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Severe Water Deficit Effects on Biophenols, Pigments, and Fatty Acids Profile in Arbequina Olive Oil

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Abstract

Water availability is a critical factor influencing olive oil quality, particularly its phenolic composition, which determines sensory properties, oxidative stability, and health benefits. This study evaluated the effects of severe water deficit on the phenolic profile, pigment content, and fatty acid composition of Arbequina olive oil over two consecutive growing seasons (2020 and 2021) in a temperate climate. The experiment was conducted using drainage lysimeters under controlled conditions, comparing fully irrigated and non-irrigated treatments. Results revealed significant differences in oil composition between treatments. Non-irrigated oils exhibited higher concentrations of p-coumaric acid, ferulic acid, total chlorophylls, and β-carotene –compounds associated with oxidative stability and nutraceutical characteristics. In contrast, irrigated oils showed elevated levels of hydroxytyrosol, tyrosol, and total phenols, which contribute to antioxidant activity. The fatty acid profile was also affected, with non-irrigated oils displaying higher levels of palmitic acid and linoleic acid. Non-irrigated treatments yielded oils with enhanced phenolic diversity and compounds associated with sensory and functional benefits, while irrigated treatments maintained a balance of antioxidants. This research emphasizes the importance of adapting irrigation strategies to achieve high-quality olive oil production under varying environmental and water-availability conditions.

Keywords: olive oil quality, water stress, carotenoids, tyrosol, hydroxytyrosol

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Impacto del déficit hídrico severo en los biofenoles, pigmentos y composición de los ácidos grasos del aceite de oliva Arbequina en un clima templado

Resumen

La disponibilidad de agua es un factor crítico en la calidad del aceite de oliva, especialmente en su composición fenólica, que determina propiedades sensoriales, estabilidad oxidativa y beneficios para la salud. Este estudio evaluó el efecto del déficit hídrico severo en el perfil fenólico, los pigmentos y los ácidos grasos del aceite de oliva Arbequina durante dos temporadas (2020 y 2021) en clima templado. Se utilizaron lisímetros de drenaje bajo condiciones controladas, comparando tratamientos irrigados y no irrigados. Los aceites no irrigados mostraron mayores niveles de ácido p-cumárico, ácido ferúlico, clorofilas totales y β-caroteno, compuestos asociados a mayor estabilidad oxidativa y características nutracéuticas. En cambio, los aceites irrigados presentaron niveles elevados de hidroxitirosol, tirosol y fenoles totales, relacionados con actividad antioxidante. El perfil de ácidos grasos también varió, con mayores niveles de ácido palmítico y linoleico en aceites no irrigados. Los tratamientos no irrigados produjeron aceites con mayor diversidad fenólica y compuestos funcionales, mientras que los irrigados mantuvieron un equilibrio de antioxidantes. Este trabajo resalta la importancia de adaptar estrategias de riego para optimizar la calidad del aceite de oliva bajo condiciones variables de disponibilidad de agua.

Palabras clave: calidad de aceite oliva, estrés hídrico, carotenoides, tirosol, hidroxitirosol

Impacto do déficit hídrico severo nos biofenóis, pigmentos e composição de ácidos graxos do azeite de oliva Arbequina em um clima temperado

Resumo

A disponibilidade de água é um fator crítico na qualidade do azeite de oliva, especialmente em sua composição fenólica, que determina propriedades sensoriais, estabilidade oxidativa e benefícios à saúde. Este estudo avaliou o efeito do déficit hídrico severo no perfil fenólico, pigmentos e ácidos graxos do azeite de oliva Arbequina durante duas safras (2020 e 2021) em clima temperado. Utilizaram-se lisímetros de drenagem sob condições controladas, comparando tratamentos irrigados e não irrigados. Os azeites não irrigados apresentaram maiores níveis de ácido p-cumárico, ácido ferúlico, clorofilas totais e β-caroteno, compostos associados à maior estabilidade oxidativa e características nutracêuticas. Já os azeites irrigados mostraram níveis elevados de hidroxitirosol, tirosol e fenóis totais, relacionados à atividade antioxidante. O perfil de ácidos graxos também variou, com maiores níveis de ácido palmítico e linoleico nos azeites não irrigados. Os tratamentos não irrigados produziram azeites com maior diversidade fenólica e compostos funcionais, enquanto os irrigados mantiveram um equilíbrio de antioxidantes. Este trabalho destaca a importância de adaptar estratégias de irrigação para otimizar a qualidade do azeite de oliva sob condições variáveis de disponibilidade de água.

Palavras-chave: qualidade do azeite de oliva, estresse hídrico, carotenoides, tirosol, hidroxitirosol

1. Introduction

Olive cultivation (*Olea europaea* L.) continues to grow in importance worldwide due to the high demand for olive oil, recognized for its health benefits and unique organoleptic properties. Olive oil is a basis of the Mediterranean diet, valued for its sensory attributes, nutritional value, and health benefits, largely attributed to its rich phenolic composition (Cicerale et al., 2010). Compounds such as hydroxytyrosol, tyrosol, and secoiridoids play a crucial role in oil quality, influencing its oxidative stability, flavor profile, and bioactive properties (Servili et al., 2004). However, olive oil quality and composition are highly dependent on agronomic and environmental factors, with water availability being one of the most significant (Tovar et al., 2001). In regions where water availability is limited, water restriction has been proposed as a strategy to enhance certain oil attributes, such as its antioxidant content (García et al., 2020; Romero et al., 2002).

