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INTEGRATED ASSESSMENT OF WATER STRESS IN TABLE GRAPE VINES: PHYSIOLOGICAL, BIOMETRIC AND SATELLITE INDICATORS AND THE IMPACT OF IRRIGATION ON YIELD AND HARVEST QUALITY

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Abstract

The integrated assessment of water stress in grapevines for table grapes, using physiological, biometric, and satellite indicators, highlighted the significant influence of irrigation and fertilization on yield and quality. Moderate irrigation (75% Active Humidity Index) combined with complex C4 fertilization proved most effective, enhancing both quantitative and qualitative production. The cultivar Țâța caprei neagră showed the highest performance, with the largest number of clusters per vine, the highest average cluster weight, and 100-berry mass, reaching yields of over 4,000 kg/vine under optimal conditions. Țâța caprei albă exhibited stable results, while Coarnă albă showed lower potential, requiring more careful management. Water stress analysis using CWSI and ΔTc–Ta indicated high deficit tolerance in Țâța caprei neagră, moderate tolerance in Țâța caprei albă, and sensitivity in Coarnă albă. Selecting a well-adapted cultivar and applying optimal irrigation and fertilization strategies are essential for achieving stable, high-quality yields under variable climatic conditions.

Key words*: cultivar selection, CWSI, fertilization, irrigation, water stress.*

INTRODUCTION

Water is one of the most important factors for vine growth and grape quality. In recent years, its importance has become even more evident as climate change brings more frequent droughts and unpredictable weather conditions. Lack of water limits table grape varieties by reducing berry size, grape weight, and their appearance for marketing (Chaves et al., 2010).

Water deficit affects the physiological processes of the vine: gas exchange is reduced, transpiration is limited, and the temperature at the leaf level increases, making it necessary to evaluate the water status in the correct establishment of irrigation regimes. In practice, thermal indicators such as the Crop Water Stress Index (CWSI) or the difference between canopy temperature and air temperature (ΔTc-Ta) are frequently used; these provide a quick assessment of the stress levels (Idso et al., 1981; Jones, 2004), and can signal stress before symptoms are visible in the vineyard.

In addition to physiological measurements, biometric indicators of production, such as the number of grapes per vine, the average weight of a grape, the mass of berries, and the weight of 100 berries, reflect how the vine has responded to the availability of water throughout the growing season.

Studies show that a moderate deficit can have positive effects by improving water use efficiency without negatively affecting the quality of the production. When water stress becomes severe, production decreases are evident and berry development is affected (Keller, 2015). Recent research confirms that careful irrigation management can support both yield and quality, even under drought conditions (El-Sayed et al., 2024; Strydom, 2025).

Satellite imagery, especially thermal and multispectral imagery, is used in water stress forecasting to analyze variations within vineyards, highlighting differences in vegetation vigor and water status (Zarco-Tejada et al., 2013). Integrating these data with field measurements leads to more accurate assessments and better informed irrigation decisions (Cohen et al., 2024).

Although the literature is rich in studies on wine varieties, information on table varieties grown in Romanian conditions is still limited.

Furthermore, approaches that simultaneously analyze irrigation, fertilization, and their effects on yield and quality are relatively few.
Starting from these aspects, the present work aims to assess water stress in several Romanian table grape varieties (Ţâţa caprei neagră, Ţâţa caprei albă şi Coarnă albă), using a combined approach. Physiological measurements, production parameters, and vegetation indices obtained from satellite data are used to understand how water availability influences both quantity and quality. The aim is to propose practical strategies for obtaining stable and quality harvests, even under increasingly unpredictable climatic conditions.

MATERIALS AND METHODS

The experiment was conducted in 2025 at the ampelographic collection of the Institute for Research and Development for Viticulture and Winemaking Valea Călugărească (ICDVV Valea Călugărească). Three Romanian table grape varieties were included: Coarnă albă, Ţâţa caprei neagră and Ţâţa caprei albă (Figure 1).



