limiting water loss to <10% in *Vicia faba* (Lazali et al., 2023). Tolerance alleles (*VuNAC1*) or adapted inoculants (e.g., *Sinorhizobium meliloti B401*) can also maintain an RWC above 80% (Souza et al., 2019) and even increase it by 18–22% (Zhang et al., 2021).

3.2.2 Photosynthetic Pigments

Chlorophyll degradation (Chl a: −29.4%; Chl b: −38.0%; Table 2), which groups ecotypes into clusters (6 for Chl a, 5 for Chl b; Figure 4), is attributed to chloroplast oxidation by reactive oxygen species (ROS) (Manivannan et al., 2007) and competition for glutamate redirected toward proline biosynthesis (Bengston et al., 1978; Saed-Moocheshi et al., 2014).

The robustness of *Vicia narbonensis* ecotypes (e.g., *N. Eco 2*: −22.2% Chl a) versus the vulnerability of *Vicia sativa* ecotypes (e.g., *S. Chelef*: −39.8% Chl b) reflects known interspecific thresholds: −20% in *Phragmites australis* under severe stress (Pagter et al., 2005) compared with early sensitivity in *Medicago sativa* (Erice et al., 2019).

3.2.3 Proline

The differential accumulation of proline (+79.6% overall; Table 2) and interecotype variability of 306% (6 clusters; Figure 5) highlight a contrast between regulated synthesis (*N. Eco 2*: +91.4%) and inefficient overinduction (*S. Var174*: +187%).

This pattern aligns with the interspecific continuum ranging from +45% in *Vigna unguiculata* (Costa et al., 2008) to over 300% in *Trifolium* spp. (Verdoy et al., 2006). ABA regulates the P5CS pathway (Xiong et al., 2001) and epigenetic mechanisms (e.g., inhibition of *ProDH* by miR2919; Li et al., 2023). These findings emphasise that moderate accumulation (50–100%) is optimal for osmotic regulation.

3.2.4 Total soluble sugars (TSSs)

The increase in the TSS (+81%; Table 2, structured into nine ecotypic groups; Figure 5) results from starch hydrolysis and the synthesis of protective oligosaccharides (e.g., trehalose, raffinose; Chen & Murata, 2002).

Contrasting responses (*N. Eco 2*: +79.8% vs *S. Chelef*: +162%) correlate with the upregulation of *AMY3* and *INV2* genes in *Vigna unguiculata* (Silva et al., 2018) and *SWEET11/SUC2* transporters in *Trifolium pratense* (Kang et al., 2021), mirroring an average increase of +52% in forage legumes (Pereira et al., 2023).