While extensive research has been conducted in Mediterranean climates, where olive cultivation is traditional, there is a growing need to understand olive oil production in non-traditional regions, particularly in humid climates like Uruguay. With its temperate and humid but highly variable climate, the region experiences irregular rainfall distribution throughout the year, leading to periods of water deficit (Puppo et al., 2014). However, the vapor pressure deficit during summer is half that of arid regions (Conde-Innamorato et al., 2022), making it relevant to study the impact of irrigation on olive oil composition under these conditions.

Most olive groves in Uruguay are located in the eastern part of the country, where soils are sandy-loam and shallow, resulting in low water retention and storage capacity. These conditions often lead to severe water deficits. Previous studies have evaluated the effects of moderate water deficit (up to less than −3.5 MPa of xylem water potential) on oil composition (Conde-Innamorato et al., 2022), but the impact of severe water deficit on oil quality and composition remains unknown.

Uruguay has emerged as a promising region for olive cultivation due to its favorable soil conditions and growing interest in diversifying agricultural production (Conde-Innamorato et al., 2019). However, the high rainfall and humidity in this region present unique challenges, such as increased disease pressure and potential alterations in olive oil composition (Torres et al., 2017). These conditions require a thorough evaluation of olive oil quality under local climatic conditions to optimize production practices and ensure competitive product quality. Studies conducted in Uruguay by Conde-Innamorato et al. (2022) have highlighted the adaptability of cultivars like Arbequina to local conditions, but have also underscored the need for tailored irrigation strategies to balance yield and oil quality. Most of the available information on olive oil composition under water stress has been generated for arid climates, with limited data for temperate regions like Uruguay, where the vapor pressure deficit (VPD) is less than half that of Mediterranean regions during summer months (Conde-Innamorato et al., 2022). VPD, which considers both humidity and temperature, is directly related to crop transpiration, increasing as the deficit rises. In Uruguay, summer VPD is lower than in Mediterranean climates due to higher relative humidity (around 70%) and average temperatures that do not exceed 24 °C. In contrast, in regions like Córdoba (Spain), relative humidity is approximately 40%, while average temperatures reach 30 °C.

This study aims to evaluate the impact of severe water restriction under controlled conditions in lysimeters on the phenolic composition, pigments, and fatty acid profile of Arbequina olive oil obtained under two irrigation treatments (full irrigation and no irrigation) over two consecutive seasons. The findings contribute to the growing body of knowledge on olive oil production in non-traditional regions and, especially, olive cultivation in humid climates.

2. Materials and Methods

2.1 Plant Material and Experimental Plot

The experiment was established in six drainage lysimeters (1.9 × 0.9 × 1.35 m depth and silty clay loam soil texture) located at the National Agriculture Research Institute, INIA-Las Brujas Experimental Station in Southern Uruguay (34˚40'S; 56˚20'W). These devices were protected from rain by a rain-out shelter, which would automatically close every time rain exceeded 3 mm (Puppo et al., 2014). Lysimeters were surrounded by irrigated olives to avoid an “oasis” effect because of advective processes. The separation between lysimeters with olive trees simulated a plantation framework of 2.5 × 5.5 m (Puppo et al., 2014).

Two irrigation treatments were imposed in four-year-old olive trees Arbequina cultivar, irrigated and non-irrigated, from the end of the pit hardening until harvest. In the irrigated treatment, the criterion was to apply water according to the maximum crop evapotranspiration (ETc) (Allen et al., 1998). Drip irrigation with 2 drippers per

tree with a flow of 4 l/h was installed. In the non-irrigated, irrigation was applied only to avoid reaching permanent wilting point according to water content in the soil profile. A randomized complete design with two irrigation treatments and three replicates was used, where the experimental unit was one tree. The experiment was repeated for two consecutive seasons (2020 and 2021).

Canopy volume (m^3/tree) and trunk diameter were measured at the beginning (November 2019) and at the end of the experiment (April 2021). Canopy volume was calculated according to the ellipsoid volume method (Miranda-Fuentes et al., 2015), and trunk diameter was measured at 40 cm above ground.

To describe the climatic conditions from January to April of 2020 and 2021 meteorological data was retrieved from a Campbell automatic weather station located at INIA Las Brujas (Instituto Nacional de Investigación Agropecuaria [INIA], n.d.) and the deficit pressure value was estimated (Figure 1). Both seasons showed a similar DPV, though in early January, early and mid-February, and early and at the end of March, the DPV in 2020 was higher than in 2021.