Figure 1. Location in the GIS system of the experimental plot

The study was designed as a three-factorial experiment to evaluate the effects of variety, irrigation level, and mineral fertilization on the physiological responses and productive performance of the vine.
Irrigation treatments were determined based on the active soil moisture index (IUA), representing the percentage of water available in the soil. Three irrigation regimes were applied: un-irrigated control, IUA 50% and IUA 75%.
Water was administered through a drip irrigation system, allowing precise regulation of the applied quantities according to evapotranspiration requirements and soil moisture levels.
Fertilization treatments were applied at different phenological stages using the following products: NPK 15:15:15 at 200 kg/ha, Atonik at 5 L/ha by foliar application, Solfert 20:20:20 enriched with microelements at 10 kg/ha and Novatec Classic at 300 kg/ha.
Physiological measurements were carried out around noon, when water stress usually reaches its peak. Photosynthesis rate (A) and respiration (R) were measured using the portable LCi photosynthesis system (µmol $CO_2/m^2/s$). Simultaneously, transpiration rate (E) and stomatal conductance (gs) (mmol $H_2O/m^2/s$) were recorded. Leaf temperature (Tc) and air temperature (Ta) were also measured to calculate ΔTc–Ta and the crop water stress index (CWSI), following the methods of Idso et al. (1981) and Jones (2004). Vegetation dynamics and canopy vigor were monitored at the vegetative phenophases of flowering (June 02), veraison (July 13 vs August 12) and ripening (September 10) using Sentinel-2 satellite images processed through the EO Browser platform.
The Normalized Difference Vegetation Index (NDVI) was calculated using the standard formula: NDVI = (NIR − RED) / (NIR + RED).
At harvest, biometric parameters, grape yield per vine, and average grape weight were measured. Data were analyzed using three-way ANOVA to evaluate the effects of cultivar, irrigation, fertilization, and their interactions. Mean comparisons were performed using the Least Significant Difference (LSD) test at $p \leq 0.05$.

RESULTS AND DISCUSSIONS

The soil water regime during the growing season was influenced by rainfall, evapotranspiration and the application of differentiated irrigation norms. In April and May, soil water reserves were sufficient due to moderate rainfall (41-172 mm) and low water consumption (82-160 m^3/ha), which is why irrigation was not necessary. In contrast, during June-September, due to low rainfall (5-49 mm) and high evapotranspiration (166-220 m^3/ha), the application of differentiated irrigation was

essential to maintain the water balance. Two irrigation levels were used: 280 m³/ha at 50% IUA and 420 m³/ha at 75% IUA. Three irrigations were applied in July (420-630 m³/ha), four irrigations in August (560-840 m³/ha) and a single irrigation in September (140-210 m³/ha). Physiological processes: photosynthesis, respiration, transpiration, and stomatal conductance, represent functional indicators of the physiological status and photosynthetic efficiency of the grapevine, and provide information on the mechanisms of adaptation to water deficit. Monitoring of physiological processes was carried out in the flowering and fruiting phenophases. Statistical analysis (ANOVA) showed that both the variety and the irrigation norms, as well as their interaction, significantly influenced the values of physiological parameters ($p \leq 0.05$). Of the three varieties analyzed, the Țâța caprei neagră variety showed the highest values, with an average of 11.13 µmol $CO_2/m^2/s$, followed by the Țâța caprei albă variety with intermediate values of 10.17 µmol $CO_2/m^2/s$ and the Coarnă albă variety with the lowest photosynthesis rate, respectively (9.53 µmol $CO_2/m^2/s$), (Table 1).

Table 1. The influence of irrigation regime on photosynthesis (µmol $CO_2/m^2/s$)

AXB Interaction	FACTOR B – irrigation regime			Average Factor A
Factor A (Variety)	b1-un irrigated	b2- 50% IUA	b3– 75% IUA	
Coarnă albă	8.8	9.7	10.1	9.53c
Țâța caprei albă	9.4	10.3	10.8	10.2b
Țâța caprei neagră	10.3	11.3	11.8	11.1a
Average Factor B	9.5c	10.4b	10.9a	

Both the variety and the level of irrigation influence the intensity of photosynthesis; the best results were obtained with the Țâța caprei neagră variety at an irrigation level of 75% of the active soil moisture index.

In the case of respiration, the highest level was recorded for the Țâța caprei neagră variety (1.34 µmol $CO_2/m^2/s$), followed by the Țâța caprei albă variety (1.23 µmol $CO_2/m^2/s$), and the lowest level was recorded for the Coarnă albă variety (1.12 µmol $CO_2/m^2/s$). The respiration level increased with the irrigation rate applied; thus, the irrigation variant with 75% IUA determined the highest respiration value (1.34 µmol $CO_2/m^2/s$), followed by the variant with 50% IUA (1.23 µmol $CO_2/m^2/s$), and the lowest value was recorded in the case of the unirrigated vineyard plot (1.12 µmol $CO_2/m^2/s$), (Table 2).

