ISPEC Tarım Bilimleri Dergisi, 10(3): 808-822, 2026
ISPEC Journal of Agricultural Sciences, 10(3): 808-822, 2026
DOI: https://doi.org/10.5281/zenodo.21788135

Yield, Quality and Water-Use Responses of Grass Pea (*Lathyrus sativus* L.) Cultivars to Different Irrigation Levels

İhsan Serkan VAROL [1*]
[1] Erciyes University, Faculty of Agriculture, Department of Biosystems Engineering, Kayseri
[*]Corresponding author: svarol@erciyes.edu.tr

Abstract
This study investigated the effects of five irrigation levels (M0, M25, M50, M75 and M100) on grain yield, grain quality traits (crude protein, crude cellulose, crude ash, NDF and ADF), water use efficiency and yield–water relations of five grass pea (*Lathyrus sativus* L.) cultivars (GAP Mavisi, Karadağ, İptaş, Eren and Gürbüz) under the semi-arid conditions of Central Anatolia. The experiment was conducted under drip irrigation in a split-plot design with three replications, with irrigation levels assigned to main plots and cultivars to subplots. Irrigation significantly increased grain yield, which rose from 1302 kg ha^{-1} under rainfed conditions (M0) to 2304 kg ha^{-1} under full irrigation (M100). Crude protein, crude cellulose, crude ash, NDF and ADF increased relatively under water deficit, revealing a distinct yield–quality trade-off. The irrigation × cultivar interaction was significant for grain yield and ADF, indicating that cultivars differed in their response to water supply. Seasonal crop evapotranspiration (ET) increased from 142 mm at M0 to 393 mm at M100, whereas water use efficiency (WUE) reached its highest value under water deficit. The FAO-33 yield response factor was determined as ky=0.66 (<1), demonstrating that grass pea is relatively tolerant to water deficit. The findings indicate that moderate deficit irrigation is a suitable strategy for Central Anatolia, where water resources are limited, providing acceptable yields together with substantial water savings.

Research Article

Article History
Received :20.04.2026
Revised :28.05.2026
Accepted :16.06.2026

Keywords
Deficit irrigation
water use efficiency
yield response factor
drought stress

Citation: Varol, İ.S., 2026. Yield, Quality and Water-Use Responses of Grass Pea (*Lathyrus sativus* L.) Cultivars to Different Irrigation Levels. *ISPEC Journal of Agricultural Sciences,* 10(3): 808-822.
DOI: https://doi.org/10.5281/zenodo.21788135

© This study was published by *ISPEC Journal of Agricultural Sciences* under a Creative Commons License (https://creativecommons.org/licenses/by-nc/4.0/).

1. Introduction

Grass pea (*Lathyrus sativus* L.), an ancient legume forage crop that has been cultivated for more than 8,000 years since the Neolithic period and is distinguished by its extraordinary resilience to adverse abiotic stresses such as drought, salinity and infertile soils (Sarkar et al., 2019). Through its ability to fix atmospheric nitrogen it enhances soil fertility, thereby constituting an important component of sustainable agriculture on nutrient-poor marginal lands; its protein-rich seeds, moreover, provide valuable nutritional security for resource-limited farmers (Abd El-Moneim et al., 2000; Vaz Patto et al., 2006). By producing stable yields in low-input, drought-prone environments, grass pea acts as a buffer against climatic uncertainty and is regarded as an "insurance crop", particularly in semi-arid regions such as Central Anatolia where precipitation is low and erratic (Hillocks and Maruthi, 2012). In semi-arid regions, low and erratic precipitation makes water the principal limiting factor in agricultural production (Çiftçi et al., 2025). Declining groundwater levels, competition among sectors and climatic variability further constrain the supply of irrigation water (Alharbi et al., 2024). Under such conditions, full irrigation often ceases to be economically and ecologically sustainable and is replaced by management strategies that balance yield with water conservation (Varol et al., 2024). Deficit irrigation is a strategic approach that, rather than meeting the entire crop water requirement, aims to maximize yield per unit of water either during growth stages that are less sensitive to water or under a controlled, mild water stress (Chen et al., 2025; Hassan et al., 2025). Its physiological adaptation mechanisms make grass pea an ideal candidate for deficit irrigation strategies, because even a reduced water supply can sustain growth and yield without causing severe stress or marked yield loss (Varol et al., 2023). Nevertheless, irrigation level strongly affects grain yield. Moreover, water stress imposed during flowering has been shown to significantly affect yield components, with more drought-tolerant genotypes maintaining higher pod number, seed weight and grain yield under water deficit, thereby demonstrating the decisive role of genotypic differences in yield stability (Boukecha et al., 2017). Irrigation level affects not only yield but also grain quality traits, including crude protein and fiber fractions such as ADF and NDF. Studies on different grass pea genotypes have reported that quality parameters vary over a wide range depending on genotype and water status, and that water stress can raise fiber components (ADF/NDF) owing to a decline in protein synthesis and changes in plant metabolism (Azak and Gülümser, 2025; Sezer and Gülümser, 2025). A trade-off thus emerges between yield and nutritional value. However, the natural drought resistance of grass pea, based on osmotic adjustment and strong antioxidative enzyme activity, keeps this trade-off more limited than in other legumes, so that yield and quality traits remain relatively stable (Jiang et al., 2013; Talukdar, 2013). Water use efficiency (WUE) and irrigation water use efficiency (IWUE), which define the yield produced per unit of limited water, constitute fundamental criteria for irrigation planning under semi-arid conditions. The FAO-33 yield response factor (ky) quantifies the relationship between the relative ET deficit and the relative yield reduction, thereby revealing a species' sensitivity to water deficit (Gusmao et al., 2012). Findings reported for grass pea point to a moderate tolerance to water deficit associated with osmotic adjustment and antioxidative responses, and hence to a ky value close to or below 1 (Jiang et al., 2013). On the other hand, differences in genotypic responses to irrigation give rise to significant genotype × environment interactions in both yield and water use parameters, underlining the need for environment-specific cultivar selection (Boukecha et al., 2017; Rubiales et al., 2020; Bahramnejad et al., 2021). Despite this, studies that comprehensively address the yield, grain quality and water use responses of grass pea cultivars to deficit irrigation under the semi-arid conditions of Central Anatolia remain limited. Accordingly, the present study aimed to determine the effects of five irrigation levels (M0, M25, M50, M75 and M100) on grain yield, quality traits (crude protein, ADF,

NDF, crude cellulose and crude ash), water use efficiency and yield-water relations (WUE, IWUE and ky) in five grass pea cultivars under the semi-arid conditions of Central Anatolia.