Figure 3 *Mean **values** of **the relative water content***

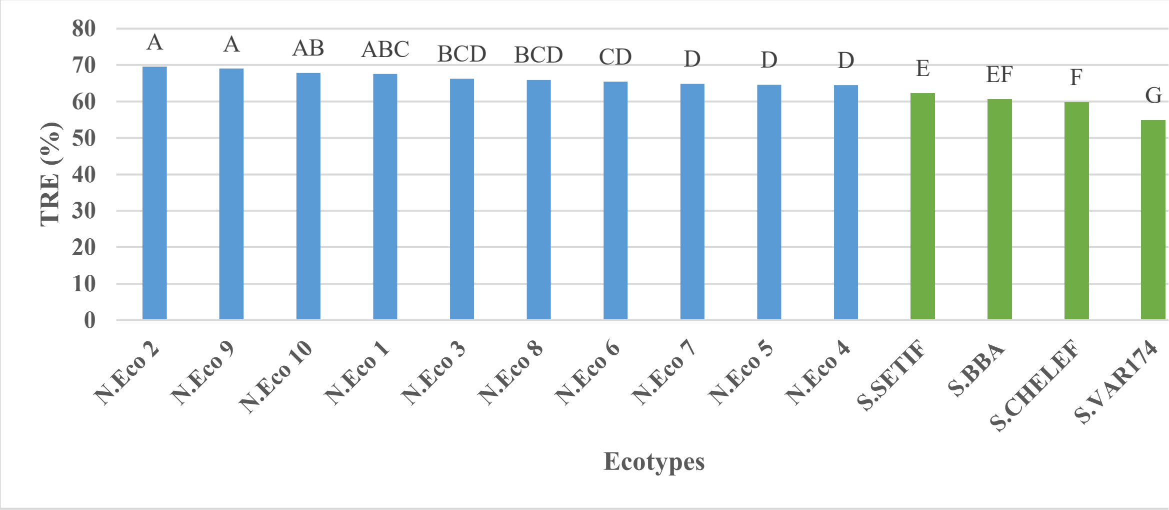


Figure 4

Mean Values of Photosynthetic Pigments

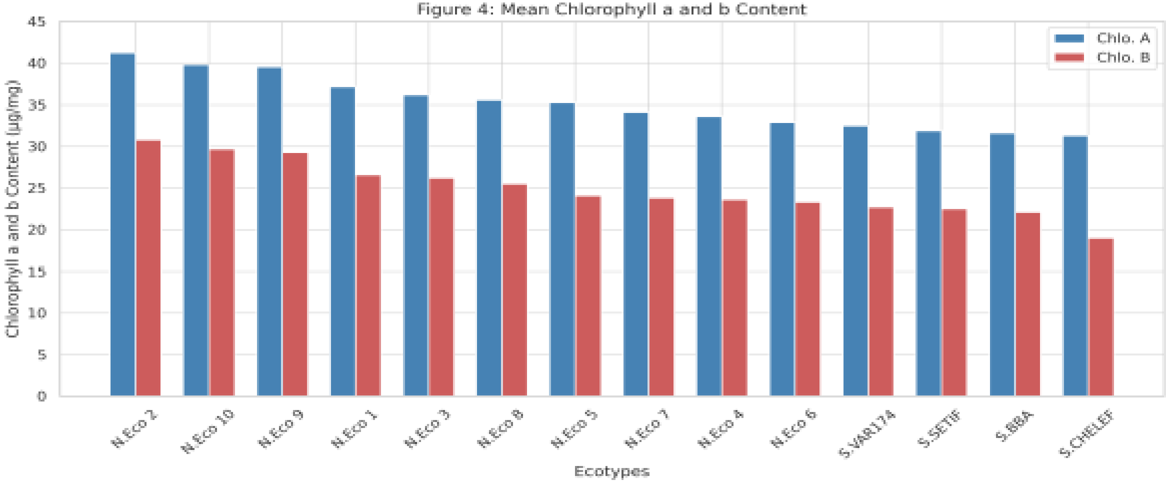
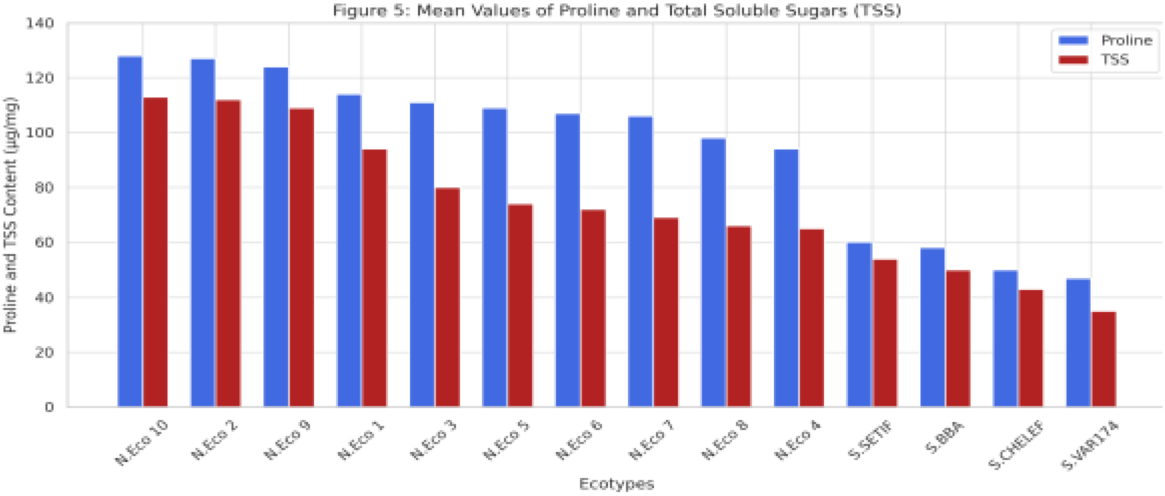