Table 2. The influence of irrigation regime on the respiration (µmol $CO_2/m^2/s$)

AXB Interaction	FACTOR B – irrigation regime			Average Factor A
Factor A (Variety)	b1 - un irrigated	b2 - 50% IUA	b3 - 75% IUA	
Coarnă albă	1.00	1.12	1.23	1.12c
Țâța caprei albă	1.12	1.23	1.34	1.23b
Țâța caprei neagră	1.23	1.34	1.45	1.34a
Average Factor B	1.12c	1.23b	1.34a	

Regarding the AXB interaction (Varieties×Irrigation), the highest response was recorded for the Țâța caprei neagră variety at an irrigation level of 75% IUA (1.45 µmol $CO_2/m^2/s$), while the lowest response was observed for the Coarnă albă variery under unirrigated conditions was observed in Coarnă albă (1.00 µmol $CO_2/m^2/s$), these results indicate that the variety has a significant influence on the respiration process. Among the three varieties analyzed, the Țâța caprei neagră variety stands out with the highest transpiration rates, with values ranging between 3.05 and 4.02 mmol $H_2O/m^2/s$, depending on the irrigation level, followed by Țâța caprei albă variety with 3.25 mmol $H_2O/m^2/s$ and Coarnă albă variety with 3.05 mmol $H_2O/m^2/s$. Analyzing the effect of the irrigation regime, a clear and consistent increase in transpiration can be observed with the intensification of water suply. The overall average transpiration increased from 2.77 mmol $H_2O/m^2/s$ in the unirrigated variant, to 3.29 mmol $H_2O/m^2/s$ in the variant with 50% IUA, reaching 3.79 mmol $H_2O/m^2/s$ under irrigation conditions at 75% IUA (Table 3).

Table 3. The influence of irrigation regime on transpiration (mmol $H_2O/m^2/s$)

AXB Interaction	FACTOR B - irrigation regime			Average Factor A
Factor A (Variety)	b1 - un irrigated	b2 - 50% IUA	b3 - 75% IUA	
Coarnă albă	2.52	3.05	3.57	3.05c
Țâța caprei albă	2.73	3.25	3.78	3.25b
Țâța caprei neagră	3.05	3.57	4.02	3.57a
Average Factor B	2.77c	3.29b	3.79a	

This phenomenon can be explained by the wider opening of the stomata in the presence of sufficient water availability, which facilitates

gas exchange, including the release of water vapor, and contributes to cooling the plant. The Coarnă albă variety appears to be the most adaptable to water stress, making it a suitable choice for areas with limited water availability.

The results obtained in the experiment clearly show a significant influence of both the variety (A factor) and the irrigation regime (B factor) on stomatal conductance. The Țâța caprei neagră variety presented average stomatal conductance values ranging between 32.02 and 36.20 mmol/m²/s, reflecting wide and efficient stomatal opening, followed by the Țâța caprei albă with intermediate values of (29.38–33.00 mmol/m²/s) and Coarnă albă with values between (25.96-29.20 mmol/m²/s). The irrigation regime significantly influenced the opening of the stomata. Stomatal conductance progressively increased from 29.12 mmol/m²/s in the non-irrigated variant to 30.87 mmol/m²/s in the variant irrigated with 50% IUA, reaching a maximum of 32.80 mmol/m²/s at 75% IUA, an evolution closely correlated with increased water availability (Table 4).

Table 4. Influence of experimental factors on stomatal conductance (mmol $H_2O/m^2/s$)

Intercation AxB	FACTOR B - irrigation regime			Average Factor A
Factor A (Variety)	b1 - un irrigated	b2 - 50% IUA	b3 - 75% IUA	
Coarnă albă	25.96	27.50	29.20	27.55c
Țâța caprei albă	29.38	31.10	33.00	31.16b
Țâța caprei neagră	32.02	34.00	36.20	34.07a
Average Factor B	29.12c	30.87b	32.80a	

The NDVI, NDWI, and Moisture Index (MI) values during the 2025 growing season highlight the evolution of vine water status and vine vigor of the vine depending on water availability. In general, a high NDVI during the flowering phenophase (0.87) indicates relatively good photosynthetic activity, even though a moderate water deficit was recorded (Figure 3).

The decrease in NDVI values to 0.78 during the veraison phenophase indicates a moderate decline in photosynthetic efficiency, and the decrease in NDWI (-0.69) and MI (-0.15), leads to stomatal closure to limit water loss due to the onset of water stress, which may affect shoot growth, berry size, and sugar accumulation in grapes (Figure 2).

