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Linking Almond Yield and Quality to the Production System and Irrigation Strategy Considering the Plantation Age in a Mediterranean Semiarid Environment

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Abstract

Almond (*Prunus dulcis* Mill.) is characterized by its water stress tolerance and adaptability to diverse management strategies, allowing it to maintain or even enhance almond quality while achieving optimal yields. Limited research has been conducted to date on how almond production and quality vary across different water regimes and production systems, or how tree age modulates crop responses to deficit irrigation and organic practices. This study examines the effects of regulated deficit irrigation (RDI) under organic (OPS) and conventional (CPS) production systems, analyzing the impact on nut quality (physical and chemical parameters) and its sensorial properties in an almond orchard during seasons in 2019 and 2023, when the trees were 3-years old and when they were close to their yield potential at 7-years old, respectively. The PS and irrigation strategy affected the nut quality, yield, and tree growth. The OPS and RDI methods accumulated season-dependent yield losses in both studied periods. The kernel weight under OPS was lower than CPS in 2019, with these differences being less evident in 2023. The highest antioxidant activity and total phenolic compound values were obtained with the OPS and RDI methods in 2019, whereas the sugar and organic acid contents showed improvements under the OPS and the RDI strategy during 2019 and 2023, respectively. Finally, significant improvements were observed in relation to the fatty acids profile for nuts harvested under OPS in both seasons, especially in the latter season with RDI. Thus, almond quality can be enhanced by the integration of both OPSs and RDI strategies, although these improvements are dependent on tree age.

Keywords: water stress; chemical composition; antioxidant capacity; sugars; fat acid profile; descriptive sensorial analysis

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1. Introduction

The almond crop (*Prunus dulcis* Mill.) is the third most planted crop in Spain in terms of surface area, contributing 84% of European production and 5% of world production [1]. In

Andalusia (south Spain), just over 170,000 ha of almond trees are currently being cultivated, of which almost 85% are under rainfed conditions, the rest mostly being recent plantations located in deficit areas [2].

Given that almond trees have traditionally been planted in marginal, water-limited areas in many Mediterranean regions, average production has been low, hovering around 150–300 kg ha^{-1} [3]. These data contrast with the average yields of 3000 kg ha^{-1} obtained in the USA or Australia, where this crop is grown under intensive conditions with water endowments of up to 13,500 m^3 ha^{-1}, as well as with the maximum water requirements in the Guadalquivir river basin, which are close to 8000 m^3 ha^{-1} [4]. Despite these data, the water endowments for this crop have never been higher than 3500 m^3 ha^{-1} in the studied region, which often necessitates the implementation of deficit irrigation (DI) strategies in water scarcity scenarios [5], together with other cultivation practices focused on reductions in the evapotranspiration surface area via canopy management [6,7].

Several studies have shown that almond is a drought-tolerant crop and that its response to DI is usually very positive [7–9]. In this regard, it has been shown that the kernel-filling period (which coincides with the months of the highest evapotranspirative demand) would be the least susceptible to moderate water stress situations, even if such situations are prolonged over successive seasons [4,5,10].

On the other hand, the application of moderate water restrictions in periods more sensitive to water stress (such as the vegetative, fruit growth, and post-harvest stages) could somewhat serve as a strategy to control vegetative development, reducing the productive potential but allowing for the application of the most appropriate DI strategy with more severe water restrictions in the following years [11].

Regarding the production system, the Andalusia region has the biggest agricultural area under an organic production system (OPS) across Spain, mostly under rainfed conditions, with almond representing almost 25% of the total [12]. CPSs and OPSs differ in many manners as both systems offer distinct agricultural approaches and generate different impacts and outcomes. The CPS is referred to as an input-dominated system and differs from the OPS as the latter is known for its complete prohibition of chemicals or heavy input, which in many cases compromises the crop productivity. These differences in production are largely caused by the difficulties in making organic amendments with an efficiency matching conventional mineral fertilization systems or in the adequate control of crop pests and diseases. These difficulties are even more evident in young trees, causing a reduction in their growth rate and in their capacity to adapt to situations of water stress.

By contrast, the low almond yields under the OPS could largely be complemented with an increase in the added value of the final product, as is inherent to the management system, but also to the potential improvements that could be achieved in terms of the nut quality [13–15]. However, despite the consumer demand for this type of product [16], very little work has been conducted on the quantitative characterization of the potential improvements in the organoleptic and nutraceutical properties of almonds under organic production systems.

In addition, one of the greatest difficulties in discerning how the DI and the management system affect production and quality is due to the different age-dependent tree responses since neither the final product nor the capacity of the crop to adapt to stress are the same. Considering this, the response of almond trees to water stress can vary significantly between young and mature trees due to their differing physiological and developmental stages.

Young almond trees are still in the establishment phase and may exhibit more pronounced sensitivity to water stress as their root systems are not yet fully developed. This can result in reduced growth rates and delayed production. However, the strategic implementation of DI during less critical growth phases can help young trees develop resilience and optimize water use efficiency. Conversely, mature almond trees which have well-established root systems generally show a higher tolerance to DI. Their ability to access deeper soil moisture reserves allows them to maintain productivity even under moderate water stress [17]. In fact, mature trees subjected to DI often exhibit improved nut quality, with enhanced physical attributes such as kernel firmness and intensified coloration.

Additionally, the chemical composition, including higher concentrations of antioxidants and beneficial fatty acids, can be positively influenced by DI in mature trees, leading to superior nutraceutical properties of the almonds and improving their nutraceutical quality, as well as improving the total phenolic content, organic acids, and sugar content, thus contributing to improvement of the flavor and nutritional value. Finally, DI can influence the fatty acid composition, enhancing the presence of unsaturated fatty acids, thus providing health benefits [18,19].

To our knowledge, To our knowledge, few studies have comprehensively examined variations in almond yield and quality under different irrigation regimes and production systems, or how tree age influences these responses. Thus, the aim of this study was to contrast the impact of conventional and organic production systems on the yield and quality parameters of Marcona almond trees at 3-years old and at 7-years old, provided the potential yield has been reached, with these being subjected to different irrigation strategies (DI and full irrigation) in a semiarid Mediterranean region of southwest Spain.

2. Materials and Methods

2.1. Location of Experimental Plots, Irrigation Treatments, and Production Systems

The trial was conducted under conventional (CPS) and organic (OPS) production systems with almond [Prunus dulcis Mill. (D.A. Webb)] cv. Marcona located in the Guadalquivir river basin (SW Spain, 37°30′38.55″ N; 05°57′44.98″ W) in the Andalusian Institute of Agricultural and Fisheries Research and Training (IFAPA). Trees were grafted onto GN15 rootstock, spaced 7 × 6 m, and drip irrigated using two pipelines with emitters of 2.3 L h^{-1} at 0.75 m intervals. The soil of the experimental plots is a silty loam typical Fluvisol [20] that is more than 2.5 m deep; additional details about soil conditions for both systems are shown in Table 1.

Table 1. Soil chemical properties at 50 cm soil depth of experimental plots under different production systems.

	CPS	**OPS**
pH	8.14	8.07
EC (dS m^{-1})	0.41	0.32
$CaCO_3$ (g kg^{-1})	210	215
Organic matter (%)	0.9	1.14
N total (g kg^{-1})	0.67	0.87
P_{olsen} (mg kg^{-1})	25.72	17.86
K (mg kg^{-1})	289.74	280.91
B (mg kg^{-1})	0.82	0.91
Fe (mg kg^{-1})	3.08	2.06
Zn (mg kg^{-1})	0.57	0.76

CPS, conventional production system; OPS, organic production system; EC, electric conductivity; K, extractable ACNH4; B: extractable Mehich-3; Fe, Zn: extractable DTPA.

The climatology in the study area is attenuated meso-Mediterranean, with an annual ET0 rate of 1400 mm and an annual rainfall of 540 mm, which is mainly distributed from

October to April, and with the months of June to August having the highest evapotranspiration rates and little or no rainfall.