2. Material and Methods

2.1. Experimental site and plant material

The study was conducted during the 2023 growing season at the Agricultural Research and Application Centre of Erciyes University. The research site at an altitude of 1094 m, is located between 34º 56' and 36º 59' east longitudes and 37º 45' and 38º 18' north latitudes. Five grass pea (*Lathyrus sativus* L.) cultivars (GAP Mavisi, Karadağ, İptaş, Eren and Gürbüz) were used as plant material. Seeds were sown at a row spacing of 30 cm, in 5 m long rows, with 10 rows per plot (Küçükkaya and Doğrusöz, 2022). Sowing was performed on 2 April 2023. At sowing, 15 kg da^{-1} of DAP (18-46-0) was applied (Sayar and Han, 2015). Weeds were controlled throughout the growing period. Plants were harvested at full maturity on 23 July 2023, after 0.5 m borders had been removed from the ends of each plot, the remaining net area (12 m^2) was harvested to determine grain yield, which was then converted to a decare basis.

2.2. Experimental design

The irrigation treatments were randomly assigned to the main plots within each block (M0: rainfed, no irrigation; M25, M50, M75 and M100 receiving, respectively, 25%, 50%, 75% and 100% of the water applied to the fully irrigated treatment), and the grass pea cultivars (GAP Mavisi, Karadağ, İptaş, Eren and Gürbüz) were randomly assigned to the subplots within each main plot. A split-plot arrangement was adopted because, under drip irrigation, water is necessarily applied at the scale of the larger main plots for practical water-distribution reasons, whereas cultivars can be randomized freely within these plots.

Table 1. Climatic data for the experimental site

Month	Mean Temperature (°C)		Minimum Temperature (°C)		Maximum Temperature (°C)		Precipitation (mm)		Relative Humidity (%)	
	2023	LTA	2023	LTA	2023	LTA	2023	LTA	2023	LTA
April	13.4	11.3	4.8	4.9	15.0	17.7	37.0	52.1	64.5	62.3
May	13.8	14.7	6.8	6.9	19.8	22.5	20.3	51.8	61.8	61.2
June	19.9	18.3	13.2	9.8	24.1	26.9	44.5	39.5	65.7	55.8
July	21.6	20.4	13.9	11.9	28.9	30.6	2.7	10.5	48.0	49.5
Mean/Total	17.2	16.2	9.7	8.4	21.9	24.4	104.5*	153.9*	59.7	57.2

* Total precipitation for April-July. LTA: long-term average

Table 2. Some physical and chemical properties of the soils at the experimental site

Property	0-30 cm	30-60 cm
Clay (%)	11.84	9.13
Silt (%)	5.08	8.99
Sand (%)	83.08	81.88
Texture class	Sandy loam	Sandy loam
pH	7.71	7.63
Organic matter (%)	1.21	1.17
$CaCO_3$ (%)	0.34	0.23
K_2O (kg ha^{-1})	1214	846
P_2O_5 (kg ha^{-1})	90.07	66.39
EC (mmhos cm^{-1})	0.67	0.51
Field capacity (Pw, %)	23.97	23.54
Wilting point (Pw, %)	13.01	11.63
Bulk density (g cm^{-3})	1.24	1.25

2.3. Weather data and soil properties

Climatic data for the experimental year (2023) and the long-term average (LTA) are given in Table 1. Mean temperatures during the growing period (April-July) were close to the long-term values, whereas total precipitation for the period, at 104.5 mm, remained below the long-term average (153.9 mm). Some physical and chemical properties of the soils at the experimental site are presented in Table 2. The soils have a sandy-loam texture at both the 0-30 and 30-60 cm depths; they are low in lime and salt, rich in phosphorus and potassium, slightly alkaline in reaction and poor in organic matter. Measured at three points with a double-ring infiltrometer, the steady infiltration rate of the soil was determined as 22.7 mm h^{-1}.

2.4. Irrigation treatments

Irrigation water was supplied through a drip irrigation system consisting of a control unit (pressure regulator, fertilizer tank, sand-gravel and screen filters, manometer, valve and water meter) and a conveyance unit (main pipe, manifold, laterals and emitters). Along each plant row, PE laterals with in-line emitters spaced 25 cm apart, 16 mm in outer diameter, operating at 4 atm and delivering 2 L h^{-1} were laid out. Drawing on the principles reported by Yıldırım (2008), the system was designed to provide a wetted-area ratio of at least 30%. A water meter was placed at the head of each block. The effective root depth was taken as 60 cm (Allen et al., 1998), and soil moisture was monitored gravimetrically at 7-day intervals down to a depth of 90 cm. In the full-irrigation treatment (M100), the available water depleted within the effective root depth was replenished to field capacity at each irrigation; the deficit treatments (M75, M50 and M25) received, respectively, 75%, 50% and 25% of this amount, while the M0 treatment was left rainfed. In total, nine irrigations were applied over the growing season. The applied irrigation water (d, mm) was calculated using the following Equation 1:

$$d = \left[\frac{Pvtk - Pvm}{100}\right] * D * P \quad (1)$$

where Pvtk is the volumetric field capacity (%), Pvm is the volumetric moisture content before irrigation (%), D is the soil depth to be wetted (cm) and P is the wetted-area ratio (%). The calculated value was multiplied by the area to be irrigated, converted to liters and applied to the plots through the water meters.

2.5. Crop water consumption and yield–water relations

Crop water consumption (ET) was calculated using the water-balance as Equation 2 (James, 1993):

$$ET = I + R + Cr - Dp - Rf \pm \Delta S \quad (2)$$

where I is irrigation water, R is effective precipitation, Cr is capillary rise, Dp is deep percolation, Rf is surface runoff and ΔS is the change in moisture within the soil profile (mm). Under the experimental conditions, deep percolation, surface runoff and capillary rise were considered negligible, ET was therefore calculated mainly from irrigation, effective precipitation and the change in soil moisture. Because soil moisture was monitored gravimetrically down to 90 cm and each irrigation replenished only the depleted available water in the root zone up to field capacity. No downward movement of water below the monitored profile occurred, even under full irrigation on this sandy-loam soil. The relationship between the relative ET deficit and the relative yield reduction, together with the yield response factor (ky), was evaluated using the Stewart model (Equation 3) (Doorenbos and Kassam, 1979):

$$\left(1-\frac{Ya}{Ym}\right)=ky\left(1-\frac{ETa}{ETm}\right) \quad (3)$$

where Ya is the actual yield, Ym is the maximum yield, ETa and ETm are the corresponding water-consumption values, and ky is the yield response factor representing the sensitivity of yield to water deficit. Water use efficiencies were calculated using Equations 4 and 5 of Howell et al. (1990):

$$WUE = Ey/ET \quad (4)$$

$$IWUE = (Ey - Ey_0)/I \quad (5)$$

where WUE is water use efficiency, IWUE is irrigation water use efficiency, Ey is the economic (grain) yield (kg ha^{-1}), ET is crop water consumption (mm), I is irrigation water (mm) and Ey$_0$ is the yield of the rainfed (M0) treatment.