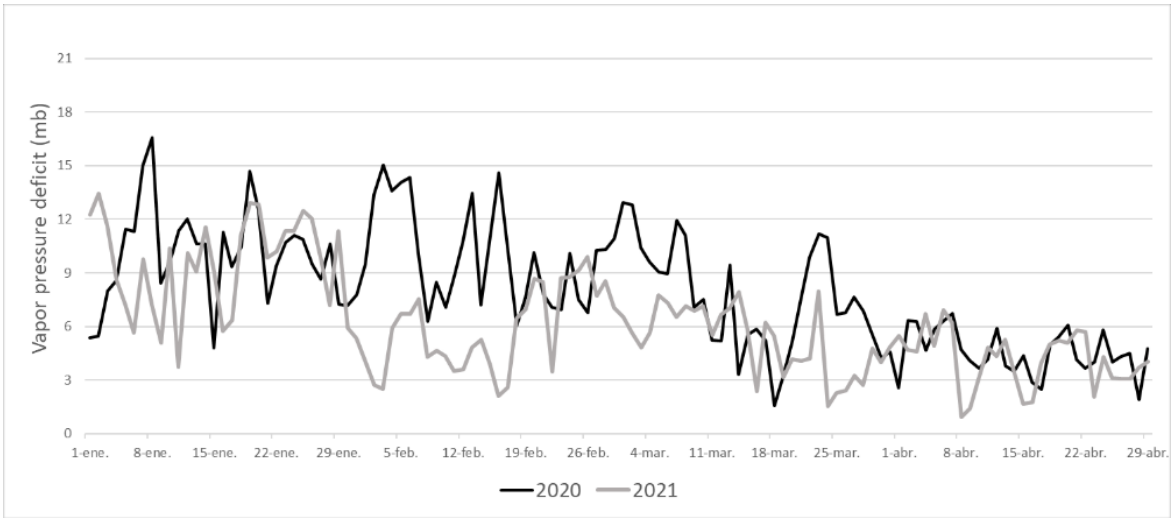

Figure 1. Daily vapor pressure deficit (mb) in Uruguay for the 2020 and 2021 seasons from January 1st to April 30

Data were recorded at an automatic weather station at the experimental site in INIA Las Brujas.

Source. INIA (n.d.)

2.2 Water Status

Tree water status was assessed by measuring the stem water potential (SWP) using a Scholander-type pressure chamber (Soil Moisture Equipment Corp., Santa Barbara, CA, USA) every 15 days from the end of pit hardening until harvest (Scholander et al., 1965). Measurements on each tree were made between 12h00 and 14h00 in mature leaves, from the middle of the branch that were exposed to the sun. Two hours before the measurement, the shoot was enclosed in a plastic bag, allowing the leaf water potential to balance with the stem water potential for a more stable value than that of the leaf water potential. The SWP was measured up to −4 MPa, a limit determined for users' safety. More detailed information about the methodology has been reported in Conde-Innamorato et al. (2025).

2.3 Olive Oil Composition Analysis

2.3.1 Oil Pigments

The total chlorophyll and carotenoid content in the oils was measured using a spectrophotometer. For this, 7.5 grams of each oil were dissolved in cyclohexane and the absorbance was recorded at 670 nm and 470 nm, respectively, following the method by Minguez-Mosquera et al. (1991). The results were expressed in mg per kg of extra virgin olive oil (EVOO).

2.3.2 Fatty Acids Profile

Fatty acid methyl esters were created through trans-esterification with a cold methanolic potassium hydroxide solution and analyzed via gas chromatography, as modified from Feippe et al. (2010). In brief, 0.1 grams of the olive oil sample were dissolved in 2 mL of heptane, vortexed for 1 minute at 20 °C, and centrifuged at 12,000 rpm for 5 minutes. The supernatant was then trans-esterified by adding 1 mL of 4 N KOH in methanol and manually stirring for 1 minute. The mixture was dried with sodium sulfate, centrifuged again at 12,000 rpm for 5 minutes, filtered, and injected into a gas chromatograph equipped with a flame ionization detector (GC-FID, Shimadzu model 2010-Plus, Kyoto, Japan). The column used was an Agilent DB-WAX (30 m × 0.25 mm ID, 0.25 µm). The injection temperature was set at 250 °C, and the FID detector temperature was 300 °C. The oven temperature started at 160 °C, increased to 200 °C after 13 minutes, held for 22 minutes, and then raised to 240 °C for the final 25 minutes. The sample injection volume was 1 µL, with nitrogen as the mobile phase at 30 mL/min. Hydrogen and air flows were set at 40 mL/min and 400 mL/min, respectively. Peaks were identified using a standard certified Fatty Acids Methyl Esters (FAME) mix (Sigma-Aldrich, St Louis, MO, USA) based on retention times and expressed as percentages.

2.3.3 Total Phenolic Analysis in Extra Virgin Olive Oils (EVOO)

The total phenol content was measured using the Folin-Ciocalteu method, with modifications from Gutfinger (1981). In summary, 5 grams of olive oil samples were dissolved in 7 mL of a methanol-water mixture (80:20) and vortexed. The mixture was centrifuged at 5800 rpm for 10 minutes, and this process was repeated twice. The supernatants were combined and diluted to 25 mL with the methanol-water mixture. A 1 mL aliquot was transferred to a 10 mL volumetric flask, to which 8 mL of distilled water, 0.5 mL of Folin-Ciocalteu reagent, and 0.5 mL of saturated sodium carbonate were added. The samples were shaken and left in the dark at room temperature for 15 minutes. Absorbance was measured at 760 nm using a UV-VIS spectrophotometer (Shimadzu model UV-3000, Kyoto, Japan). The total phenolic content was calculated and expressed as mg of gallic acid equivalents (GAE) per kg of oil, using a calibration curve prepared with pure gallic acid standard solution.

2.3.4 Biophenols Profile Analysis by HPLC

The analysis was performed according to the International Olive Council Official Method: COI/T.20/Doc. No 29/Rev.1 (International Olive Council, 2017). Briefly, the biophenolic minor polar compounds in olive oils, including natural and oxidized derivatives of oleuropein and ligstroside, lignans, flavonoids, and phenolic acids, were extracted using a methanol:water solution (80:20) and quantified by HPLC with a UV detector at 280 nm. Syringic acid was used as the internal standard. The content of these compounds was expressed in mg/kg of tirosol.