Since the experimental plots were transplanted in 2016, two irrigation strategies were performed in the OPS and CPS: (i) a full irrigated treatment (FI), which covered ~100% of the irrigation requirements (II.RR), and (ii) a regulated deficit irrigation (RDI) treatment, which covered ~80% of the II.RR during the vegetative stage (from March to June, stage II) and post-harvest (from harvesting to the end of October, coinciding with the beginning of autumn rainfall, stage IV). Additionally, during the kernel-filling period (from June to the beginning of September, just before harvesting, stage III), trees were irrigated by applying ~40% of the II.RR. This irrigation strategy was defined according to the theory that the period with the least sensitivity to water stress coincides with stage III in the case of almond trees, which also coincides with the maximum evapotranspirative demand period; this strategy is preferable in terms of avoiding severe stress situations during the vegetative development and post-harvest periods.

Irrigation doses were calculated according to the methodology proposed by Allen et al. [21], obtaining the values of reference evapotranspiration (ET0) by using a weather station close to the experimental orchards (<500 m). The local crop coefficients used during the experimental period ranged between 0.4 and 1.2, according to García-Tejero et al. [22].

The orchard management strategies were modeled after CPS and OPS practices. In this regard, the organic plot was fertilized with an annual application 2 kg m^{-2} of composed beef cattle manure (moisture of 222 g kg^{-1}, total organic carbon of 211 g kg^{-1}, and total N, P, and K of 18, 4.9, and 6.3 g kg^{-1}, respectively), and the use of green cover crops with a mixture legume and cereal (75% *Vicia sativa* L. + 25% *Avena sativa* L.), which was used as green manure, this being sowed in autumn after the first rainfall, mechanically cut, and incorporated into the soil in April of the following year. Pest and disease management in the organic orchard was carried out according to the Regulation (EU) 2018/848 of the European Parliament on the organic production and labeling of organic products [23].

In the case of CPS, the regulations for integrated production in Andalusia according to BOJA [24] were used, where the conventional plot received one application of a NPK complex fertilizer (15-15-15, 150 kg ha^{-1}) at flowering without any cover crop, with phytosanitary management corresponding to the cultivation practices established for this system.

In order to analyze the effects of the production system and irrigation treatments on trees of different ages (both three- and seven-years old), the yield was measured and almond nut samples were taken in 2019, coinciding with the first important harvest, and in 2023, once the trees were fully consolidated.

2.2. Yield Response and Vegetative Growth for the Different Production Systems and Irrigation Treatments

The vegetative growth and vigor of four replications (n = 4) per irrigation treatment and production system was evaluated by measuring the diameter of the trunk 20 cm above the graft. These measurements were carried out in November of each year (2019 and 2023) at the end of the growing season. The trunk cross section area (TCSA) was calculated according to Equation (1), and the estimation of tree growth between 2019 and 2023 was performed according to the difference between the TCSAs obtained during the studied seasons.

$$TCSA\ (\text{cm}^2) = \frac{D^2}{4\pi} \quad (1)$$

where D corresponds to the trunk diameter (in cm).

In addition, the kernel yield was determined using the total almond nuts collected in each repetition (n = 4, 2 trees per repetition) per production system and irrigation treatment.

2.3. Analysis of Kernel Physical Parameters: Weight, Size, Instrumental Color, and Texture

For each season, twenty-five almonds were randomly selected per orchard management and irrigation treatment, analyzing the weight and size (length, width, and thickness) of the kernel with a precision scale (model AG204 scale; Mettler Toledo, Barcelona, Spain) and a digital caliper (model 500-197-20 150 mm; Mitutoyo Corp., Aurora, IL, USA), respectively.

Color determinations were carried out using a colorimeter (model CR-300, Minolta, Osaka, Japan) which uses an illuminant D65 and 10° observer, measuring a total of 25 kernels per cultivar and irrigation treatment. The results are presented as CIEL*a*b* coordinates, defining color in three dimensions, namely L*, a*, and b*, which represent the lightness (0–100 values); the green–red coordinates, where negative values denote green and positive values red; and the blue–yellow coordinates, in which negative values represent blue and positive values yellow.

Additionally, we determined the kernel texture (fracturability (mm), hardness (N), work carried out on the shear (Ns), average force (N), and number of fractures (peaks count) via the use of a Stable Micro Systems analyzer (TA-XT2i, Godalming, UK) with a 30 kg load cell and a probe (Volodkevich Bite Jaw HDP/VB).

2.4. Kernel Chemical Composition

2.4.1. Antioxidant Activity and Total Phenolic Content

The antioxidant activity (AA) and total phenolic content (TPC) were measured as previously described by Cano-Lamadrid et al. [25]. ABTS+ and DPPH• were used for the AA determination, as previously described by others [19,26]. The absorbance decreases for DPPH• and ABTS+ were measured at 515 nm and at 734 nm, respectively. Analysis was carried out using a UV–visible spectrophotometer (Helios Gamma model, UVG 1002E, Helios, Cambridge, UK). Calibration curves (3.5–5.0 mmol Trolox L^{-1}) with good linearity (R^2 = 0.999) were used for the quantification of AA. The analyses were run in triplicate, and the results are expressed in mmol Trolox kg^{-1} of dry weight (dw).

The TPC was determined using Folin-Ciocâlteu's reagent, as described in previous almond studies [19]. Absorbance was measured using a UV-visible spectrophotometer (Helios Gamma model, UVG 1002E, Helios, Cambridge, UK) at 765 nm. Gallic acid was used to prepare the calibration curves. This analysis was run in triplicate, and the results are expressed as gallic acid equivalents (GAE) per kg^{-1} (dw).

2.4.2. Organic Acids and Sugars

Organic acids and sugars were identified and quantified with high-performance liquid chromatography (HPLC), as previously described by Lipan et al. [19]. Additionally, 1 g of grinded almond was homogenized with 5 mL of phosphate buffer 50 mM (pH = 7.8) with a homogenizer (Ultra Turrax T18 Basic, IKA Works, Barcelona, Spain) for 2 min at 11,300 rpm which the tube was maintained in an ice bath and then centrifuged (Sigma 3–18 K; Sigma Laborzentrifugen, Osterode and Harz, Germany) for 20 min at 15,000 rpm and 4 °C and filtered (0.45 µm Millipore membrane filter). The supernatant (10 µL) was injected into a a high-performance liquid chromatograph (HPLC) system (HP Series 1100, Hewlett-Packard, Wilmington, DE, USA) using 0.1% ortophosphoric acid elution buffer.

Sugars were determined using a Supelcogel TM C-610H column (30 cm × 7.8 mm) with a pre-column (Supelguard 5 cm × 4.6 mm; Supelco, Bellefonte, PA, USA) and were detected with a refractive index detector (RID). Organic acid absorbance was measured at 210 nm with a diode-array detector (DAD). Calibration curves were run in triplicate with different standards of organic acids and sugars provided by Sigma (Poole, UK). The analyses were run in triplicate, and the results are expressed as g kg^{-1} (dw).

2.4.3. Fatty Acids

The fatty acids methyl esters (FAMEs) were prepared as previously described by Lipan et al. [18] and analyzed according to Tuberoso et al. [27]. The FAMEs were separated in a Shimadzu GC17 A gas chromatographer with a flame ionization detector and a DB-23 capillary column (30 m length, 0.25 mm internal diameter, and 0.25 μm film thickness) (J&W Scientific, Agilent Technologies, Madrid, Spain). Helium was used as carrier gas at a flow rate of 1.1 mL min^{-1} and 35 mL min^{-1} at the make-up point, with an injector and detector temperature of 240 °C and 260 °C, respectively. The injection volume was 0.8 mL (split ratio of 1:34). The temperature program was as follows: an initial temperature of 100 °C was held for 1 min and the temperature gradient of 3 °C min^{-1} was held until 220 °C, followed by a gradient of 5 °C min^{-1} until 245 °C and maintaining 245 °C for 1 min. The identification of FAME peaks was conducted by comparing the retention times of the FAME Supelco MIX-37 standards. The analysis was carried out in triplicate, and the results are expressed as g kg^{-1} concentration, using methyl nonadecanoate as the internal standard.

2.5. Sensory Analysis

Twenty-four judges were asked to objectively rank the intensity of the following three sensory descriptors of almonds: aromatics reminiscent of almond (almond ID), sweetness, and crunchiness. The scale ranged from 1 to 3 with 0.5 increments, in which 1 means low intensity and 3 means high intensity. Both irrigation and production system samples were presented. Water and crackers were used in between samples to cleanse the palate. Three evaluations were carried out per sample.