2.6. Agronomic and quality traits

Grain yield (kg ha^{-1}) was determined by threshing the plants harvested from the area remaining after the borders had been removed, weighing the grain and converting it to a hectare basis. Crude protein content (%) was calculated as N × 6.25 after the nitrogen content had been determined by the Kjeldahl method (AOAC, 1990). ADF, NDF and crude cellulose contents (%) were analyzed on grain samples ground through a 1 mm sieve using an ANKOM 200 Fiber Analyzer (ANKOM Technology Corp., Fairport, NY, USA) (ANKOM Technology, 2017). Crude ash content (%) was determined by burning a 1 g grain sample in a porcelain crucible at 550 °C for 8 h (ANKOM Technology, 2017).

2.7. Statistical analysis

The data obtained were subjected to analysis of variance (ANOVA) according to the split-plot design. Means were grouped using the least significant difference (LSD) test at the $p<0.05$ level. Error(a) was used for comparing irrigation means and Error(b) for comparing cultivar means; for traits in which the interaction was significant, the irrigation × cultivar cell means located in different main plots were compared using a pooled standard error and a weighted t value calculated with the Satterthwaite approximation (Gomez and Gomez, 1984). Means sharing a common letter are not statistically different from one another. The analyses were performed using the SPSS statistical software package.

3. Results

3.1. Grain yield (kg ha^{-1})

The effect of irrigation level on grain yield was significant ($p<0.001$). As the amount of irrigation water increased, grain yield rose markedly, and the mean values ranged from 1302 kg ha^{-1} in the M0 treatment to 2304 kg ha^{-1} in the M100 treatment. The cultivar effect was also statistically highly significant ($p<0.001$). Because the irrigation × cultivar interaction was significant ($p=0.002$), the cultivars differed in their response to irrigation, and comparisons were therefore made on the basis of cell means. The highest value was recorded for the İptaş cultivar in the M100 treatment (2669 kg ha^{-1}), whereas the lowest was recorded for the GAP Mavisi (GAP) cultivar in the M0 treatment (1240 kg ha^{-1}). The coefficients of variation for the main plots and subplots were 10.31% and 8.33%, respectively. The differing responses of the cultivars to irrigation and the crossover pattern are clearly visible in Figure 1.

Table 3. Grain yield (kg ha⁻¹) of grass pea cultivars grown under different irrigation levels and the corresponding analysis of variance

Irrigation	GAP	Karadağ	İptaş	Eren	Gürbüz	Mean
M0	1240^{n}	1275^{mn}	1326^{lmn}	1354^{klmn}	1317^{lmn}	1302
M25	1478^{jklmn}	1583^{ijkl}	1666^{hij}	1550^{jkl}	1727^{ghij}	1601
M50	1963^{defg}	1522^{jklm}	1853^{fghi}	1613^{ijk}	2160^{cde}	1822
M75	2142^{cde}	1674^{hij}	2327^{bc}	1934^{efgh}	2280^{bc}	2071
M100	2230^{cd}	1966^{defg}	2669^{a}	2124^{cdef}	2529^{ab}	2304
Mean	1811	1604	1968	1715	2003	1820
SOV	df	SS	MS	F	p	Sig.
Block	2	49208	24604	0.70	0.525	ns
Irrigation	4	9195436	2298859	65.24	<0.001	***
Error(a)	8	281909	35239			
Cultivar	4	1695870	423968	18.46	<0.001	***
I × C	16	1127522	70470	3.07	0.002	**
Error(b)	40	918713	22968			
Total	74	13268658				

*** p<0.001; ** p<0.01; * p<0.05; ns: not significant. Error(a): main-plot (irrigation) error; Error(b): subplot (cultivar) error. The F test for irrigation was performed against Error(a), and the F tests for cultivar and I × C against Error(b). Means sharing a common letter are not significantly different according to the LSD test (p<0.05).

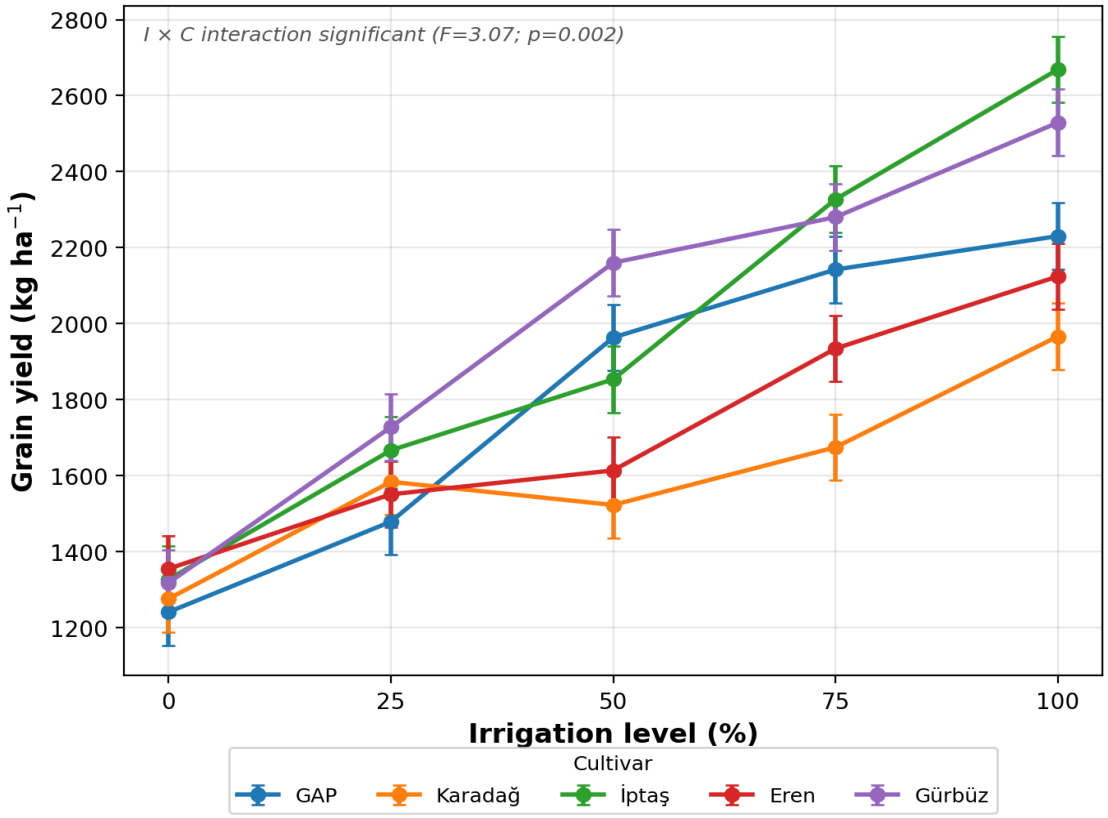

Figure 1. Grain yield (kg ha⁻¹) of five grass pea cultivars across irrigation levels. Points are treatment means, bars show standard error. The crossover among cultivars reflects the significant irrigation × cultivar interaction.