2.4 Statistical Analysis

An analysis of variance (ANOVA) was performed for vegetative growth and for biophenolic profile, pigments, and fatty acid composition considering irrigation treatment for both seasons. Tukey's test at $p \leq 0.05$ was calculated to separate means. In all cases the statistical software used was InfoStat version 2020.

3. Results

The midday stem water potential (SWP) revealed clear differences in the average SWP values for each treatment (Figure 2). In the first season until December 2020, the values for both treatments were similar. As the water in the soil profile was depleted, the value increased until reaching −4.0. In the case of the irrigated treatment, the values remained consistent throughout the season, ranging from −1.5 to −1.0. In the 2021 season,

irrigation conditions were not optimal for the irrigated treatment; due to logistical constraints, three scheduled irrigation events in the 2021 season were delayed by approximately 36 hours each, resulting in transient periods of moderate water stress within the irrigated treatment. However, the differences are clear, as in the previous season. The values for the non-irrigated treatment ranged between −3.7 and −3.5, while the irrigated treatment ranged from −2.2 to −1.5 MPa (Figure 2).

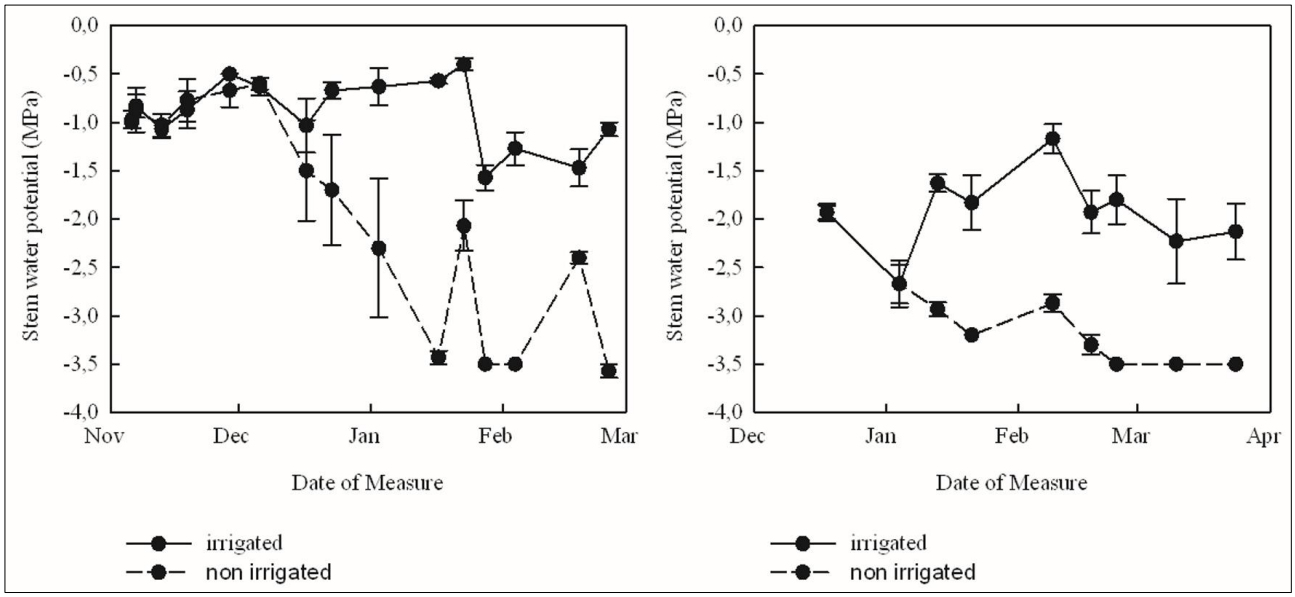

Figure 2. Stem water potential of Arbequina cv. in lysimeters located at INIA Las Brujas, Uruguay, through 2020 (left) and 2021 (right) seasons, under two treatments: irrigated and non-irrigated

Just as the SWP was affected in both treatments, the trunk diameter was also impacted in both seasons. A clear decrease in diameter is evident (Figure 3) in both the 2020 and 2021 seasons. Variations in the trunk diameter of olive trees (expansion and contraction) are rarely used as a tool for irrigation scheduling due to their high sensitivity to fluctuating environmental conditions, cultivar-specific physiological responses, and the complexity involved in translating real-time diameter data into actionable irrigation decisions under field settings (Goldhamer & Fereres, 2001; Ortuño et al., 2010).The trunk diameter was therefore not employed for irrigation scheduling, but measured at the beginning and end of each season to verify that the imposed water deficit treatments induced a detectable physiological stress response, thereby confirming the effectiveness of the experimental water regimes on tree water status.