2.6. Statistical Analysis

The statistical analyses were completed by subjecting the data to a two-way analysis of variance (ANOVA; factor 1: production system and factor 2: irrigation treatment) and then to Tukey's multiple range test. Statistically significant differences were considered when $p < 0.05$ and were studied using XLSTAT Premium 2016 (Addinsoft, New York, NY, USA). For the yield and TCSA, n = 4 replications per production system and irrigation treatment were considered. In addition, for quality parameters, n = 3 replications per production system x irrigation treatment were considered.

To ease the visualization of the relationships between all variables and to discern between the treatments, a principal component analysis (PCA) including all the studied variables was made for each season using SPSS (SPSS Software 11.0). Thus, the PCA was used to identify variables or underlying factors that better explain the correlation or covariance matrix of several variables, identifying the main factor of variability (production system or irrigation treatment) for each season.

3. Results and Discussion

3.1. Climatic Conditions, Irrigation Doses Applied, Tree Growth and Yield

Table 2 summarizes the average climatic conditions during the studied period, these being slightly different during both seasons studied. In 2019, 282 mm of rainfall was registered from January to May, whereas in 2023, the total rainfall was 133.4 mm. By contrast, the kernel-filling and post-harvest period (from harvesting to leaves senescence) was characterized by less rainfall, coinciding with the highest evapotranspiration rates, with registered values of 672.4 and 505.6 mm for ET_0 and ET_C in 2019 and 691 and 722 mm for ET_0 and ET_C in 2023, respectively. The climatic conditions during the kernel-filling period (from the beginning of June to the end of August) were very similar, especially in terms of average temperatures, rainfall, or sunlight duration, among others. Relating to the irrigation doses applied, in 2019, FI received 72.5 mm of irrigation water in stage

II, whereas RDI received only 55.5, with 75% being in FI plots. During the kernel-filling period, FI and RDI received 413 and 169 mm, respectively, with a percentual difference of 60%. It is remarkable that during the month of May, 77 mm of rainfall was registered, which allowed for a reduction in the irrigation water applied in both treatments during the beginning of the kernel-filling period. At the end of 2019, FI received 504 mm, whereas RDI received 239 mm, allowing water savings of 53%.

Table 2. Total rainfall, reference (ET_0) and crop (ET_C) evapotranspiration rates, and irrigation water amounts applied during the different phenological stages and studied seasons.

	2019					2023				
	Stage I	**Stage II**	**Stages III**	**Stage IV**	**Total I–IV**	**Stage I**	**Stage II**	**Stages III**	**Stage IV**	**Total I–IV**
	(mm)									
Rain	102	180	0	0	282	21.2	112	10	75	219
ET_0	89	319	536	136	1081	92	412	550	141	1195
ET_C	0	144	452	54	649	0	271	551	99	921
Treatment	Irrigation doses applied									
FI	0	73	413	18	504	0	184	535	10	729
RDI	0	56	169	14	239	0	144	277	8	429

FI, Full-irrigation; RDI, regulated deficit irrigation; Stage I, dormant bloom-flowering period; Stage II, vegetative and fruit-growth period; Stage III, kernel-filling period; Stage IV, postharvest (until leaves fall).

During 2023, FI and RDI received 184 and 144 mm of irrigation water during the vegetative and fruit growth period and 545 and 285 mm during the kernel-filling and post-harvest period, respectively, allowing water savings of 41% across the whole season. The low irrigation amount applied during stage IV was as a result of the rainfall accumulated in this period and the onset of abscission.

The different management conditions and irrigation doses applied in each treatment were reflected not only in terms of vegetative growth (Table 3) but also in terms of the final yield. Regarding crop vegetative development, since the plantation has been in operation in 2016, until the first year of study (2019), trees under RDI saw a decline in vegetative development of 20% under both production systems. In addition, in 2023, this decline was around 17 and 21% under the CPS and OPS, respectively. Taking into consideration the differences between production systems, trees under the OPS saw a decline in vegetative development close to 60% compared to the CPS. Moreover, in 2023, these declines in vegetative development in the OPS vs. CPS were 57 and 59% for FI and RDI treatments, respectively. Thus, the highest reduction in vegetative development was promoted by the production system (~60% in OPS vs. CPS), followed by the irrigation strategy (~20% in RDI vs. FI).

In addition, the irrigation treatments employed had significant effects on the yield ($p < 0.05$). During the 2019 season, average yields of 780 kg ha^{-1} and 226 kg ha^{-1} were obtained under the CPS and OPS, the latter of which saw yield reductions close around to 70%. Concretely, within the CPS, the FI and RDI treatments obtained 790 and 770 kg ha^{-1} (with these differences being insignificant; $p > 0.05$), while in the OPS, the FI and RDI treatments recorded similar yields of 231 and 223 kg ha^{-1}, respectively.

During the season of 2023, average yields of 1023 kg ha^{-1} were obtained under the CPS, whereas within the OPS, the yields were again significantly lower ($p < 0.05$) than those found in the CPS (~348 kg ha^{-1}, on average), with differences between FI and RDI in both production systems. Thus, for the OPS, average yields of 480 and 215 kg ha^{-1} for FI and RDI were obtained, whereas for the CPS, FI and RDI registered 1261 and 786 kg ha^{-1}, respectively (with these differences being significant; $p < 0.05$). Therefore, these values suggest significant yield reductions ($p < 0.05$) of around to 66% for the OPS compared to the CPS. These findings are in agreement with those obtained by different authors and experimental studies, with expected yield reductions of between 10 and 40%, depending on different factors such as orchard management, pest pressure, and soil health [28]. It was also noticeable that in the yield reductions registered on RDI were around 38% and 55% for the CPS and OPS, respectively. Yield reductions can result from the application of deficit irrigation strategies or the application of organic farming practices in the almond crop, as opposed to conventional systems without water reduction, and these differences can be compensated for to a certain degree in terms of the almond quality and, therefore, the almond marketability [29,30].

Table 3. Trunk cross section (TCS) and ΔTCS of almonds trees of tree-years (2019) and seven-years old (2023) trees under conventional (CPS) and organic (OPS) production systems and subjected to full irrigation (FI) and regulated-deficit irrigation (RDI) strategies.

	2019		**2023**		**2019–2023**	
	TCS		**TCS**		**ΔTCS**	
	CPS	**OPS**	**CPS**	**OPS**	**CPS**	**OPS**
			(cm^2)			
FI	147 a	63 b	571 a	247 b	424 a	184 b
RDI	117 a	50 b	473 a	195 b	356 a	146 b
Irrigation	*	*	**	*	*	*

Different letters evidence significant differences ($p < 0.01$) between managements for each irrigation treatment and season. * and ** show significant differences ($p < 0.05$ and $p < 0.01$; respectively) between irrigation treatments for each system.

3.2. Effects of Production System and Irrigation on Kernel Physical Parameters, Antioxidant Activity, and Total Phenolic Content

Table 4 shows the results of the physical analysis of the studied almonds for both monitored seasons. During the first season, corresponding to young trees, significant differences ($p < 0.001$) were observed in the kernel size, with higher values being produced under the CPS than the OPS. These differences were also apparent in the color (lighter and redder almonds under the OPS) and the almond texture. In this sense, OPS almonds showed a higher hardness, being more difficult to shear (under FI conditions), thus requiring a higher average force to break the shell.

During the second year of study, significant differences in kernel size were again detected ($p < 0.001$), with higher kernel weights observed in those obtained under the CPS than the OPS; in turn, within conventional systems, the RDI treatment showed higher seed weight values than those obtained under IF conditions. Likewise, morphological parameters (length, width, and thickness) were generally higher in the CPS than in the OPS. Differences in color were not as evident as for those found in 2019; even in 2023, color trends were inverse to those detected in the first monitoring season, with generally higher values for the CPS than the OPS.

Finally, regarding the texture, no differences were determined between the production and irrigation systems in 2023.

The effects of water stress on the almond size, texture, and color parameters are not quite clear, with different results depending on the cultivar and management conditions. Goldhamer and Viveros [31] found that water stress reduced almond size due to limited water availability, which restricts cell expansion and growth during kernel development, especially under severe water stress conditions, which lead to smaller and lighter kernels. Egea et al. [17] demonstrated that water stress can result in harder kernels due to the reduced water uptake, which affects the moisture content and texture of the almond. Also, they conclude that insufficient water during critical growth stages may also result in shriveled or wrinkled kernels. Other authors like López-López et al. [32] stated that RDI strategies could affect the almond color, often leading to darker or less uniform kernel coloration. They suggested that water stress induced changes in metabolic processes, such as sugar accumulation and phenolic compound synthesis, which could influence the kernel pigmentation.