3.2. Crude protein content (%)

The effect of irrigation on crude protein content was significant (F=23.67; p<0.001). In contrast to the other traits, protein content decreased with irrigation; the highest mean was reached in the M0 treatment, where water deficit was most severe (28.58%), and the lowest under full irrigation (M100; 26.02%). This can be interpreted as a concentration effect arising from the limitation of dry-matter accumulation under water deficit. The difference among cultivars was also significant (F=15.89; p<0.001), with Karadağ having the highest protein content (28.31%) and İptaş the

lowest (26.60%). The irrigation × cultivar interaction was not significant (F=1.13; p=0.366), so the two factors were evaluated independently. The coefficients of variation were 2.99% for the main plots and 2.47% for the subplots.

Table 4. Crude protein (%) of grass pea cultivars grown under different irrigation levels and the corresponding analysis of variance

Irrigation	GAP	Karadağ	İptaş	Eren	Gürbüz	Mean
M0	28.58	29.50	27.26	29.08	28.46	28.58[a]
M25	28.31	29.28	27.20	28.53	27.30	28.12[ab]
M50	27.18	28.40	27.72	28.12	27.01	27.69[b]
M75	26.43	27.58	26.00	27.45	26.55	26.80[c]
M100	26.82	26.76	24.84	26.42	25.26	26.02[d]
Mean	27.46[b]	28.31[a]	26.60[c]	27.92[ab]	26.92[c]	27.44
SOV	df	SS	MS	F	p	Sig.
Block	2	4.978	2.489	3.70	0.073	ns
Irrigation	4	63.733	15.933	23.67	<0.001	***
Error(a)	8	5.385	0.673			
Cultivar	4	29.275	7.319	15.89	<0.001	***
I × C	16	8.297	0.519	1.13	0.366	ns
Error(b)	40	18.420	0.460			
Total	74	130.089				

*** p<0.001; ** p<0.01; * p<0.05; ns: not significant. Error(a): main-plot (irrigation) error; Error(b): subplot (cultivar) error. The F test for irrigation was performed against Error(a), and the F tests for cultivar and I × C against Error(b). Means sharing a common letter are not significantly different according to the LSD test (p<0.05)

3.3. Crude cellulose content (%)

Irrigation level significantly affected crude cellulose content (F=58.20; p<0.001); the content tended to increase under water deficit, rising to 5.49% in the M0 treatment and declining to 4.48% under full irrigation. The cultivar effect was also significant (F=21.13; p<0.001), with the highest values in Karadağ (5.31%), GAP Mavisi (5.21%) and Eren (5.17%), and the lowest value in İptaş (4.67%). Because the irrigation × cultivar interaction was not significant (F=1.11; p=0.376), mean separation was based on the main effects. The coefficients of variation were calculated as 4.01% for the main plots and 4.81% for the subplots.

Table 5. Crude cellulose (%) of grass pea cultivars grown under different irrigation levels and the corresponding analysis of variance

Irrigation	GAP	Karadağ	İptaş	Eren	Gürbüz	Mean
M0	5.38	5.85	5.13	5.85	5.21	5.49[a]
M25	5.75	5.59	4.99	5.33	4.94	5.32[a]
M50	5.16	5.39	4.54	5.10	4.84	5.01[b]
M75	4.99	5.17	4.51	4.97	4.48	4.83[c]
M100	4.74	4.56	4.17	4.59	4.36	4.48[d]
Mean	5.21[a]	5.31[a]	4.67[b]	5.17[a]	4.77[b]	5.02
SOV	df	SS	MS	F	p	Sig.
Block	2	0.104	0.052	1.28	0.329	ns
Irrigation	4	9.457	2.364	58.20	<0.001	***
Error(a)	8	0.325	0.041			
Cultivar	4	4.944	1.236	21.13	<0.001	***
I × C	16	1.043	0.065	1.11	0.376	ns
Error(b)	40	2.340	0.059			
Total	74	18.214				

*** p<0.001; ** p<0.01; * p<0.05; ns: not significant. Error(a): main-plot (irrigation) error; Error(b): subplot (cultivar) error. The F test for irrigation was performed against Error(a), and the F tests for cultivar and I × C against Error(b). Means sharing a common letter are not significantly different according to the LSD test (p<0.05)

3.4. Crude ash content (%)

The difference among irrigation levels in crude ash content was significant (F=11.95; p=0.002). Ash content took relatively high values under water deficit (M0: 3.27%) and, as irrigation level increased, decreased to 2.94%

under full irrigation. The cultivars differed significantly in ash content (F=7.84; p<0.001). In contrast, the irrigation × cultivar interaction was not significant (F=0.93; p=0.540), so the irrigation and cultivar effects were evaluated separately. The coefficients of variation were low, at 4.84% for the main plots and 3.53% for the subplots.

Table 6. Crude ash (%) of grass pea cultivars grown under different irrigation levels and the corresponding analysis of variance

Irrigation	GAP	Karadağ	İptaş	Eren	Gürbüz	Mean
M0	3.33	3.28	3.16	3.35	3.24	3.27[a]
M25	3.20	3.36	3.19	3.30	3.19	3.25[a]
M50	3.19	3.19	2.98	3.25	3.15	3.15[ab]
M75	2.99	3.24	2.98	3.20	2.98	3.08[b]
M100	2.97	3.06	2.90	2.93	2.82	2.94[c]
Mean	3.14[bc]	3.23[a]	3.04[d]	3.21[ab]	3.07[cd]	3.14
SOV	df	SS	MS	F	p	Sig.
Block	2	0.027	0.013	0.58	0.579	ns
Irrigation	4	1.102	0.275	11.95	0.002	**
Error(a)	8	0.184	0.023			
Cultivar	4	0.385	0.096	7.84	<0.001	***
I × C	16	0.184	0.011	0.93	0.540	ns
Error(b)	40	0.491	0.012			
Total	74	2.373				

*** p<0.001; ** p<0.01; * p<0.05; ns: not significant. Error(a): main-plot (irrigation) error; Error(b): subplot (cultivar) error. The F test for irrigation was performed against Error(a), and the F tests for cultivar and I × C against Error(b). Means sharing a common letter are not significantly different according to the LSD test (p<0.05)

3.5. NDF content (%)

The effect of irrigation on NDF content was significant (F=25.61; p<0.001); increasing slightly under water deficit, the content reached its highest value in the M0 treatment (12.80%) and its lowest under full irrigation (M100; 11.17%). The cultivar effect was also significant (F=13.00; p<0.001), with the highest NDF content in Karadağ (12.70%) and the lowest in İptaş (11.30%). Because the irrigation × cultivar interaction was not significant (F=1.16; p=0.342), comparisons were evaluated based on the main-effect means. The coefficients of variation were 4.00% for the main plots and 4.60% for the subplots.