Figure 5 *Mean Values of Proline and Total Soluble Sugars*



3.3. Effect of Stress on Yield Components

The assessment of agronomic parameters revealed a significant impact of water stress ($p < .001$) on all the components studied:

- **Number of pods per plant**: A decrease of 59.9% (from 13.61 to 5.46 pods)
- **Pod weight**: Reduction of 36.6% (from 0.776 g to 0.568 g)
- **100-seed** weight: A decrease of 16.6% (from 18.719 g to 16.048 g)
- **Number of seeds per pod**: Reduction of 10.5% (from 4.696 to 4.25)
- **Overall yield**: Sharp decline of 73.8% (from 24.638 to 14.18 qx/ha) (Table 2)

Significant ecotypic variability ($p < .001$) was observed across all the traits (Figures 6, 7, and 8).
Notable interactions (ecotype × water stress) were recorded as follows:

- **Pod weight ($p < .001$)**: *N.Eco2* showed high productivity under irrigation (1.31 g) but was highly vulnerable under stress (−34%).
- **100-seed weight ($p < .001$)**: Genotypes showed differential reductions (*N.Eco2*: −17.6%; *S.BBA*: −13.7%).
- **Yield ($p < .001$)**: *N.Eco9* experienced a drastic loss of its initial productive advantage (−150%).

The absence of interactions for the number of pods per plant ($p = .97$) and number of seeds per pod ($p = .94$) indicates a common sensitivity among ecotypes.

The drastic reduction in pod number reflects a profound alteration in reproductive processes under water stress. This sensitivity is explained by early floral abortion induced by disruptions in the hormonal balance (ABA/ethylene) and limited carbon resources (Sánchez-Rodríguez et al., 2019).

The lack of significant ecotypic variability confirms the universality of this mechanism in legumes, where critical stress thresholds exceed the metabolic adjustment capacity of plants (Sehgal et al., 2021).

The decline in pod weight (−36.6%) reflects a failure in seed filling, which is linked to reduced photoassimilate availability and the impairment of sugar transporters to sink organs (Durand et al., 2020).

The genotype−irrigation interaction reveals contrasting strategies: high-performing genotypes under irrigation suffer disproportionate losses under stress, whereas local ecotypes maintain greater stability through conservative resource allocation (Boutasknit et al., 2022).

The moderate yet significant decrease in seed weight suggests metabolic prioritisation for survival rather than productivity. This phenomenon is driven by the inhibition of storage biosynthesis enzymes (e.g., ADP–glucose pyrophosphorylase) and a shortened effective grain-filling period (Farooq et al., 2022).

Interecotype variability underscores the crucial role of grain size regulatory genes in mitigating yield loss (Kumar et al., 2023).

For the number of seeds per pod, the relative stability of this parameter (−10.5%) despite water stress suggests developmental canalisation of reproductive structures. This homeostasis may result from compensatory mechanisms between ovule abortion and the preservation of residual ovule viability (Baudet et al., 2021). The lack of genotypic interaction supports its status as an evolutionarily conserved trait in Fabaceae (Varshney et al., 2021).