Table 4. Physical analysis of kernel almond obtained from tree-years (2019) and seven-years old (2023) trees under conventional (CPS) and organic (OPS) production systems and subjected to full irrigation (FI) and regulated-deficit irrigation (RDI) strategies.

Treatment	Weight	Size			Kernel Color Coordinates					Texture			
	(g)	Length	Width	Thickness	L*	a*	b*	C	Hue	Hardness (N)	Work to Shear	Average Force (N)	Number of Fractures
2019													
ANOVA test													
	***	***	**	NS	***	***	***	***	NS	***	***	***	**
Tukey's Multiple Range test													
CPS-FI	1.79 a	23.71 a	18.72 a	9.30 a	42.92 b	12.24 b	24.27 b	27.23 b	63.38 a	82.91 b	78.04 b	42.31 c	14.52 bc
CPS-RDI	1.80 a	23.52 a	18.48 ab	9.35 a	43.04 b	12.81 ab	24.92 b	28.04 b	62.81 a	81.32 b	79.71 b	41.04 c	13.24 c
OPS-FI	1.63 b	22.03 b	17.81 b	9.17 a	44.58 a	13.31 a	27.14 a	30.23 a	63.77 a	114.02 a	131.24 a	60.13 a	19.33 a
OPS-RDI	1.63 b	22.24 b	17.84 b	9.10 a	44.61 a	13.28 a	26.88 a	30.03 a	63.72 a	106.90 a	103.63 b	52.31 b	18.19 ab
2023													
ANOVA test													
	***	***	***	*	***	NS	*	NS	***	NS	NS	NS	NS
Tukey's Multiple Range test													
CPS-FI	1.39 b	21.41 ab	16.32 b	8.65 a	41.82 a	13.64 a	23.49 ab	27.21 a	59.94 a	84.51 a	70.53 a	42.21 a	7.44 a
CPS-RDI	1.50 a	21.93 a	17.14 a	8.75 a	42.11 a	13.62 a	23.62 a	27.20 a	60.02 a	89.32 a	73.10 a	42.47 a	9.67 a
OPS-FI	1.29 b	20.92 bc	16.22 b	8.24 b	40.94 b	13.71 a	23.26 ab	26.93 a	59.51 a	83.44 a	66.71 a	39.52 a	8.49 a
OPS-RDI	1.30 b	20.63c	16.13 b	8.46 ab	40.23 b	13.83 a	22.53 b	26.42 a	58.42 b	85.09 a	69.53 a	39.10 a	8.59 a

NS = not significant at $p < 0.05$; *, **, and *** significant at $p < 0.05$, 0.01, and 0.001, respectively. Values (mean of 3 replications, each one consisting on 25 almonds) followed by the same letter, within the same column and factor, were not significantly different ($p < 0.05$), according to Tukey's least significant difference test.

Lipan et al. [18,19] argued that moderate water stress can be managed without severely compromising the almond size, texture, or color. However, severe water stress leads to smaller, harder, and darker kernels, thus reducing overall quality. These findings emphasize the importance of strategic irrigation management to balance water conservation and almond quality. In our case, the RDI strategy imposed did not clearly cause a reduction in kernel size, with the greatest impact being from the production system (CPS vs. OPS), thus corroborating the results obtained in previous studies by this research group.

Even more interesting were the differences in kernel size between management systems and between the two seasons studied. Thus, in general, organic kernels showed a smaller size than those obtained by conventional practices. In addition, according to the results obtained in both campaigns, the size of the almond was reduced in older trees (7-years old), obtaining larger almonds in 2019, thus improving the most commercially important production factor. The effects of conventional and organic management practices on almond size can vary due to differences in input use, soil health, pest management, and overall farming strategies. Currently, only a few studies have studied the effects of management systems (OPS vs. CPS) in almond production [14]. As far as we are concerned, conventional systems often rely on synthetic fertilizers to provide readily available nutrients like nitrogen, phosphorus, and potassium. This can lead to rapid growth and potentially larger almonds if managed correctly. Moreover, the immediate availability of nutrients can support robust tree health and kernel development, potentially leading to larger almond sizes. By contrast, organic systems often have lower yields compared to conventional systems, but the almonds may be larger due to fewer fruits competing for the tree's resources. In this regard, Karat [33] reported an improvement in kernel size in Ferraduel almonds produced under an OPS. However, these differences were not found in the Ferragnes cultivar. This emphasizes the importance of the cultivar, necessitating scientific studies focused on the advantages/disadvantages of OPSs and CPSs.

Additionally, significant differences were observed in the AA and TPC during the 2019 season ($p < 0.001$; Table 5), with higher values being found for ABTS, FRAP, and the TPC in almonds obtained under OPS conditions. In relation to the water stress imposed in both systems, almonds produced under RDI reflected a higher AA and TPC for both the OPS and CPS, evidencing the benefits of this strategy in fostering quality parameters.

Table 5. Effect of production system and irrigation dose on the antioxidant activity (AA) and total phenolic content (TPC) of raw almonds obtained from tree-years (2019) and seven-years old (2023) trees under conventional (CPS) and organic (OPS) production systems and subjected to full irrigation (FI) and regulated-deficit irrigation (RDI) strategies.

	ABTS	FRAP	TPC
	(mmol Trolox kg^{-1})		(g GAE kg^{-1})
		2019	
		ANOVA	
	***	***	***
		Tukey Multiple Range Test	
CPS-FI	1.95 b	1.48 d	0.55 c
CPS-RDI	1.91 b	2.06 c	0.67 bc
OPS-FI	2.26 a	2.96 b	0.80 b
OPS-RDI	2.96 a	4.24 a	1.08 a
		2023	
		ANOVA	
	*	NS	NS
		Tukey Multiple Range Test	
CPS-FI	0.68 ab	1.02 a	0.35 a
CPS-RDI	0.58 b	0.97 a	0.29 a
OPS-FI	0.89 a	1.31 a	0.34 a
OPS-RDI	0.61 b	1.08 a	0.24 a

NS = not significant at $p < 0.05$; *, **, and *** significant at $p < 0.05$, 0.01, and 0.001, respectively. Values (mean of 3 replications, each one consisting on 25 almonds) followed by the same letter, within the same column and factor, were not significantly different ($p < 0.05$), according to Tukey's least significant difference test.

During 2023, no significant differences were found in the TPC, between the production systems, nor regarding the irrigation treatment; however, in the case of the AA, differences were again found in relation to ABTS ($p < 0.05$), meaning the highest values were found under OPS and FI conditions, while the lowest values were obtained in both production systems for the RDI plots.

Water stress can affect the AA and TPC in almonds, which are important for their nutritional and health benefits. Several studies have reported that moderate water stress can enhance AA in almonds. This is often attributed to the plant's defense mechanism against oxidative stress caused by drought. Additionally, phenolic compounds, which are secondary metabolites, play a crucial role in the antioxidant defense system. Under water stress, almonds tend to accumulate higher levels of phenolic compounds, which contribute to increased AA [8,34]. According to Dixon and Paiva [35], within the response to water stress, the phenylpropanoid pathway is responsible for the production of phenolics, leading to higher concentrations of these compounds in almonds. In addition, the response to water stress can vary among different almond cultivars.

Some cultivars show an increase in the TPC under drought conditions, while others may display a more modest response. It can be assumed from our findings that water stress has a positive impact on the AA and TPC in almonds. In this agreement, Lipan et al. [19] suggested that water stress induced phenolic accumulation in almonds, leading to higher AA, highlighting that moderate RDI strategies are a positive practice for improving almond quality.

Even more interesting were the improvements in the AA and TPC determined in organic almonds compared to those obtained in the CPS. These improvements are in line with the results obtained by García-Martínez et al. [36], who reported that the OPS augmented the synthesis of secondary metabolites, including phenolics, which contribute to the enhanced nutraceutical quality of organic almonds.