Table 7. NDF (%) of grass pea cultivars grown under different irrigation levels and the corresponding analysis of variance

Irrigation	GAP	Karadağ	İptaş	Eren	Gürbüz	Mean
M0	12.97	13.40	11.93	13.25	12.42	12.80[a]
M25	12.72	12.84	11.95	12.59	12.09	12.44[ab]
M50	12.34	13.44	10.70	12.08	12.05	12.12[bc]
M75	11.52	11.96	11.40	11.93	11.81	11.72[c]
M100	11.04	11.84	10.51	11.51	10.96	11.17[d]
Mean	12.12[b]	12.70[a]	11.30[c]	12.27[b]	11.87[b]	12.05
SOV	df	SS	MS	F	p	Sig.
Block	2	2.903	1.452	6.24	0.023	*
Irrigation	4	23.837	5.959	25.61	<0.001	***
Error(a)	8	1.861	0.233			
Cultivar	4	15.985	3.996	13.00	<0.001	***
I × C	16	5.686	0.355	1.16	0.342	ns
Error(b)	40	12.299	0.307			
Total	74	62.572				

*** p<0.001; ** p<0.01; * p<0.05; ns: not significant. Error(a): main-plot (irrigation) error; Error(b): subplot (cultivar) error. The F test for irrigation was performed against Error(a), and the F tests for cultivar and I × C against Error(b). Means sharing a common letter are not significantly different according to the LSD test (p<0.05)

3.6. ADF content (%)

The effect of irrigation level on ADF content was significant (F=28.58; p<0.001), the content increasing under greater water deficit to 6.78% at M0 and 5.89% at M100. The cultivar effect was also significant (F=12.47; p<0.001). As with grain yield, the irrigation × cultivar interaction was significant for ADF content (F=1.91; p=0.0496), so comparisons were made on the basis of cell means. The highest ADF content was recorded for the Karadağ cultivar in the M0 treatment (7.59%) and the lowest for the GAP Mavisi cultivar in the M100 treatment (5.55%). The coefficients of variation were 4.33% for the main plots and 5.31% for the subplots.

Table 8. ADF (%) of grass pea cultivars grown under different irrigation levels and the corresponding analysis of variance

Irrigation	GAP	Karadağ	İptaş	Eren	Gürbüz	Mean
M0	6.78^{bcd}	7.59^{a}	6.25^{defghi}	6.94^{bc}	6.33^{defghi}	6.78
M25	6.52^{cdef}	7.03^{bc}	6.07^{fghij}	7.18^{ab}	6.34^{defgh}	6.63
M50	6.10^{fghi}	7.03^{bc}	6.13^{efghi}	6.67^{bcde}	6.38^{defg}	6.46
M75	6.16^{efghi}	6.25^{defghi}	5.89^{ghij}	5.82^{hij}	6.11^{fghi}	6.05
M100	5.55^{j}	6.00^{fghij}	5.79^{ij}	6.26^{defghi}	5.84^{ghij}	5.89
Mean	6.22	6.78	6.02	6.57	6.20	6.36
SOV	df	SS	MS	F	p	Sig.
Block	2	0.179	0.090	1.18	0.355	ns
Irrigation	4	8.676	2.169	28.58	<0.001	***
Error(a)	8	0.607	0.076			
Cultivar	4	5.685	1.421	12.47	<0.001	***
I × C	16	3.477	0.217	1.91	0.0496	*
Error(b)	40	4.559	0.114			
Total	74	23.183				

*** p<0.001; ** p<0.01; * p<0.05; ns: not significant. Error(a): main-plot (irrigation) error; Error(b): subplot (cultivar) error. The F test for irrigation was performed against Error(a), and the F tests for cultivar and I × C against Error(b). Means sharing a common letter are not significantly different according to the LSD test (p<0.05).

3.7. Crop water consumption, water use efficiency and yield–water relations

The seasonal crop water consumption (ET) measured together with the irrigation water applied to the treatments is given in Table 9. ET increased from 142 mm in the rainfed treatment (M0) to 393 mm under full irrigation (M100). In the deficit treatments, the plants used a greater proportion of the moisture stored in the soil profile. The water use efficiency (WUE) values of the cultivars are presented in Table 10. WUE reached its highest value under rainfed conditions (mean 9.2 kg ha^{-1} mm^{-1}) and decreased with increasing irrigation to 5.9 kg ha^{-1} mm^{-1} at M100. This trend arises because the production function has a positive intercept and is linear over the range examined; that is, the crop provides a substantial baseline yield even with limited water. Irrigation water use efficiency (IWUE) ranged from 4.1 (M25) to 3.5 kg ha^{-1} mm^{-1} (M100) and decreased with increasing irrigation.

Table 9. Applied irrigation water (mm), precipitation (mm) and seasonal crop evapotranspiration (ET, mm) for the irrigation treatments

Treatment	Irrigation (mm)	Precipitation (mm)	ET (mm)
M0	0	91	142
M25	72	91	202
M50	144	91	270
M75	216	91	329
M100	288	91	393

Table 10. Water use efficiency (WUE, kg ha^{-1} mm^{-1}) of grass pea cultivars by irrigation treatment

Treatment	GAP	Karadağ	İptaş	Eren	Gürbüz	Mean
M0	8.7	9.0	9.3	9.5	9.3	9.2
M25	7.3	7.8	8.2	7.7	8.5	7.9
M50	7.3	5.6	6.9	6.0	8.0	6.7
M75	6.5	5.1	7.1	5.9	6.9	6.3
M100	5.7	5.0	6.8	5.4	6.4	5.9
Mean	7.1	6.5	7.7	6.9	7.8	7.2

When the relationship between the relative ET deficit and the relative yield reduction was evaluated with the Stewart model, the yield response factor was determined as ky=0.66 (95% CI: 0.63–0.70; SE=0.01; R^2=0.996) from regression through the origin. A ky value below 1 indicates that grass pea is relatively tolerant to water deficit and that yield loss develops more slowly than the relative water deficit. The water–yield production function was obtained as the linear form Y=770 + 3.93·ET (R^2=0.996), so that yield increased by approximately 3.9 kg ha^{-1} for every 1 mm increase in ET. Because the apex of the quadratic model (1373 mm) lies far outside the experimental range (142-393 mm), the relationship is practically linear over the range examined and no yield plateau was observed (Figure 2).