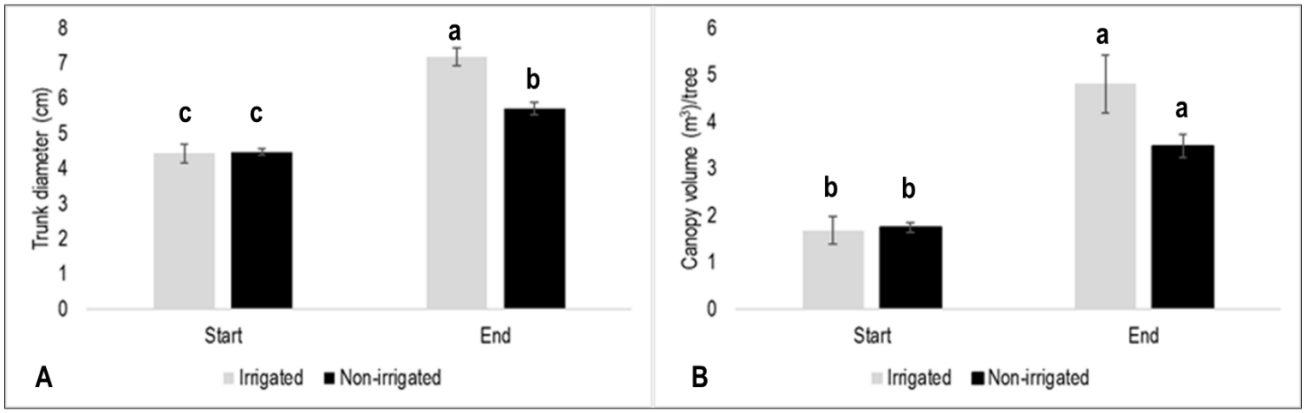

Figure 3. Trunk diameter (A) and canopy volume (B) of Arbequina cv. at the start (January 2020) and end (April 2021) of the experiment, under two treatments: irrigated and non-irrigated

The vertical bars indicate the standard error.

The trunk diameter at the start of the experiment (November 2019) was similar in both treatments, averaging 4.5 cm. After two years (April 2021), both treatments showed an increase in trunk diameter, with the irrigated treatment being significantly larger than the non-irrigated one (Figure 3A). Similarly, the canopy volume was similar in both treatments at the beginning of the experiment, with an average of 1.7 m³ per tree. By the end of the study, both treatments exhibited a significant increase in canopy volume; however, there were no differences between them, with values of 4.8 m³ for the irrigated treatment and 3.5 m³ for the non-irrigated treatment (Figure 3B).

The effects of irrigation and non-irrigation treatments on the phenolic composition, fatty acid profile, and pigment content of Arbequina olive oils were evaluated over two growing seasons (2020 and 2021). Significant differences were observed between the treatments for most parameters, highlighting the impact of water availability on olive oil quality.

The pigment content of the oils, including total chlorophylls and total β-carotene, was significantly higher in non-irrigated oils compared to irrigated oils (Table 1). In 2020, non-irrigated oils had a mean total chlorophyll content of 6.3 mg/kg, compared to 4.4 mg/kg in oils from irrigated plants. Similarly, in 2021, non-irrigated oils contained 6.7 mg/kg total chlorophylls, while irrigated oils contained 4.8 mg/kg. Total β-carotene levels followed the same trend, with non-irrigated oils consistently showing higher concentrations.

Table 1. Impact of irrigation and non-irrigation conditions on total chlorophylls and total β-carotene for olive oil Arbequina cv (2020 and 2021)

	Pigments	Total chlorophylls (mg/kg)	Total β-carotene (mg/kg)
2020	*Non-irrigated*	6.3 a	0.8 a
	Irrigated	4.4 b	0.6 b
2021	*Non-irrigated*	6.7 a	0.9 a
	Irrigated	4.8 b	0.7 b

Mean value for each treatment. Letters in columns (a, b) indicate significant differences between treatments within the same year. Treatments with the same letter are not significantly different.

The fatty acid profile of the oils was also affected by the irrigation regime (Table 2). Non-irrigated oils had higher levels of palmitic acid (C16:0) and linoleic acid (C18:2), while irrigated oils showed slightly elevated levels of oleic acid but not statistically significant. For instance, in 2020, non-irrigated oils contained 17.8% palmitic acid, compared to 16.9% in irrigated oils. Similar trends were observed in 2021, with non-irrigated oils containing 17.2% and irrigated oils containing 16.7% palmitic acid. The MUFA/PUFA ratio remained consistent across treatments, indicating that water severe stress did not significantly alter the balance of monounsaturated and polyunsaturated fatty acids.

The phenolic composition of oils was significantly influenced by the irrigation regime (Table 3). Irrigated oils exhibited higher concentrations of hydroxytirosol, pinoresinol, vanillin, tyrosol, and total phenols, while non-irrigated oils showed elevated levels of ferulic and p-coumaric acids. For example, in 2020, non-irrigated oils had a mean total phenol content of 119.2 mg/kg, compared to 122.4 mg/kg for irrigated oils. Similar trends were observed in 2021, with non-irrigated oils containing 98.2 mg/kg and irrigated oils containing 121.5 mg/kg of total phenols. Phenolic acids such as p-coumaric and ferulic acids showed significant differences between treatments, with non-irrigated oils consistently displaying higher concentrations.