3.3. Effects of Production System and Irrigation Treatments on the Organic Acid and Sugar Contents

Figure 1 shows the organic acid content presented in the almonds for both studied seasons. During 2019, significant differences ($p < 0.001$) were observed considering the CPS and irrigation strategy (Figure 1A). By contrast, the almonds obtained under the OPS and RDI registered lower levels of Σ organic acids compared to the almonds obtained in the rest of the treatments.

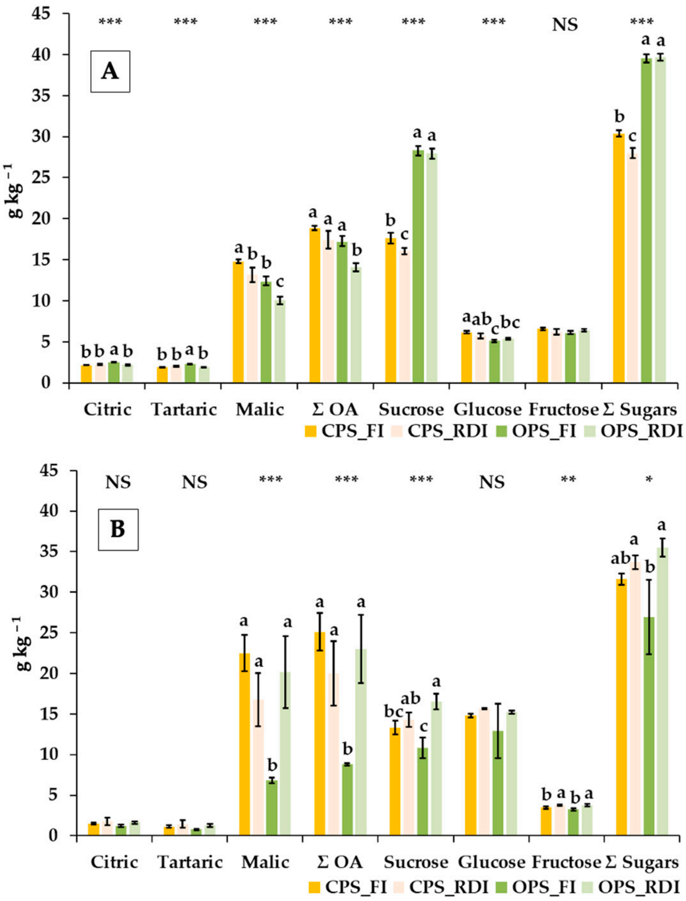

Figure 1. Organic acids and sugar content in raw almonds obtained from tree-years ((**A**), 2019) and seven-years old ((**B**), 2023) trees under conventional (CPS) and organic (OPS) production systems and subjected to full irrigation (FI) and regulated-deficit irrigation (RDI) strategies. NS = not significant at $p < 0.05$; *, **, and *** significant at $p < 0.05$, 0.01, and 0.001, respectively. Values (mean of 3 replications, each one consisting of 25 almonds) followed by the same letter, within the same column and factor, were not significantly different ($p < 0.05$), according to Tukey's least significant difference test. ΣOA = total organic acids.

Meanwhile, during 2023, mature trees presented higher levels of Σ organic acids compared to the previous period (Figure 1B). Differences were also found between the irrigation treatment and production system only in the malic acid results, which were higher in CPS_FI; the highest levels of Σ organic acids were reached in the OPS_RDI plots.

Comparing both seasons, an increase in the levels of Σ organic acids could be observed for mature trees (2023), mainly due to the higher levels of malic acid, since the proportions of tartaric and citric acid decreased between 2019 and 2023. However, anomalous levels of malic acid in almonds under OPS_FI were detected, although the current results do not allow us to determine the cause of this outcome.

For citric and tartaric acids, mature trees may have lower levels of organic acids due to the establishment of root systems and the optimization of nutrient uptake, while young trees maintain higher metabolic levels due to structural and vegetative development [37]. However, the increase found in this study could imply that the trees remained a higher metabolically activity, presumably due to the water stress and adverse weather conditions (high air temperature and vapor pressure deficit) during the kernel-filling period.

Relating to the sugar content in 2019, significant differences were found in young trees regarding crop management ($p < 0.001$; Figure 1A). Thus, the OPS obtained a higher overall sugar content (>25%) than the CPS. In addition, in 2023, differences related to both the production system and irrigation strategy were obtained, increasing Σ sugars in organic almonds, but without any differences in the fructose levels.

When both monitored seasons were compared, a significant decrease was observed in the sucrose and fructose levels (2019 > 2023), while there was a great increase in the glucose content (2023 > 2019). These differences may be due to the higher photosynthetic efficiency and carbohydrate storage and allocation capacity in mature trees, thus affecting the kernel composition and resulting in almonds with higher glucose content. As for fructose and sucrose, higher levels of these carbohydrates are found in almonds from young trees due to the metabolic demands and the active growth and development of these trees.

In this context, Venkatachalam and Sathe [38] concluded that factors such as cultivar, kernel maturity, growing conditions, and growth location are known to affect the contents of sugar in nuts. These results are highly in agreement with different studies previously developed in other commercial almond cultivars. Comparing the results obtained by Gutiérrez Gordillo et al. [39] in young almonds (cvs. Guara, Marta, and Lauranne) with those reported by Lipan et al. [40] in mature almond trees of the same cultivar, all subjected to similar irrigation strategies, it can be observed that the sucrose and fructose content decreases in mature tree nuts, whereas the glucose content increases in mature tree almonds, emphasizing the importance of tree age in the almond chemical composition. Considering that young trees prioritize the growth and development of the entire vegetative part, it is very likely that there is a greater consumption of glucose (and therefore less storage in the seed) than of other sugars such as fructose or sucrose, which are more complex to metabolize. Stitt and Zeeman [41] suggested that sucrose must be cleaved (into glucose + fructose) before being fully utilized, making it a less immediate energy source compared to glucose. In this line, Lemoine et al. [42] reported that sucrose is often transported to sinks (like seeds) but may be broken down into glucose for immediate growth needs in young trees. In addition, Rolland et al. [43] highlighted that glucose is a key signaling molecule and primary substrate for energy metabolism, often being prioritized over sucrose or fructose in growing tissues.

3.4. Effects of Production System and Irrigation Treatments on Fatty Acids Profile

Tables 6 and 7 summarize the fatty acid profiles and some quality parameters derived from them during the 2019 and 2023 seasons. Twenty-one fatty acids were identified in the Marcona almond in both seasons. Oleic and linoleic acids were the major fatty acids, accounting for 80–90% of the total, followed by Stearic and Palmitic, as has been reported by other authors [39,40,44,45].

Table 6. Fatty acids profile in raw almonds affected by production system and irrigation dose. Samples taken from three-years old trees (2019).

Compounds	ANOVA	CPS_FI	CPS_RDI	OPS_FI	OPS_RDI
			(%)		
C12:0 (Lauric)	NS	0.010	0.010	0.010	0.010
C14:0 (Myristic)	NS	0.120	0.130	0.130	0.130
C14:1 (Myristoleic)	NS	0.050	0.060	0.050	0.050
C15:0 (Pentadecylic)	**	0.021 a	0.017 bc	0.015 c	0.019 ab
C15:1 (Pentadecenoic)	NS	0.030	0.030	0.020	0.030
C16:0 (Palmitic)	NS	10.750	11.130	11.040	11.080
C16:1c7	*	0.086 ab	0.091 a	0.083 ab	0.075 b
C16:1c9 (Palmitoleic)	*	1.81 b	1.94 ab	2.05 a	1.970 ab
C16:1c10	**	0.098 b	0.104 ab	0.114 a	0.115 a
C17:0 (Margaric acid)	NS	0.200	0.220	0.220	0.190
C17:1c10 (*cis*-Heptadecenoic)	NS	0.350	0.370	0.350	0.340
C18:0 (Stearic)	**	3.650 b	3.870 b	4.190 a	4.080 a
C18:1t9 (Elaidic)	NS	0.110	0.120	0.100	0.080
C18:1c9n9 (Oleic)	NS	60.000	60.900	58.900	59.200
C18:1n7 (*cis*-Vaccenic)	NS	5.620	5.570	5.990	5.650
C18:2n6 cis 9,12 (Linoleic)	*	19.300 b	20.100 ab	20.500 a	20.400 a
C20:0 (Arachidic)	NS	0.170	0.150	0.170	0.180
C20:1c11 (Eicosenoic)	NS	0.170	0.170	0.180	0.140
C18:3n3c9,12,15 (α-Linolenic)	NS	0.110	0.110	0.100	0.090
C21:0 (Heneicosylic)	*	0.021 ab	0.024a	0.022 ab	0.020 b
C20:2n6c11,14 (Eicosadienoic)	***	0.010 b	0.014a	0.013 a	0.0130 a
C22:0 (Behenic)	***	0.050 c	0.070b	0.090 a	0.060 c
C24:1c15 (Nervonic)	NS	0.240	0.260	0.290	0.270
C22:6n3 (Docosahexaenoic DHA)	NS	0.240	0.260	0.290	0.270
Oleic:Linoleic	NS	3.110	3.030	2.880	2.910
Saturated Fatty Acids (SFA)	NS	14.620	14.850	15.160	15.130
Monounsaturated Fatty Acids (MUFA)	NS	66.310	66.750	64.920	65.040
Polyunsaturated Fatty Acids (PUFA)	*	18.680 b	19.390 ab	19.920 a	19.830 ab
PUFA:SFA	NS	1.310	1.310	1.310	1.310
PUFA:MUFA	NS	0.290	0.300	0.310	0.310
(MUFA+PUFA)/SFA	**	5.850 a	5.740 ab	5.580 b	5.600 b
Atherogenic index	NS	0.130	0.130	0.130	0.130
Thrombogenic index	**	0.320 b	0.330 ab	0.340 a	0.340 a