The collapse in yield synthesises the cumulative effects on all yield components. This exponential reduction reflects synergistic interactions between limited photosynthesis, disrupted assimilate allocation, and hormonal imbalances (Tardieu et al., 2022).

The strong ecotype−environment interaction validates the concept of **"negative plasticity"**, whereby genotypes with high potential under irrigation conditions exhibit increased vulnerability under stress (Messina et al., 2023).

Figure 6 *Mean* ***values*** *of* ***the number of pods per plant and the number of seeds per pod***

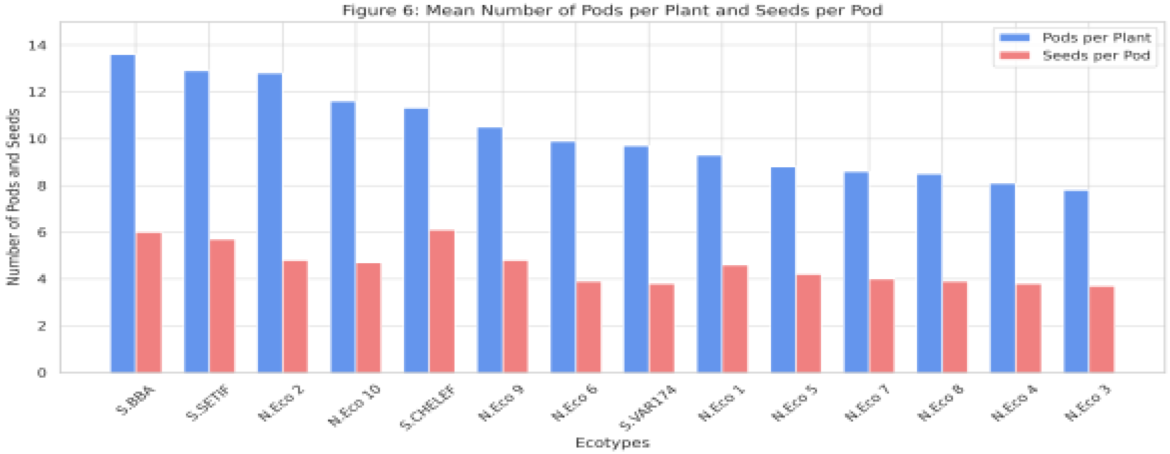


Figure 7 *Mean 100-seed weight and pod weight*

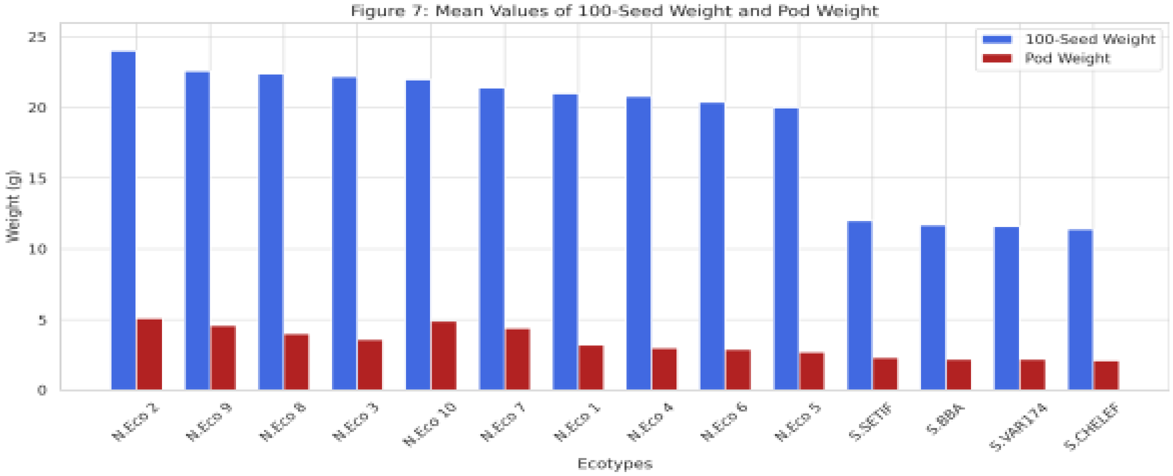
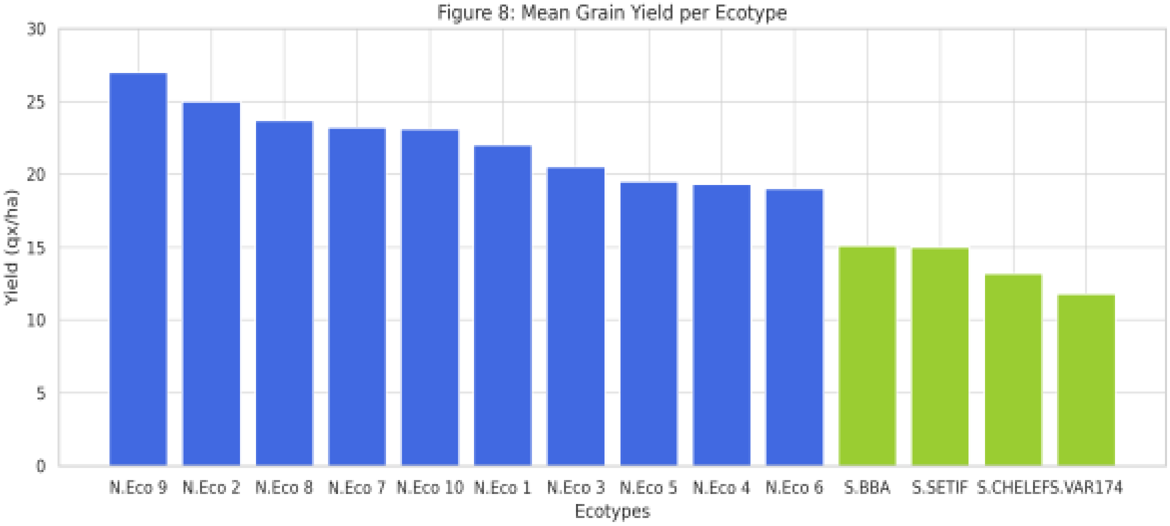


Figure 8 *Mean Grain Yield per Ecotype*



3.4. Results and discussion of tolerance indices:

The data revealed significant variability among ecotypes (Table 4). Ecotypes N. Eco 9 (STI = 1.04) and N. Eco 2 (STI = 0.96) are elite genotypes that combine high productivity under stress (Ysi > 19.5 qx/ha) with a low yield reduction (TOL < 10), confirming the superiority of the STI and GMP (>24) as key indicators of drought tolerance—an observation consistent with the findings of Fernandez (1992) and Rosielle and Hamblin (1981) and further validated in legumes by Bakry et al. (2022).

The functional redundancy between STI, GMP, and HARM (r > 0.99) (Table 5) demonstrates their interchangeability for selecting high-performing genotypes. In contrast, the weak correlation between TOL and STI (r = -0.47) highlights the inability of simple yield reduction to predict overall performance, as previously noted by Khalili et al. (2004).

The SSI, which is strongly correlated with TOL (r = 0.94) but weakly correlated with productivity indices, shows its complementary value for specifically quantifying sensitivity to stress, in line with studies on *Medicago sativa* (Annicchiarico et al., 2021), where it helps distinguish "avoidant" genotypes. Conversely, sensitive ecotypes (S-Var 174, S-Chelef) present low values (STI < 0.15, GMP < 12.5, SSI > 0.8) and a marked imbalance (HARM < 12), reflecting poor adaptation to severe stress—a phenomenon also documented in marginal legume populations by Maxted et al. (2020).