Table 2. Impact of irrigation and non-irrigation conditions on main fatty acid methyl esters (FAMEs), as % of total fatty acids (2020 and 2021)

Fatty acids	*2020*		*2021*	
	Non-irrigated	*Irrigated*	*Non-irrigated*	*Irrigated*
Myristic (C14:0)	0.02 a	0.02 a	0.02 a	0.02 a
Palmitic (C16:0)	**17.8 a**	**16.9 b**	**17.2 a**	**16.7 b**
Palmitoleic (C16:1)	2.9 a	2.8 a	2.7 a	2.9 a
Heptadecanoic (C17:0)	0.08 a	0.09 a	0.09 a	0.08 a
Heptadecenoic (C17:1)	0.23 a	0.24 a	0.21 a	0.23 a
Stearic (C18:0)	1.6 a	1.5 a	1.4 a	1.3 a
Oleic (C18:1)	62.0 a	62.5 a	63.0 a	63.5 a
Linoleic (C18:2)	**13.8 a**	**12.9 b**	**13.2 a**	**12.7 b**
Linolenic (C18:3)	0.6 a	0.6 a	0.6 a	0.6 a
Arachidic (C20:0)	0.3 a	0.3 a	0.3 a	0.3 a
Eicosenoic (C20:1)	0.6 a	0.6 a	0.6 a	0.6 a
Behenic (C22:0)	0.09 a	0.10 a	0.10 a	0.09 a
Lignoceric (C24:0)	0.05 a	0.05 a	0.05 a	0.05 a
MUFA/PUFA ratio	4.7 a	4.9 a	4.9 a	5.1 a

Mean value for each treatment. Letters (a, b) indicate significant differences between treatments within the same year. Treatments with the same letter are not significantly different.

Table 3. Summarized results of minor biophenols in EVOOs from irrigated and non-irrigated Arbequina cv (2020/21 seasons)

Biophenols (mg/kg)	*2020*		*2021*	
	Non-irrigated	*Irrigated*	*Non-irrigated*	*Irrigated*
Hydroxytyrosol	0.1 a	0.4 b	0.2 a	0.5 b
Tyrosol	0.9 a	1.6 b	0.8 a	1.8 b
Vanillic + Caffeic acid	2.3 a	4.4 b	2.1 a	4.7 b
Vanillin	1.3 a	1.7 b	1.9 a	2.2 b
p-Coumaric acid	3.2 b	1.4 a	1.5 b	1.4 a
Ferulic acid	0.5 b	0.4 a	0.4 b	0.2 a
Pinoresinol	29.5 a	39.8 b	16.8 a	26.6 b
Luteolin	4.0 a	4.7 b	3.7 a	4.6 b
Total biophenols	119.2 a	122.4 b	98.2 a	121.5 b

Mean value for each treatment. Letters (a, b) indicate significant differences between treatments within the same year. Treatments with the same letter are not significantly different.

4. Discussion

This study was conducted over two consecutive years on productive Arbequina olive trees grown under controlled conditions in lysimeters.

Most olive plantations in Uruguay are concentrated in the eastern part of the country, where soils are predominantly shallow and sandy-loam, with low water storage and retention capacity (Oficina de Estadísticas Agropecuarias, 2020). Additionally, the irregular distribution of rainfall throughout the year leads to periods of water deficit, particularly during the summer (Tiscornia et al., 2016).

To provide a broader context for the oil composition results presented in this study, agronomic and physiological data from the same lysimeter experiment were analyzed in a parallel investigation (Conde-Innamorato et al., 2025) That work details how the water deficit treatments affected tree water status, fruit development, and yield parameters –key factors influencing the raw material from which the oils in this study were extracted. It was reported that the non-irrigated treatment showed significantly lower fruit moisture content than the fully irrigated treatment (less than 43% and more than 64%, respectively), and the fruit yield (kg/tree) was half that of the irrigated treatment, with fresh fruit weight less than half than that of the irrigated treatment. In terms of oil yield on a dry basis, the non-irrigated treatment had lower values, with a difference of approximately 10 percentage points. The fruit maturity index (MI) was higher under severe water deficit conditions compared to the irrigated treatment (MI = 3.9 and 1.6, respectively, averaged over the two seasons), consistent with findings by Inglese et al. (1996), Motilva et al. (2000), and Conde-Innamorato et al. (2022). However, the primary factor affecting fruit maturity is tree load (Trentacoste et al., 2010). While the present study focuses specifically on oil composition (phenolics, pigments, and fatty acids), the agronomic study shows how the contrasted water regimes created markedly different fruit physiological conditions, which in turn affect the compositional profiles evaluated herein.

The total polyphenol content in Arbequina fruits increased under moderate water deficit conditions (Conde-Innamorato et al., 2022), showing a negative regression in relation to plant water status. This increase in phenolic compounds, such as p-coumaric acid, pinoresinol, and total phenols, enhances the oxidative stability and sensory properties of the oil, as reported in previous studies (Gómez-del-Campo, 2013; Romero et al., 2002). Therefore, the level of water deficit must be carefully managed to avoid compromising productivity. For example, the lower VPD in Uruguay results in less severe water stress compared to arid regions, which may explain the relatively moderate increases in phenolic compounds observed in this study.

The pigment content of the oils, including total chlorophylls and total β-carotene, was significantly higher in non-irrigated oils, consistent with findings by Romero et al. (2002). Carotenoids contribute to the color and stability of the oil, and their increased concentration under water stress may enhance the oil's marketability.

The fatty acid profile of the oils was also influenced by the irrigation regime, with non-irrigated oils showing higher levels of palmitic acid and linoleic acid, while irrigated oils had slightly elevated levels of oleic acid. These findings are consistent with previous studies (García-Inza et al., 2014), which have reported that water stress can alter fatty acid composition, particularly by increasing the proportion of saturated fatty acids. These shifts in fatty acid composition under water stress carry practical implications: elevated palmitic acid may slightly reduce oxidative stability, while higher linoleic acid content can increase susceptibility to oxidation. In contrast, the greater oleic acid content observed in irrigated oils is associated with improved oxidative stability and longer shelf life, which is highly desirable from a quality and commercial standpoint.