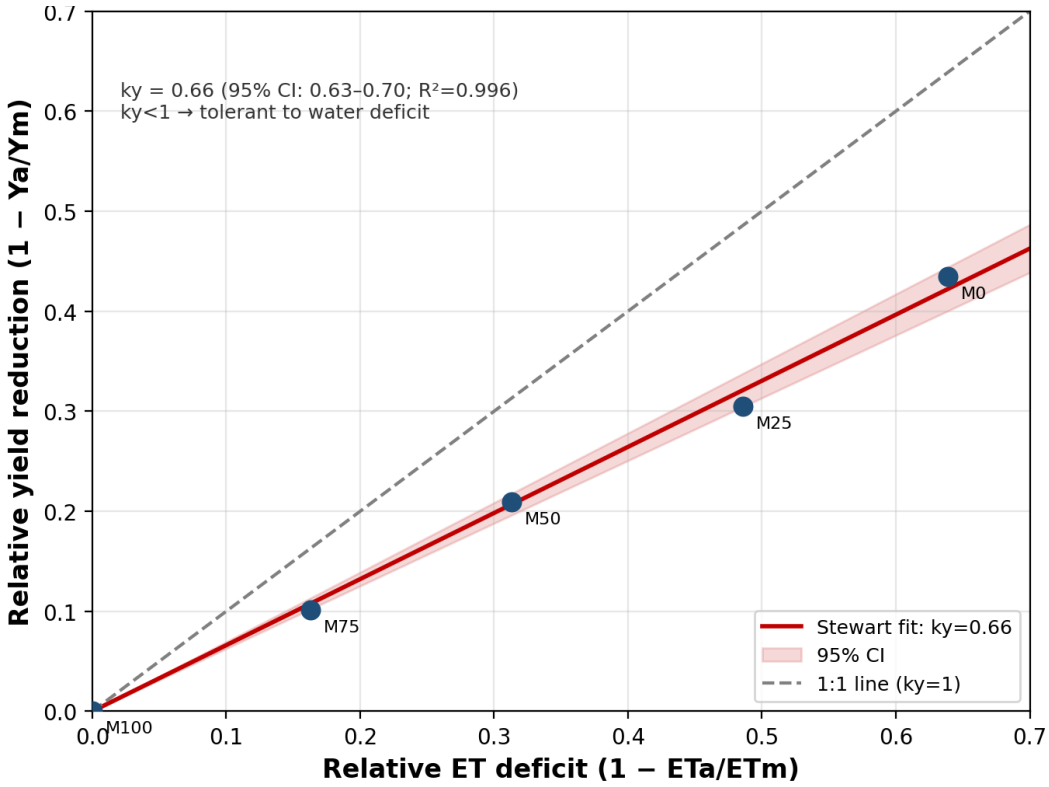

Figure 2. Relative yield reduction (1 − Ya/Ym) versus relative ET deficit (1 − ETa/ETm), fitted with the Stewart model. The dashed line is the 1:1 reference (ky=1). ky<1 indicates tolerance to water deficit

3.8. Relationships among the examined traits

The relationships among the examined traits were evaluated by Pearson correlation analysis on a plot basis (n=75), and the coefficients are presented in Figure 3; all coefficients shown were significant at p<0.01. The traits defining grain quality (crude protein, crude cellulose, crude ash, NDF and ADF) were moderately to strongly and positively

correlated with one another, indicating that these components increase and decrease together. In contrast, grain yield was negatively correlated with all of the quality traits, the strongest inverse relationships being between yield and crude protein and crude cellulose. This picture clearly reflects the yield–quality trade-off, in which yield rises with increasing irrigation while the quality components decline through a concentration effect. In terms of water relations, a strong positive relationship was found between crop water consumption (ET) and grain yield; ET was also negatively correlated with all quality traits. WUE, in turn, was strongly and negatively correlated with ET, showing that the yield obtained per unit of water declines as seasonal water consumption increases.

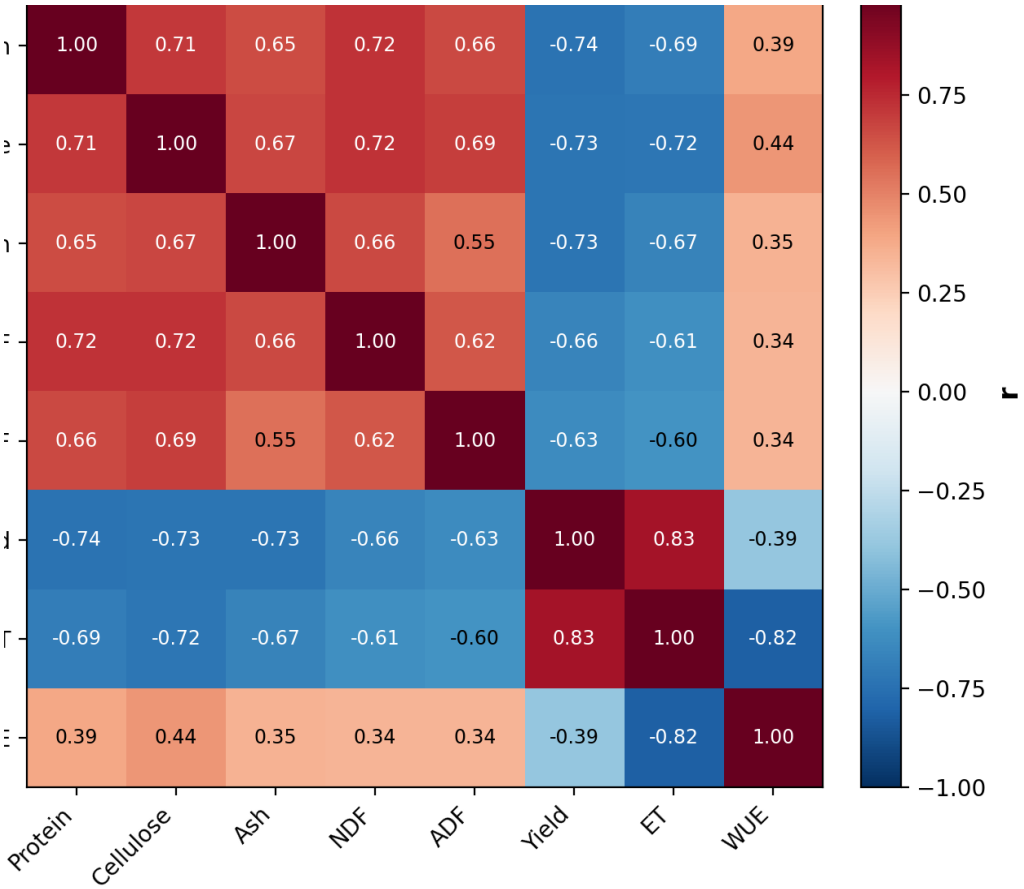

Figure 3. Pearson correlation matrix among grain yield and the examined traits. Values are correlation coefficients (r), color-scaled from −1 to +1