Table 4 *Mean values of yields, grains, and indices of tolerance and sensitivity to stress in the fourteen ecotypes studied.* (Stress intensity for grain yield: SI = 42.24%)

Ecotype	YPI	YPS	TOL	MP	GMP	SSI	STI	HARM
N Eco 1	25.70	15.26	10.44	20.48	19.80	0.80	0.41	19.09
N Eco 2	29.49	19.49	10.00	24.49	24.00	0.68	0.96	23.50
N Eco 3	25.83	14.84	10.99	20.33	19.58	0.84	0.39	18.78
N Eco 4	24.91	13.88	11.03	19.40	18.60	0.85	0.35	17.70
N Eco 5	24.87	13.90	10.97	19.38	18.60	0.85	0.35	17.71
N Eco 6	24.80	13.21	11.59	19.01	18.09	0.89	0.33	17.17
N Eco 7	28.10	17.15	10.95	22.63	21.94	0.85	0.62	21.27
N Eco 8	28.44	18.00	10.44	23.22	22.67	0.80	0.68	22.08
N Eco 9	29.64	20.94	8.70	25.29	24.92	0.66	1.04	24.55
N Eco 10	27.89	17.29	10.60	22.59	21.95	0.82	0.63	21.27
S-BBA	20.28	10.15	10.13	15.22	14.33	0.78	0.21	13.48
S-Setif	19.57	9.96	9.61	14.77	13.97	0.74	0.19	13.17
S-Chelef	18.11	8.10	10.01	13.11	12.13	0.78	0.14	11.22
S-Var 174	16.82	6.37	10.45	11.60	10.36	0.81	0.11	9.26
Mean	24.45	14.08						

Table 5 *Correlation Matrix Between Tolerance Indices*

Indice	TOL	MP	GMP	SSI	STI	HARM
TOL	1.00					
MP	-0.20	1.00				
GMP	-0.25	1.00	1.00			
SSI	0.94	-0.25	-0.30	1.00		
STI	-0.47	0.98	0.99	-0.39	1.00	
HARM	-0.26	0.99	0.99	-0.30	0.99	1.00

3.4.1 Relationship between the stress tolerance index and yield

Our results establish a strong correlation (r = 0.997, $p < 0.001$) between the stress tolerance index (STI) and yield under water stress (Ysi) (Table 6), as confirmed by the regression model:

Ysi=13.967×STI+7.786(R2=0.88)\text{Ysi} = 13.967 \times \text{STI} + 7.786 \quad (R^2 = 0.88) (Figure 9).

The identification of a critical threshold STI > 0.7, ensuring yields above 17 qx/ha under semiarid conditions, aligns with the findings of Anzooman et al. (2023) on *Vicia sativa*, who defined a similar optimal threshold (STI > 0.68) for reliable minimum productivity.

Our top-performing ecotypes illustrate this robustness:

- N. Eco 9 (STI = 1.04 → Ysi = 20.94 qx/ha)
- N. Eco 2 (STI = 0.96 → Ysi = 19.49 qx/ha)