FI, full irrigation; RDI, regulated deficit irrigation; CPS, conventional production system; OPS, organic production system. NS = not significant at $p < 0.05$; *, **, and *** significant at $p < 0.05$, 0.01, and 0.001, respectively. Values (mean of 3 replications, each one consisting on 25 almonds) followed by the same letter, within the same column and factor, were not significantly different ($p < 0.05$), according to Tukey's least significant difference test.

In the individual fatty acid data presented for young almond trees (Table 6), it can be seen that most of them did not show differences in terms of treatments. The biggest differences were found with respect to the production system, taking into account the ranges of occurrence of minor acids, such as Pentadecylic (0.021–0.015), C16:1c7 (0.091–0.075), Stearic (4.19–3.65), Heneicosyic (0.024–0.02), Eicosadienoic (0.014–0.01), and Behemic (0.09–0.05) acids, and one of the major fatty acids, linoleic acid (20.5–19.3). In terms of the studied indices, differences were observed in PUFA levels (19.92 in OPS_FI vs. 18.68 in CPS_FI), (MUFA+PUFA)/SFA (5.85 in CPS_FI vs. 5.58 in OPS_FI), and in the thrombogenic index (0.34 in OPS vs. 0.32 in CPS_FI). These data indicate that, in young trees, the almonds obtained under CPSs are nutritionally better than under OPSs since the differences in linoleic acid cause the oleic–linoleic ratio to change, although these differences are not significant.

For mature trees (Table 7), the observed differences between treatments were also reduced, with significant changes seen for Palmitoleic (0.532–0.498) and Stearic (1.626–1.308) acid. As for the indices–, newly significant differences were found in the PUFA content, the best results being reached for OPS_RDI (20.05), in contrast to the OPS_FI (18.28), CPS_RDI (18.15), and CPS_FI (19.09) plots.

Table 7. Fatty acids profile in raw almonds affected by production system and irrigation dose. Samples taken from seven-years old trees (2023).

Compounds	ANOVA	CPS_FI	CPS_RDI	OPS_FI	OPS_RDI
			(%)		
C12:0 (Lauric)	NS	0.000	0.000	0.000	0.000
C14:0 (Myristic)	NS	0.030	0.030	0.020	0.030
C14:1 (Myristoleic)	NS	0.000	0.000	0.000	0.000
C15:0 (Pentadecylic)	NS	0.000	0.010	0.010	0.010
C15:1 (Pentadecenoic)	NS	0.000	0.000	0.000	0.000
C16:0 (Palmitic)	NS	6.450	6.370	6.410	6.520
C16:1c7	NS	0.020	0.020	0.02	0.020
C16:1c9 (Palmitoleic)	*	0.513 ab	0.532 a	0.498 b	0.524 ab
C16:1c10	NS	0.010	0.010	0.010	0.020
C17:0 (Margaric acid)	NS	0.050	0.040	0.050	0.050
C17:1c10 (*cis*-Heptadecenoic)	NS	0.090	0.090	0.090	0.090
C18:0 (Stearic)	**	1.408 b	1.308 b	1.453 ab	1.626 a
C18:1t9 (Elaidic)	NS	0.000	0.000	0.000	0.000
C18:1c9n9 (Oleic)	NS	72.070	73.320	73.020	70.940
C18:1n7 (*cis*-Vaccenic)	NS	0.030	0.030	0.030	0.030
C18:2n6 cis 9,12 (Linoleic)	NS	19.000	18.080	18.210	19.970
C20:0 (Arachidic)	NS	0.060	0.060	0.060	0.070
C20:1c11 (Eicosenoic)	NS	0.000	0.000	0.000	0.000
C18:3n3c9,12,15 (α-Linolenic)	NS	0.080	0.070	0.080	0.080
C21:0 (Heneicosylic)	NS	0.000	0.000	0.000	0.000
C20:2n6c11,14 (Eicosadienoic)	*	0.001 ab	0.000 b	0.001 ab	0.001 a
C22:0 (Behenic)	NS	0.010	0.010	0.020	0.020
C24:1c15 (Nervonic)	NS	0.020	0.010	0.010	0.010
C22:6n3 (Docosahexaenoic DHA)	NS	0.000	0.000	0.000	0.000
Oleic:Linoleic	NS	3.810	4.060	4.020	3.560
Saturated Fatty Acids (SFA)	NS	8.150	7.840	8.030	8.310
Monounsaturated Fatty Acids (MUFA)	NS	72.750	74.010	73.680	71.640
Polyunsaturated Fatty Acids (PUFA)	*	19.090 b	18.150 c	18.280 c	20.050 a
PUFA:SFA	NS	2.340	2.320	2.280	2.410
PUFA:MUFA	NS	0.260	0.250	0.250	0.280
(MUFA+PUFA)/SFA	NS	11.290	11.760	11.450	11.040
Atherogenic index	NS	0.070	0.070	0.070	0.070
Thrombogenic index	*	0.171 ab	0.167 b	0.171 ab	0.177 a

FI, full irrigation; RDI, regulated deficit irrigation; CPS, conventional production system; OPS, organic production system. NS = not significant at $p < 0.05$; * and **, significant at $p < 0.05$ and 0.01, respectively. Values (mean of 3 replications, each one consisting on 25 almonds) followed by the same letter, within the same column and factor, were not significantly different ($p < 0.05$), according to Tukey's least significant difference test.

In relation to the thrombogenic (TI) and atherogenic index (AI), a positive effect was detected, with slight improvements in the TI in FI, although the values observed for the OPS can also be being considered very low; hence, this slight improvement for FI cannot be considered better in terms of its health benefits as all of them were below 1 [46,47]. Moreover, an improvement in the TI and AI can be observed in almonds provided by mature trees in comparison to young trees, with higher and similar values of oleic and linoleic content, respectively, thus leading to higher values of the oleic–linoleic ratio. Something similar was observed when comparing the values obtained by Gutiérrez-Gordillo et al. [39] in young trees and Lipan et al. [40] in mature trees (both experiments were developed with the same almond cultivars and irrigation treatments).

3.5. Descriptive Sensorial Analysis

Figure 2 shows the most relevant information from the descriptive sensory analysis developed for almonds harvested in 2019 (A) and 2023 (B).