4. Discussion

In the present study, the increase in grain yield with rising irrigation water, from 1302 kg ha^{-1} at M0 to 2304 kg ha^{-1} at M100, shows that grass pea responds positively and strongly to supplemental water under semi-arid conditions. The attainment of a baseline yield of about 1300 kg ha^{-1} even under rainfed conditions reflects the species' ability to avoid and escape drought; indeed, the resistance mechanisms of grass pea, based on osmotic adjustment and strong antioxidative enzyme activity, allow growth to continue under water deficit (Jiang et al., 2013; Talukdar, 2013). This behavior was also confirmed quantitatively by the yield response factor obtained. The ky value of 0.66 is below 1, indicating that the relative yield loss develops more slowly than the relative ET deficit. Considering the ky range reported for field crops in the FAO datasets (0.20-1.15) (Doorenbos and Kassam, 1979; Kirda, 2002), grass pea falls in the lower-middle part of this range and its sensitivity to water deficit

remains markedly below that of species such as maize (ky ≈ 1.25). A comparably low ky (0.25) has likewise been reported for lavender under deficit irrigation in a semi-arid climate (Yetik and Şen, 2025). Similarly, Gusmao et al. (2012) reported that a water deficit imposed during the generative period reduced grain yield in grass pea but preserved seed size, suggesting that the yield loss arises mainly from a reduction in seed number while the grain-filling quality is maintained. Comparing cool-season legumes under Mediterranean conditions, Karrou and Oweis (2012) showed that, under deficit irrigation at two-thirds of full irrigation, the yield loss in chickpea, lentil and faba bean was limited to 5-16% and that water productivity increased markedly; the fact that the M75 treatment in our findings (2071 kg ha^{-1}) reached 90% of full irrigation is consistent with these results. The significant irrigation × cultivar interaction detected for grain yield revealed that the cultivars differed in their response to water and that a crossover pattern occurred (Figure 1). While the difference among cultivars narrowed under rainfed conditions (1240-1354 kg ha^{-1}), it widened as irrigation level increased, with the İptaş and Gürbüz cultivars standing out (2669 and 2529 kg ha^{-1} at M100, respectively). By contrast, the Karadağ cultivar gave the weakest response to irrigation (1966 kg ha^{-1} at M100) but had the highest protein content. This pattern is consistent with studies emphasizing the decisive role of the genotype × environment interaction in grass pea; Boukecha et al. (2017) reported that, under drought stress, genotype and the genotype × stress interaction were significant for pod number, seed weight and grain yield in Algerian populations, while Bahramnejad et al. (2021) found that the Shahrekord ecotype showed higher yield and water use efficiency than Lalehzar under deficit irrigation. Rubiales et al. (2020) likewise demonstrated marked differences in adaptation and yield stability among grass pea genotypes in Mediterranean environments. Cultivar recommendation in grass pea therefore cannot be made independently of the water regime: highly responsive cultivars should be preferred where water is available, and cultivars with high yield stability where water is limited. The trend detected in grain quality traits clearly revealed the trade-off between yield and nutritional value. The increase in crude protein content under water deficit (M0: 28.58%; M100: 26.02%) can be explained by a classic concentration (dilution) effect linked to the limitation of dry-matter accumulation; a relative increase in grain protein under water deficit has similarly been reported for various grain crops. However, the literature on this point is not unidirectional: it has also been reported that protein synthesis may decline because drought suppresses nitrogen fixation and nitrogen assimilation, and that protein content may fall under severe stress (Sarker et al., 2023). In the present study, the moderate levels of deficit applied and the ability of grass pea to preserve its nodulation relatively well (Talukdar, 2013) explain why the concentration effect prevailed. The increase in the fiber fractions (ADF, NDF and crude cellulose) and ash content under water deficit can be associated with an increase in the share of cell-wall components in the total dry matter. Here, too, the literature is inconsistent: some studies report that ADF and NDF contents decrease under drought owing to delayed maturation (Küchenmeister et al., 2013), whereas others report an increase. This difference indicates that the organ examined (grain or herbage), the severity and timing of the stress, and species differences are all decisive. The protein values obtained (26.0-28.6%) are consistent with the ranges reported for grass pea genotypes (Azak and Gülümser, 2025), and the fact that the ADF and NDF contents measured in the grain samples (5.9-6.8% and 11.2-12.8%) are lower than the values reported for silage herbage stems from the naturally lower cell-wall content of the grain. A limitation of the present study is that β-N-oxalyl-L-α,β-diaminopropionic acid (β-ODAP), the neurotoxic non-protein amino acid that primarily determines the dietary safety of grass pea, was not measured; the quality results reported here therefore describe nutritional composition only and should not be interpreted as evidence of dietary safety, which would

require quantification of the β-ODAP response to irrigation. Water use efficiency reached its highest value under rainfed conditions even on an ET basis (9.2 kg ha^{-1} mm^{-1}) and decreased gradually with increasing irrigation (M100: 5.9 kg ha^{-1} mm^{-1}). This behavior is due to the water-yield production function having a positive intercept and being linear over the range examined ($Y=770 + 3.93 \cdot ET$; $R^2=0.996$); when written as $WUE=770/ET + 3.93$, a decline in WUE with increasing ET is a mathematical necessity, because the contribution of the constant term diminishes as ET increases. The fact that the apex of the quadratic model lies far outside the experimental range (~1373 mm) also shows that neither a yield plateau nor luxury water consumption was reached within the 142-393 mm range. The decline in irrigation water use efficiency (IWUE) from 4.1 at M25 to 3.5 kg ha^{-1} mm^{-1} at M100 reflects diminishing marginal water productivity; that is, the contribution of each additional mm of irrigation water to yield progressively decreases. Similarly, Karrou and Oweis (2012) reported that deficit irrigation increased water productivity in legumes by 126-190% relative to rainfed conditions, while Geerts and Raes (2009) emphasized that deficit irrigation is the key strategy for raising water productivity in dry areas. Taken together, these findings show that the M100 treatment, which gives the highest absolute yield, is not the best option in terms of water productivity.

5. Conclusion

In conclusion, grass pea stands out as a tolerant species that adapts well to deficit irrigation under the semi-arid conditions of Central Anatolia, can produce stable yields even with a low water input, and has a ky value below 1. Where water is not limiting, full irrigation (M100) provides the highest grain yield; by contrast, where water is limited and costly, the M75 treatment can be regarded as the most balanced option, offering about 90% of the yield of full irrigation while saving 25% of the water. In years when the water resource is even more limited, the M50 treatment allows production to continue with high productivity per unit of water. Cultivar choice should be considered together with the water regime: the highly responsive İptaş and Gürbüz cultivars under adequate water conditions, and the high-protein Karadağ cultivar under limited water or for forage-oriented production. Because the findings are based on a single-year, single-location experiment, it would be useful to confirm the yield stability and the ky value across different years and additional locations.

Funding Statement

This work was funded by the Erciyes University Scientific Research Projects Coordination Unit under project number FHD-2023-12778.

Ethical Statement

Ethics committee approval was not required for this study.

Artificial Intelligence Declaration

The author declare that no generative artificial intelligence tools were used at any stage of the preparation of this manuscript, including the writing, editing, or refinement of the text, or the creation of tables, or related titles.

References

Abd El-Moneim, A.M.A., Van Dorrestein, B., Baum, M., Mulugeta, W., 2000. Improving the nutritional quality and yield potential of grass pea (*Lathyrus sativus* L.). *Food and Nutrition Bulletin*, 21(4): 493-496.

Alharbi, S., Felemban, A., Abdelrahim, A., Al-Dakhil, M., 2024. Agricultural and Technology-based strategies to improve water-use efficiency in arid and semiarid areas. *Water*, 16(13): 1842.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. FAO, Rome.

ANKOM Technology, 2017. Neutral detergent fiber in feeds-filter bag technique (for A2000 and A2000I). ANKOM Technology, Macedon, NY.