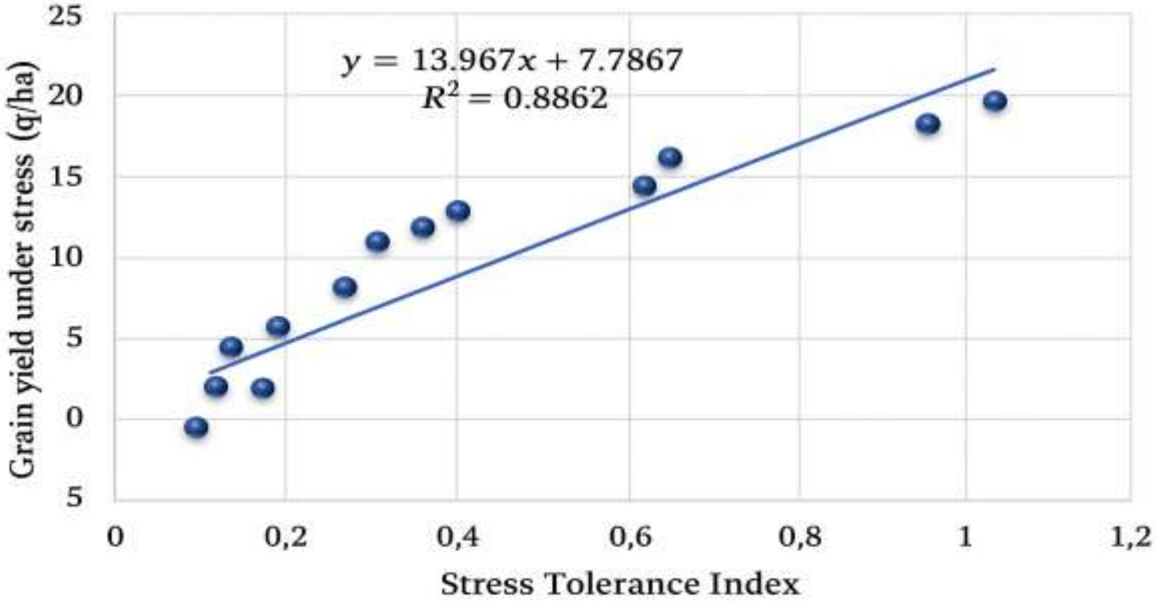
The superiority of the STI, demonstrated initially by Fernandez (1992) in legumes, is supported by multidisciplinary studies:

- Golabadi et al. (2020) validated its statistical reliability (91% explained variance in *Vicia faba*).
- Rajendran et al. (2021) established its molecular basis through its correlation with the expression of LEA/P5CS genes.

Table 6 *Correlation Coefficients of the Different Indices for the Fourteen Ecotypes Under Irrigation and Water Stress Conditions*

Indice	Yi (Ypi)	Ys (Ysi)	ISS	TOL	MP	GMP	(STI)	HARM
YP	1.000							
YS	0.987**	1.000						
ISS	-0.900**	-0.964**	1.000					
TOL	-0.568*	-0.693*	0.858**	1.000				
MP	0.996**	0.997**	-0.941**	-0.637*	1.000			
GMP	0.995**	0.998**	-0.946**	-0.647*	1.000**	1.000		
STI	0.997**	0.994**	-0.932**	-0.618*	0.999**	0.999**	1.000	
MHA	0.994**	0.999**	-0.950**	-0.657*	1.000**	1.000**	0.998**	1.000

Figure 9 *Relationship* ***between grain yield under rainfed conditions*** *(YS) and the* ***stress tolerance index*** *(STI)*



4. CONCLUSION

At the end of this study, the results revealed that water stress severely disrupted the development and physiology of *Vicia* sp., which induced critical phenological delays (especially at reproductive stages), compromised cellular water homeostasis (collapse of RWC), degraded photosynthetic pigments, and disturbed the osmoregulatory balance (unbalanced accumulation of proline and sugars).

These dysfunctions result in significant agronomic collapse (drastic reduction in pod number and yield). Ecotypic variability shapes the response: *Sativa* ecotypes (S.Var 174, S.Chelef) show heightened vulnerability at key stages and exacerbated metabolic alterations, whereas *Narbonne* ecotypes (N.Eco 9; N.Eco 2) demonstrate integrated resilience through chloroplast preservation, efficient osmoregulation, and partial yield stability. Ecotype N.Eco 9 has emerged as a pivotal genotype that combines early phenology, physiological robustness, and homology with tolerant legumes (e.g., *Medicago truncatula*).

These findings advocate for selection targeting early flowering and the enhancement of osmoprotective mechanisms, coupled with engineering of adapted rhizobial symbioses and strategic irrigation during sensitive stages, positioning *Vicia* sp. as a model species for designing climate-resilient agroecosystems.

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