In this study, the non-irrigated treatment resulted in significantly higher concentrations of p-coumaric acid and ferulic acid, while the irrigated treatment showed elevated levels of other phenolic compounds, such as hydroxytyrosol and tyrosol, as well as higher total phenolic content. This suggests that severe water deficit promotes the accumulation of specific phenolic compounds, such as p-coumaric acid and ferulic acid, probably due to the activation of stress-responsive biosynthetic pathways. These compounds are derived from the phenylpropanoid pathway, which is known to be upregulated under water stress as a protective mechanism against oxidative damage (García et al., 2020; Romero et al., 2002). However, the irrigated treatment favored the accumulation of other phenolics, such as hydroxytyrosol and tyrosol, which are associated with antioxidant activity and health benefits. This divergence in phenolic profiles highlights the complex interplay between water availability and phenolic metabolism, where different compounds respond differently to water stress. Similar findings have been reported in other studies, where moderate water stress enhanced specific phenolic compounds while reducing others (Servili et al., 2004; Tovar et al., 2001). For instance, Tovar et al. (2001) observed that water stress

increased the concentration of secoiridoids and lignans but reduced hydroxytyrosol derivatives in Arbequina olive oil. These results suggest that while severe water deficit can enhance certain phenolic compounds, it may also limit the accumulation of others, emphasizing the need for balanced irrigation strategies to optimize the phenolic profile of olive oil. The higher total phenolic content in the irrigated treatment further highlights the importance of water management in achieving a balance between phenolic diversity and overall oil quality.

5. Conclusions

Severe water deficit in a temperate climate significantly alters the composition of Arbequina olive oil, specifically enhancing its phenolic profile and pigment content. Non-irrigated conditions produced oils with higher concentrations of beneficial compounds such as p-coumaric acid and ferulic acid, which are linked to improved sensory attributes and potential functional quality. These compositional shifts suggest that carefully managed water stress can be leveraged as a sustainable strategy to optimize olive oil quality. However, to implement such practices effectively, future irrigation management must balance the enhancement of oil composition with the preservation of overall productivity. This study provides evidence-based insights for olive oil producers in temperate regions aiming to improve oil quality through adjusted water management, within a framework of sustainable and climate-adaptive agriculture.

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Transparency of Data

Data not available: The data set that supports the results of this study is not publicly available.

Author Contribution Statement

	F Ibáñez	C García	F Bonjour	C Martínez	JJ Villamil	P Conde-Innamorato
Conceptualization	■	■				■
Data curation			■	■	■	
Formal analysis			■	■	■	
Investigation	■	■	■	■	■	■
Methodology	■	■	■	■	■	■
Writing – original draft	■	■				■
Writing – review and editing	■	■				■

References

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements*. FAO.

Cicerale, S., Lucas, L., & Keast, R. (2010). Biological activities of phenolic compounds present in virgin olive oil. *International Journal of Molecular Sciences*, *11*(2), 458-479. https://doi.org/10.3390/ijms11020458

Conde-Innamorato, P., Arias-Sibillotte, M., Villamil, J. J., Bruzzone, J., Bernaschina, Y., Ferrari, V., Zoppolo, R., Villamil, J., & Leoni, C. (2019). It is feasible to produce olive oil in temperate humid climate regions. *Frontiers in Plant Science*, *10*, Article 1544. https://doi.org/10.3389/fpls.2019.01544

Conde-Innamorato, P., Borsani, O., Villamil, J. J., García, C., Girona, J., Leoni, C., Arias-Sibillote, M., & García-Inza, G. P. (2026). *Colletotrichum acutatum* infection in 'Arbequina' olive fruits under severe drought stress. *Acta Horticulturae*, (1446), 275-284. https://doi.org/10.17660/ActaHortic.2026.1446.37

Conde-Innamorato, P., García, C., Villamil, J. J., Ibáñez, F., Zoppolo, R., Arias-Sibillotte, M., Ponce De León, I., Borsani, O., & García-Inza, G. P. (2022). The impact of irrigation on olive fruit yield and oil quality in a humid climate. *Agronomy*, *12*(2), Article 313. https://doi.org/10.3390/agronomy12020313

Feippe, A., Ibáñez, F., & Altier, G. P. (2010). Fruit ripening stage effect on the fatty acid profile of 'Arbequina' and 'Picual' olives in Uruguay. *Acta Horticulturae,* (877), 1495-1499. https://doi.org/10.17660/ActaHortic.2010.877.204

García, J. M., Hueso, A., & Gomez-del-Campo, M. (2020). Deficit irrigation during the oil synthesis period affects olive oil quality in high-density orchards (cv. Arbequina). *Agricultural Water Management*, *230*, Article 105858. https://doi.org/10.1016/j.agwat.2019.105858

García-Inza, G. P., Castro, D. N., Hall, A. J., & Rousseaux, M. C. (2014). Responses to temperature of fruit dry weight, oil concentration, and oil fatty acid composition in olive (*Olea europaea* L. var. 'Arauco'). *European Journal of Agronomy, 54*, 107-115. https://doi.org/10.1016/j.eja.2013.12.005

Goldhamer, D. A., & Fereres, E. (2001). Irrigation scheduling protocols using continuously recorded trunk diameter measurements. *Irrigation Science, 20*, 115-125. https://doi.org/10.1007/s002710000034