AOAC, 1990. Official Methods of Analysis (15th ed.). Association of Official Analytical Chemists, Washington, DC.

Azak, M., Gülümser, E., 2025. Silage yield and quality of different grass pea (*Lathyrus sativus* L.) genotypes. *Turkish Journal of Agriculture and Forestry*, 49(2): 272-282.

Bahramnejad, A.R., Abad Sharif Heidari, H., Madani, H., 2021. Effect of irrigation regimes and phosphorus fertilization on water-use efficiency, phosphorus-agronomic efficiency and yield of grass pea (*Lathyrus sativus* L.) ecotypes. *Legume Research*, 44(9): 1038-1045.

Boukecha, D., Laouar, M., Mekliche-Hanifi, L., Harek, D., 2017. Drought tolerance in some populations of grass pea (*Lathyrus sativus* L.). Legume Research, 41(1): 12-19.

Chen, F., Cui, N., Jiang, S., Zhang, W., Li, H., Li, X., Wang, Z., 2025. Effects of deficit drip irrigation at different growth stages on citrus leaf physiology, fruit growth, yield, and water productivity in South China. *Agricultural Water Management*, 307: 109206.

Ciftci, B., Kardes, Y.M., Varol, I.S., Tas, I., Akcura, S., Coskun, Y., Kaplan, M., 2025. Effects of drip irrigations with different irrigation intervals and levels on nutritional traits of paddy cultivars. *Foods*, 14(3): 528.

Doorenbos, J., Kassam, A.H., 1979. Yield response to water. FAO Irrigation and Drainage Paper No. 33. FAO, Rome.

Geerts, S., Raes, D., 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agricultural Water Management*, 96(9): 1275-1284.

Gomez, K.A., Gomez, A.A., 1984. Statistical Procedures for Agricultural Research (2nd ed.). John Wiley & Sons, New York.

Gusmao, M., Siddique, K.H.M., Flower, K., Nesbitt, H., Veneklaas, E.J., 2012. Water deficit during the reproductive period of grass pea (*Lathyrus sativus* L.) reduced grain yield but maintained seed size. *Journal of Agronomy and Crop Science*, 198(6): 430-441.

Hassan, I.F., Kalaji, H.M., Ajaj, R., Zarrouk, O., Athar, H.U.R., Mira, A.M., Hatterman-Valenti, H.M., 2025. A deficit irrigation strategy for 'Solar eclipse' plum in semi-arid climates. *Journal of Water and Land Development*. 66: 206–213.

Hillocks, R.J., Maruthi, M.N., 2012. Grass pea (*Lathyrus sativus*): Is there a case for further crop improvement? *Euphytica*, 186(3): 647-654.

Howell, T.A., Cuenca, R.H., Solomon, K.H., 1990. Crop yield response. In G.J. Hoffman, T.A. Howell & K.H. Solomon (Eds.), *Management of Farm Irrigation Systems* (pp. 93-122). ASAE, St. Joseph, MI.

James, L.G., 1993. Principles of Farm Irrigation System Design. Krieger Publishing Company, Malabar, FL.

Jiang, J., Su, M., Chen, Y., Gao, N., Jiao, C., Sun, Z., Li, F., Wang, C., 2013. Correlation of drought resistance in grass pea (*Lathyrus sativus*) with reactive oxygen species scavenging and osmotic adjustment. *Biologia*, 68(2): 231-240.

Karrou, M., Oweis, T., 2012. Water and land productivities of wheat and food legumes with deficit supplemental irrigation in a Mediterranean environment. *Agricultural Water Management*, 107: 94-103.

Kirda, C., 2002. Deficit irrigation scheduling based on plant growth stages showing water stress tolerance. In: *Deficit Irrigation Practices*, FAO Water Reports No. 22 (pp. 3-10). FAO, Rome.

Küchenmeister, K., Küchenmeister, F., Kayser, M., Wrage-Mönnig, N., Isselstein, J., 2013. Influence of drought stress on nutritive value of perennial forage legumes. *International Journal of Plant Production*, 7(4): 693-710.

Küçükkaya, U., Doğrusöz, M.Ç., 2022. Mürdümük (*Lathyrus sativus* L.) popülasyon ve çeşitlerinin Yozgat ekolojisinde morfolojik ve agronomik özelliklerinin belirlenmesi. *ISPEC Journal of Agricultural Sciences*, 6(4): 786-796.

Rubiales, D., Emeran, A.A., Flores, F., 2020. Adaptation of grass pea (*Lathyrus sativus*) to Mediterranean environments. *Agronomy*, 10(9): 1295.

Sarkar, A., Emmrich, P.M.F., Sarker, A., Zong, X., Martin, C., Wang, T.L., 2019. Grass pea: Remodelling an ancient insurance crop for climate resilience. In C. Kole (Ed.), *Genomic Designing of Climate-Smart Pulse Crops* (pp. 425-489). Springer, Cham.

Sarker, U., Rahman, M.M., Hossain, M.N., Azam, M.G., Oba, S., 2023. Impact of heat and drought stress on grass pea and its wild relatives. *Plants*, 12(19): 3341.

Sayar, M.S., Han, Y., 2015. Determination of seed yield and yield components of grass pea (*Lathyrus sativus* L.) lines and evaluations using GGE Biplot analysis method. *Journal of Agricultural Sciences*, 21(1): 78-92.

Sezer, M., Gülümser, E., 2025. Comparison of grass pea (*Lathyrus sativus* L.) genotypes in forage yield, nutrient composition and phytotrapic traits. *Journal of Tekirdag Agricultural Faculty*, 22(4): 1004-1019.

Talukdar, D., 2013. Comparative morpho-physiological and biochemical responses of lentil and grass pea genotypes under water stress. *Journal of natural science, biology, and medicine*, 4(2): 396.

Varol, I.S., Kırnak, H., Irik, H.A., Ozaktan, H., 2023. Effects of supplementary drip irrigations applied in different growth stages on yield and yield components of Chickpea plants grown under semiarid climate conditions. *Gesunde Pflanzen*, 75(4): 1307-1314.

Varol, I.S., Ünlükara, A., Kaplan, M., 2024. Water productivity, yield response factors, yield and quality of alfalfa cultivars in semi-arid climate conditions. *Environmental and Experimental Botany*, 224: 105826.

Vaz Patto, M.C., Skiba, B., Pang, E.C.K., Ochatt, S.J., Lambein, F., Rubiales, D., 2006. Lathyrus improvement for resistance against biotic and abiotic stresses: From classical breeding to marker assisted selection. *Euphytica*, 147(1-2): 133-147.

Yetik, A.K., Şen, B., 2025. Optimizing lavender (*Lavandula angustifolia* Mill.) yield and water productivity with deficit irrigation in semi-arid climates. *Agronomy*, 15(5): 1009.

Yıldırım, O., 2008. Sulama Sistemlerinin Tasarımı. Ankara: Ankara Üniversitesi, Ziraat Fakültesi, Ankara.