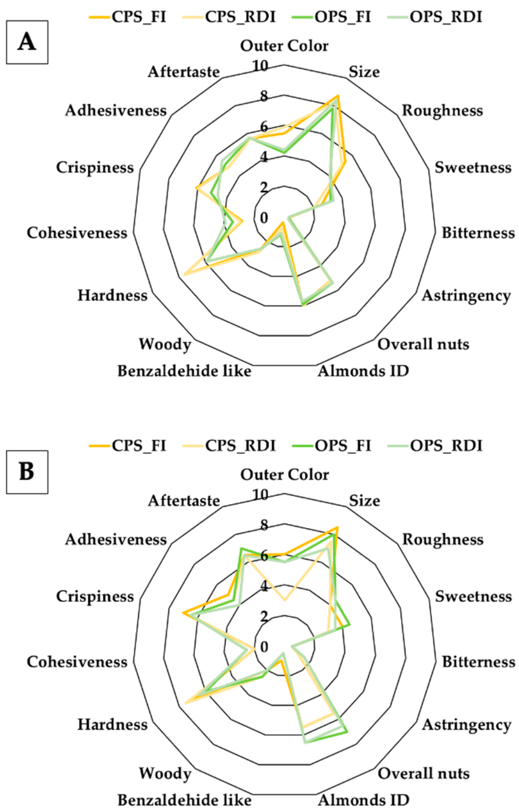

Figure 2. Descriptive sensory analysis of raw almonds obtained from tree-years ((**A**), 2019) and seven-years old ((**B**), 2023) trees under conventional (CPS) and organic (OPS) production systems and subjected to full irrigation (FI) and regulated-deficit irrigation (RDI) strategies. The scale used ranged from 0 = no intensity to 10 = extremely strong intensity.

Regarding the samples obtained from young trees (2019), the main differences between the irrigation treatments and production systems were detected in the external color of the seeds and their hardness. Thus, in the case of almonds grown under the CPS, a more pronounced color was observed compared to those under organic farming techniques. The same occurred regarding hardness, with greater values observed in almonds grown under the CPS compared to those from the OPS. These effects were also detected in almonds obtained from mature trees (2023). Thus, relating to the outer color, the highest and lowest values were observed for CPS_FI and CPS_RDI plots, respectively. Additional differences were observed in the almonds from mature trees. Thus, size was also affected, with larger almonds being observed for FI conditions. The most interesting result was detected for the Overall Nut and Almond ID parameters, with the best results being reflected in those almonds obtained under OPS plots.

Although generally the differences found between the production systems and irrigation treatments were minimal, the results have at least allowed us to discern that organic farming strategies in conjunction with moderate deficit irrigation do not worsen the sensory characteristics of the almond, improving some of the parameters related to its flavor, as is the case with the Overall Nut and Almond ID parameters.

3.6. Disentangling the Effect of Production System and Irrigation Strategy on Almond Quality, Depending on the Tree Age

Considering all the results from this experiment, a two-factor principal components analysis was performed for each monitored season, determining what percentage of the data variability could be explained by each factor. For 2019, the principal component analysis determined that more than 91% of the variability in the data set studied could be explained by the production system and the irrigation strategy, with weights of 74% and 17%, respectively (Figure 3A).

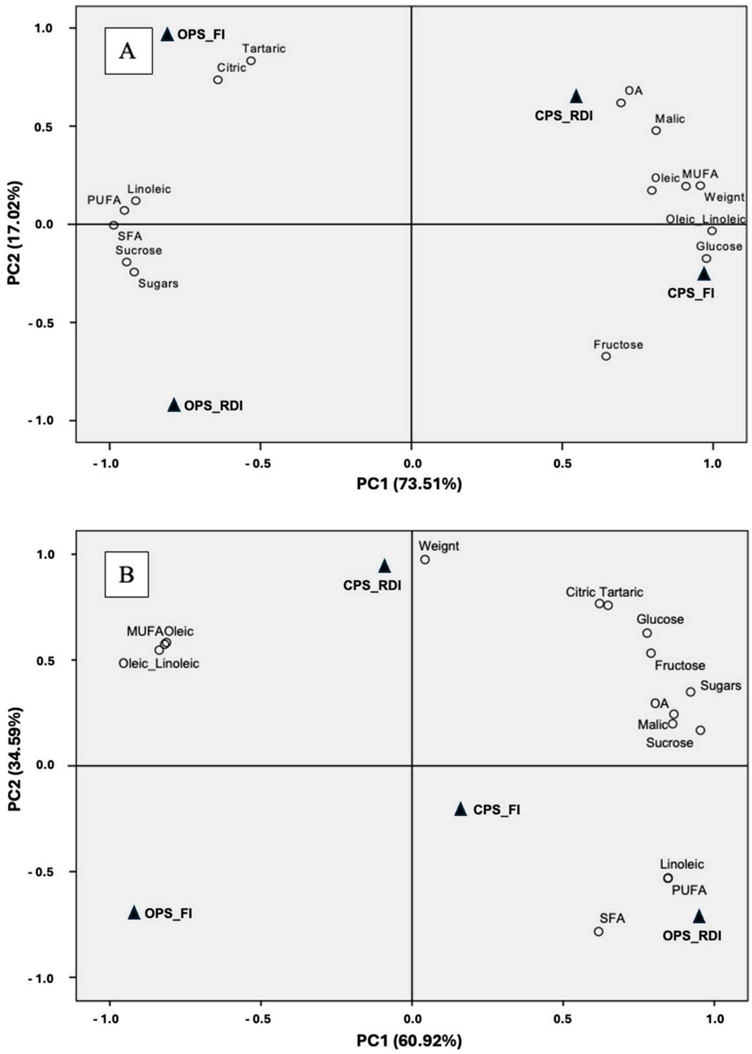

Figure 3. Principal component analysis (PCA) score biplot showing the relationship among physicochemical parameters of raw almonds obtained from tree-years ((**A**), 2019) and seven-years old ((**B**), 2023) trees under conventional (CPS) and organic (OPS) production systems and subjected to full irrigation (FI) and regulated-deficit irrigation (RDI) strategies. Legend: ▲ samples; W = kernel weight; OA = total organic acids; oleic_Linoleic = oleic/linoleic ratio; SFA = saturated fatty acids; MUFA = monounsaturated fatty acids; PUFA = polyunsaturated fatty acids.

In contrast, the same analysis performed for the set of results recorded for 2023 determined that more than 95% of the variability was explained by the irrigation strategy and the production system, with weights of 61% and 34.6%, respectively (Figure 3B).

For 2019, PC1 mainly determined the total organic acids, tartaric, citric, and fructose contents, with a clear separation between the OPS (negative values) and CPS (positive values). Taking into consideration the distribution of significant differences between treatments in 2019 (these being mainly detected for the production system), it could be assumed that PC1 explains the variability as a response to the production system (Figure 3A). In addition, in 2019, PC2 would explain the separation between the FI and RDI. In contrast, by 2023 (Figure 3B), although PC1 continued to play a key role and largely determined the variability of parameters such as weight, glucose content, and certain acids like tartaric, citric, and linoleic acids, PC2 increases the percentage of variability explained; that is, for mature trees, the irrigation factor would increase its importance. The role played by the production system and irrigation strategy in crop development is therefore noteworthy, something already observed in relation to production and vegetative growth. In addition, a factor that could determine the different responses to drought in young and adult trees is related to the root system architecture. Thus, root distribution, root formation, and root development will limit the ability of the crop to respond to stress, as has been recently discussed [48]. According to the quality parameters determined, this largely regulates the composition of the young almond trees. In contrast, the subsequent crop development and its approach to that of mature trees largely mitigates the effects of the production system, with the irrigation rates having the greatest impact on almond production and quality. This fact is worth highlighting, emphasizing the importance of considering alternative organic management strategies, such as implementing a conventional system until the tree reaches the age and size of an adult in full production, for subsequent conversion to an organic system. This could mitigate production losses, achieving optimal vegetative development, and enhance the value of treatments that have an insignificant impact on the almond yield and its quality.

4. Conclusions

The implementation of deficit irrigation strategies together with sustainable agricultural practices such as organic farming can offer significant advantages for almond cultivation. According to our findings, the obtained results allow us to conclude that RDI enhances the main almond quality parameters cultivated under CPSs and OPSs in semi-arid Mediterranean environments. However, comparing both production systems, almond productivity under organic farming is reduced, especially for young trees, with this reduction being mainly linked to a decrease in tree vegetative growth. In addition, we observed a high dependence of crop responses on water stress and production systems dependent on the tree's age. Thus, for young trees, the nut quality is more affected by the production system (CPS or OPS) than the irrigation treatment, whereas for mature almonds (7-years old), the effects of the irrigation strategy is more pronounced. Regarding the improvements obtained under moderate RDI, notable improvements are observed in the TPC, AA, sugars, OA, and PUFA contents, although this response can vary depending on the production system and tree age. Something similar happens when comparing the OPS with the CPS, with significant improvements being observed in these parameters, especially for young trees. Taking into consideration the obtained results, additional research is needed to elucidate the almond response to different soil and water management strategies and the importance of the tree's age; developing similar studies for other cultivars with different degrees of drought resistance and under alternative environmental conditions and water allocations is necessary to narrow down the required action of farmers under future climate change conditions that are singularly exacerbated by water scarcity.