Gómez-del-Campo, M. (2013). Summer deficit-irrigation strategies in a hedgerow olive orchard cv. 'Arbequina': Effect on fruit characteristics and yield. *Irrigation Science, 31*, 259-269. https://doi.org/10.1007/s00271-011-0299-8

Gutfinger, T. (1981). Polyphenols in olive oils. *Journal of the American Oil Chemists' Society*, *58*(11), 966-968. https://doi.org/10.1007/BF02659771

Inglese, P., Barone, E., & Gullo, G. (1996). The effect of complementary irrigation on fruit growth, ripening pattern and oil characteristics of olive (*Olea europaea* L.) cv. Carolea. *Journal of Horticultural Science*, *71*(2), 257-263. https://doi.org/10.1080/14620316.1996.11515404

Instituto Nacional de Investigación Agropecuaria. (n.d.). *Banco de Datos Agroclimáticos*. https://www.inia.uy/gras/Clima/Banco-datos-agroclimatico

International Olive Council. (2017). *Method of analysis: Determination of biophenols in olive oils by HPLC* (COI/T.20/Doc. No 29/Rev.1). https://www.internationaloliveoil.org/wp-content/uploads/2019/11/COI-T.20-Doc.-No-29-Rev-1-2017.pdf

Minguez-Mosquera, M. I., Rejano-Navarro, L., Gandul-Rojas, B., Sánchez-Gómez, A. H., & Garrido-Fernández, J. (1991). Color-pigment correlation in virgin olive oil. *Journal of the American Oil Chemists' Society, 68*, 332-336. https://doi.org/10.1007/BF02657688

Miranda-Fuentes, A., Llorens, J., Gamarra-Diezma, J. L., Gil-Ribes, J. A., & Gil, E. (2015). Towards an optimized method of olive tree crown volume measurement. *Sensors (Basel)*, *15*(2), 3671-3687. https://doi.org/10.3390/s150203671

Motilva, M. J., Tovar, M. J., Romero, M. P., Alegre, S., & Girona, J. (2000). Influence of regulated deficit irrigation strategies applied to olive trees (*Arbequina* cultivar) on oil yield and oil composition during the fruit ripening period. *Journal of the Science of Food and Agriculture*, *80,* 2037-2043. https://doi.org/10.1002/1097-0010(200011)80:14<2037::AID-JSFA733>3.0.CO;2-0

Oficina de Estadísticas Agropecuarias. (2020). *Anuario estadístico agropecuario 2020*. MGAP.

Ortuño, M. F., Conejero, W., Moreno, F., Moriana, A., Intrigliolo, D. S., Biel, C., Mellisho, C. D., Pérez-Pastor, A., Domingo, R., Ruiz-Sánchez, M. C., Casadesús, J., Bonany, J., & Torrecillas, A. (2010). Could trunk diameter sensors be used in woody crops for irrigation scheduling?: A review of current knowledge and future perspectives. *Agricultural Water Management, 97*(1), 1-11. https://doi.org/10.1016/j.agwat.2009.09.008

Puppo, L. , García, C. , Girona, J., & García-Petillo, M. (2014). Determination of young olive-tree water consumption with drainage lysimeters. *Journal of Water Resource and Protection*, *6*, 841-851. http://dx.doi.org/10.4236/jwarp.2014.69079

Romero, M. P., Tovar, M. J., Girona, J., & Motilva, M. J. (2002). Changes in the HPLC phenolic profile of virgin olive oil from young trees (Olea europaea L. Cv. Arbequina) grown under different deficit irrigation strategies. *Journal of Agricultural and Food Chemistry*, *50*(19), 5349-5354. https://doi.org/10.1021/jf020357h

Scholander, P. F., Bradstreet, E. D., Hemmingsen, E. A., & Hammel, H. T. (1965). Sap pressure in vascular plants: Negative hydrostatic pressure can be measured in plants. *Science*, *148*(3668), 339-346. https://doi.org/10.1126/science.148.3668.339

Servili, M., Selvaggini, R., Esposto, S., Taticchi, A., Montedoro, G., & Morozzi, G. (2004). Health and sensory properties of virgin olive oil hydrophilic phenols: Agronomic and technological aspects of production that affect their occurrence in the oil. *Journal of Chromatography A*, *1054*(1-2), 113-127.

Tiscornia, G., Cal, A., & Giménez, A. (2016). Análisis y caracterización de la variabilidad climática en algunas regiones de Uruguay. *Revista de Investigaciones Agropecuarias*, *42*(1), 66-71.

Torres, M., Pierantozzi, P., Searles, P., Rousseaux, M. C., García-Inza, G., Miserere, A., Bodoira, R., Contreras, C., & Maestri, D. (2017). Olive cultivation in the Southern Hemisphere: Flowering, water requirements and oil quality responses to new crop environments. *Frontiers in Plant Science*, *8*, Article 1830. https://doi.org/10.3389/fpls.2017.01830

Tovar, M. J., Motilva, M. J., & Romero, M. P. (2001). Changes in the phenolic composition of virgin olive oil from young trees (Olea europaea L. cv. Arbequina) grown under linear irrigation strategies. *Journal of Agricultural and Food Chemistry*, *49*(11), 5502-5508. https://doi.org/10.1021/jf0102416

Trentacoste, E. R., Puertas, C. M., & Sadras, V. O. (2010). Effect of fruit load on oil yield components and dynamics of fruit growth and oil accumulation in olive (*Olea europaea* L.). *European Journal of Agronomy, 32*, 249-254. https://doi.org/10.1016/j.eja.2010.01.002