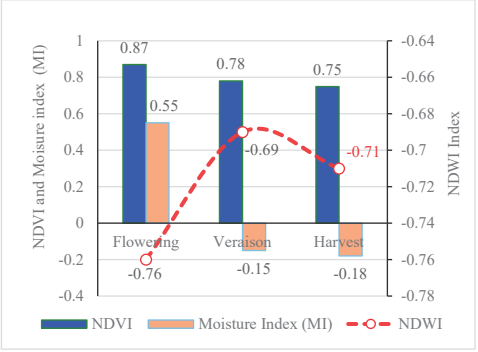

Figure 2. NDVI, NDWI, and Moisture Index (MI) values during the main vegetative phenophases

During the harvest phenophase, NDVI (0.75), NDWI (-0.71) and MI (-0.18) indicate a significant reduction in soil water reserves, with direct implications for grape production and its quality. Thus, the combined analysis of these indices NDVI, NDWI, and MI confirms the importance of efficient irrigation management to maintain vine vigor, hydration status, and productive potential of the vine.

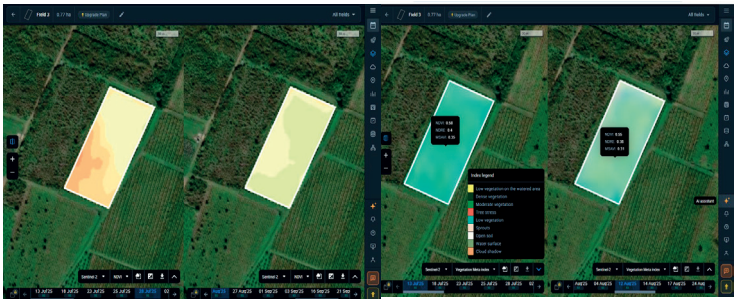

Figure 3. July-August NDVI index (left), July-August vegetation index (right)
*Note (image from July 13 vs August 12, periods with high temperatures)

The analysis of the Crop Water Stress Index (CWSI) and the leaf air temperature difference (ΔTc-Ta) highlights the different physiological responses of the three grapevine varieties to irrigation regimes during the flowering and veraison phenophases. In both phenophases, a consistent decrease in CWSI and ΔTc-Ta values is observed as the irrigation level changes from un-irrigated to 50% and 75% of the active soil moisture index (IUA), indicating the reduction of water stress and the improvement of physiological conditions. During the flowering phenophase, the Țâța caprei neagră variety presented the lowest CWSI and ΔTc-Ta values under all irrigation variants (0.55/+2.9 in the un-irrigated variant, 0.36/+1.7 in 50% IUA, and 0.19/+0.9 in 75% IUA), which reflects an efficient capacity for stomatal regulation and transpiration, even under water deficit conditions. The Țâța caprei albă variety showed an intermediate behavior, with moderate values (0.61/+3.2 in the un-irrigated variant and +0.22/+1.0 at 50% of IUA). The Coarnă albă variety recorded the highest values across all irrigation regimes, indicating a higher sensitivity to drought (Table 5).

Table 5. CWSI and ΔTc-Ta of grapevine varieties under irrigation regimes

Varieties/Irrigation regimes	CWSI/ΔTc–Ta Flowering	CWSI/ΔTc–Ta Veraison
Coarnă albă control	0.64a/ +3.4a	0.85a/+4.7a
Coarnă albă 50% IUA	0.44b/+2.1b	0.52b/+2.6b
Coarnă albă 75% IUA	0.24c/+1.1c	0.30c/+1.4c
Țâța caprei albă control	0.61a/+3.2a	0.88a/+5.0a
Țâța caprei albă 50% IUA	0.41b/+2.0b	0.57b/+2.8b
Țâța caprei albă 75% IUA	0.22c/+1.0c	0.33c/+1.5c
Țâța caprei neagrăcontrol	0.55a/+2.9a	0.76a/+4.3a
Țâța caprei neagră 50% IUA	0.36b/+1.7b	0.46b/+2.3b
Țâța caprei neagră 75% IUA	0.19c/+0.9c	0.27c/+1.1c

Note: Different letters (a, b, c) indicate statistically significant differences between irrigation regimes ($p<0.05$, Tukey HSD).

During the veraison phenophase, when evapotranspiration is more intense and soil water reserves are reduced, the differences among the three varieties become more evident. Țâța caprei neagră continues to have the lowest values (0.76/+4.3 in the un-irrigated variant and 0.27/+1.1 at 75% of IUA). The Țâța caprei albă and Coarnă albă varieties show higher values, especially in the un-irrigated variant, which indicates a pronounced water stress (CWSI 0.88-0.85 and ΔTc–Ta +5.0-+4.7°C). Overall, the application of irrigation norms at 50% and 75% of IUA reduces water stress for all varieties.

The combined effects of variety and irrigation were also evident in yield parameters. Regarding yield per vine, Țâța caprei neagră recorded the highest values (4.394 kg at 75% IUA), followed by (4.394 kg at 75% IUA), followed by Țâța caprei albă and Coarnă albă. A similar hierarchy was observed for the average berry weight of a grape: Țâța caprei neagră produced heavier berries (338 g at 75% IUA), followed by Țâța caprei albă and Coarnă albă.

Increasing the irrigation level from unirrigated to 75% IUA led to progressive increases in both production and grape weight, demonstrating the importance of an optimal water supply for supporting grape development.

The statistical significances (letters a, b, c) show that the differences between the combinations of variety × irrigation regime are significant, which confirms that both variety genetics and irrigation influence the yield parameters and average berry weight. Therefore, combining a productive variety, such as Țâța caprei neagră, with an adequate irrigation level (75% IUA) optimizes both the yield per vine and the maximization of the variety's performance (Table 6).

Table 6. The grape yield and average berry weight

Varieties/Irrigation regimes	Grape yield (kg/vine)	Average berry weight (g)
Coarnă albă control	1.325c	265c
Coarnă albă 50% IUA	1.776b	296b
Coarnă albă 75% IUA	2.844a	316a
Țâța caprei albă control	1.944c	312c
Țâța caprei albă 50% IUA	2.808b	324b
Țâța caprei albă 75% IUA	3.696a	336a
Țâța caprei neagră control	2.584c	323c
Țâța caprei neagră 50% IUA	4.277b	329b
Țâța caprei neagră 75% IUA	4.394a	338a

Note: Different letters (a, b, c) indicate statistically significant differences between irrigation regimes ($p<0.05$, Tukey HSD).

The analysis of the interaction between irrigation level and fertilization type (B×C) showed a significant influence on average grape weight and yield per vine. The average grape weight values increased progressively with increasing irrigation intensity, from 305 g in un-irrigated, 315 g at 50% IUA, and 325 g at 75% IUA, regardless of the type of fertilization applied. In terms of fertilization, Novatec classic fertilizer resulted in the highest average weights

(330 g), followed by Solfert (320 g), Atonik (310 g) and NPK 15:15:15 (300 g) (Table 7).

Table 7. Effect of irrigation and fertilization on average berry weight (g) and yield per vine (kg)

Fertilization	Unirrigated	50% IUA	75% IUA
NPK 15:15:15	290 g/2.000 kg (c/d)	300 g/2.717 kg (c/c)	310 g/3.367 kg (d/a)
Atonik	300 g/2.150 kg (c/d)	310 g/2.850 kg (b/c)	320 g/3.500 kg (c/a)
Solfert 20:20:20+ME	310 g/2.300 kg (b/c)	320 g/2.983 kg (b/b)	330 g/3.633 kg (b/a)
Novatec classic	320 g/2.433 kg (a/c)	330 g/3.117 kg (a/b)	340 g/3.767 kg (a/a)

The average grape yield per vine followed the same trend: increasing irrigation levels led to average values of 2.221 kg/vine in the un-irrigated variant, 2.917 kg/vine at 50% IUA, and 3.567 kg/vine at 75% IUA. Fertilization with Novatec classic led to the highest yield (3.106 kg/vine), while Solfert, Atonik, and NPK 15:15:15 recorded average values of 2.972, 2.833 and 2.695 kg/vine, respectively. The significant differences (letters a-d) confirm that both the irrigation level and the type of fertilization determine changes in the average grape weight and grape yield per vine, with the combined effect of the two factors being most pronounced at the 75% IUA irrigation level associated with the Novatec classic fertilization, representing the optimal strategy for maximizing grapevine performance.

CONCLUSIONS

Grapevine physiological processes were strongly influenced by both irrigation and fertilization. The application of 75% IUA irrigation ensured optimal soil water availability and mitigated water stress, as reflected by decreased CWSI values (from 0.64-0.85 to 0.24-0.33) and consistently high NDVI values (up to 0.87), indicating active photosynthesis and an overall favorable physiological status.

In terms of yield, the variety Tâța caprei neagră consistently outperformed the others, producing 4.394 kg per vine and 372 g per berry at 75% IUA, followed by Tâța caprei albă, while Coarnă albă exhibited the lowest performance. Fertilization also had a significant effect on yield, with Novatec Classic resulting in the highest average yield and berry weight.

These findings highlight that the combination of an optimal irrigation regime (75% IUA) with complex fertilization effectively enhances grapevine physiological status and maximizes grape yield.

Additionally, NDVI and CWSI proved to be reliable indicators for monitoring vine water status and guiding irrigation strategies. Among the varieties studied, Țâța caprei neagră demonstrated the highest efficiency in water and nutrient utilization, making it the most suitable choice under water deficit conditions and for adaptation to climate change.

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