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Conflicts of Interest: The authors declare no conflicts of interest.

References

1. FAOSTAT. Food and Agriculture Organisation of the United Nations. 2025. Available online: https://www.fao.org/faostat/en/#data/QC (accessed on 14 April 2025).
2. ESYRCE. Encuesta Sobre Superficies y Rendimientos de Cultivos. 2024. Available online: https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/informe_esyrce_tendencias_rendimiento_agosto_2024_tcm30-692846.pdf (accessed on 1 May 2025).
3. Arquero, O. *Manual del Almendro*; Consejería de Agricultura, Pesca y Desarrollo Rural: Sevilla, Spain, 2013.
4. Goldhamer, D.A.; Fereres, E. Establishing an almond water production function for California using long-term yield response to variable irrigation. *Irrig. Sci.* **2016**, *35*, 169–179. [CrossRef]
5. García-Tejero, I.F.; Gutiérrez-Gordillo, S.; Souza, L.; Cuadros-Tavira, S.; Durán-Zuazo, V.H. Fostering sustainable water use in almond (Prunus dulcis Mill.) orchards in a semiarid Mediterranean environment. *Arch. Agron. Soil. Sci.* **2019**, *65*, 164–181. [CrossRef]
6. Rubio-Asensio, J.S.; Abbatantuono, F.; Ramírez-Cuesta, J.M.; Hortelano, D.; Ruíz, J.L.; Parra, M.; Martínez-Meroño, R.M.; Intrigliolo, D.S.; Buesa, I. Effects of cover crops and drip fertirrigation in a young almond agroecosystem. *Agronomy* **2022**, *12*, 2606. [CrossRef]
7. Durán-Zuazo, V.H.; Cárceles, B.; Gutiérrez, S.; Benítez, M.; Sacristan, P.; Parra, J.; García-Tejero, I.F. Rethinking irrigated almond and pistachio intensification: A shift towards a more sustainable water management paradigm. *Rev. Cienc. Agrar.* **2021**, *43*, 24–49. [CrossRef]
8. Prgomet, I.; Gonçalves, B.; Domínguez-Perles, R.; Santos, R.; Saavedra, M.J.; Aires, A.; Pascual-Seva, N.; Barros, A. Irrigation deficit turns almond by-products into a valuable source of antimicrobial (poly)phenols. *Ind. Crops Prod.* **2019**, *132*, 186–196. [CrossRef]
9. Mirás-Avalos, J.M.; Gonzalez-Dugo, V.; García-Tejero, I.F.; López-Urrea, R.; Intrigliolo, D.S.; Egea, G. Quantitative analysis of almond yield response to irrigation regimes in Mediterranean Spain. *Agric. Water Manag.* **2023**, *279*, 108208. [CrossRef]
10. Alcon, F.; Egea, G.; Nortes, P. Financial feasibility of implementing regulated and sustained deficit irrigation in almond orchards. *Irrig. Sci.* **2012**, *31*, 931–941. [CrossRef]
11. González-Gómez, L.; Intrigliolo, D.; Rubio-Asensio, J.S.; Buesa, I.; Ramírez-Cuesta, J. Assessing almond response to irrigation and soil management practices using vegetation indexes time-series and plant water status measurements. *Agric. Ecosys. Environ.* **2022**, *339*, 108124. [CrossRef]
12. MAPA. *Análisis de Caracterización de la Producción Ecológica en España. Producción Ecológica. Estadísticas 2024*; Ministerio de Agricultura, Pesca y Alimentación: Madrid, Spain, 2024. Available online: https://www.mapa.gob.es/dam/mapa/contenido/alimentacion/temas/produccion-ecologica/1-estrategias-y-estudios/estudios-de-caracterizacion-de-la-prod.-ecolog./analisisdelacaracterizaciondelaproduccionecologicaenespana2023def.pdf (accessed on 28 February 2025).
13. Aznar, S.J.A.; Belmonte, L.; Velasco, M.J. Caracterización del cultivo del almendro en secano en Andalucía y propuestas de reconversión. *ITEA—Inf. Tec. Econ. Agrar.* **2016**, *112*, 317–335. [CrossRef]
14. Cárceles, R.B.; Durán, Z.V.H.; Herencia, G.J.F.; Lipan, L.; Soriano, M.; Hernández, F.; Sendra, E.; Carbonell, B.A.A.; Gálvez, R.B.; García-Tejero, I.F. Soil Management Strategies in Organic Almond Orchards: Implications for Soil Rehabilitation and Nut Quality. *Agronomy* **2023**, *13*, 749. [CrossRef]
15. Iglesias, I.; Foles, P.; Oliveira, C. El almendro en España y Portugal: Situación, innovación tecnológica, costes, rentabilidad y perspectivas. *Fruticultura* **2021**, *81*, 6–49.
16. de-Magistris, T.; Gracia, A. Consumers' willingness-to-pay for sustainable food products: The case of organically and locally grown almonds in Spain. *J. Clean. Prod.* **2016**, *118*, 97–104. [CrossRef]
17. Egea, G.; González-Real, M.M.; Baille, A.; Nortes, P.A.; Domingo, R. The effects of contrasted deficit irrigation strategies on the fruit growth and kernel quality of mature almond trees. *Agric. Water Manag.* **2009**, *96*, 1605–1614. [CrossRef]
18. Lipan, L.; Martín-Palomo, M.J.; Sánchez-Rodríguez, L.; Cano-Lamadrid, M.; Sendra, E.; Hernández, F.; Burló, F.; Vázquez-Araujo, L.; Andreu, L.; Carbonell-Barrachina, Á.A. Almond fruit quality can be improved by means of deficit irrigation strategies. *Agric. Water Manag.* **2019**, *217*, 236–242. [CrossRef]
19. Lipan, L.; Moriana, A.; López Lluch, D.B.; Cano-Lamadrid, M.; Sendra, E.; Hernández, F.; Carbonell-Barrachina, Á.A. Nutrition quality parameters of almonds as affected by deficit irrigation strategies. *Molecules* **2019**, *24*, 2646. [CrossRef]
20. USDA. *Soil Taxonomy. A Basic System of Soil Classification for Making and Interpreting Soil Surveys*, 2nd ed.; USDA: Washington, DC, USA, 1999. Available online: https://www.nrcs.usda.gov/sites/default/files/2022-06/Soil%20Taxonomy.pdf (accessed on 6 June 2024).

21. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration. FAO Irrigation and Drainage Paper (56)*; FAO: Rome, Italy, 1998.
22. García-Tejero, I.F.; Hernández, A.; Rodríguez, V.; Ponce, J.; Ramos, V.; Muriel, J.; Durán-Zuazo, V. Estimating almond crop coefficients and physiological response to water stress in semiarid environments (SW Spain). *J. Agric. Sci. Technol.* **2015**, *17*, 1255–1266.
23. OJEU. Regulation (EU) 2018/848 of the European Parliament and of the Council of 30 May 2018. *Off. J. Eur. Union L* **2018**, *150*, 1–92.
24. BOJA. ORDEN de 20 de marzo de 2012, Reglamento específico de producción integrada de almendro. *Boletín Oficial de la Junta de Andalucía*, 29 March 2012.
25. Cano-Lamadrid, M.; Hernández, F.; Corell, M.; Burló, F.; Legua, P.; Moriana, A.; Carbonell-Barrachina, Á.A. Antioxidant capacity, fatty acids profile, and descriptive sensory analysis of table olives as affected by deficit irrigation. *J. Sci. Food Agric.* **2016**, *97*, 444–451. [CrossRef] [PubMed]
26. Brand-Williams, W.; Cuvelier, M.E.; Berset, C. Use of a free radical method to evaluate antioxidant activity. *LWT Food Sci. Technol.* **1995**, *28*, 25–30. [CrossRef]
27. Tuberoso, C.; Kowalczyk, A.; Sarritzu, E.; Cabras, P. Determination of antioxidant compounds and antioxidant activity in comercial oilseeds for food use. *Food Chem.* **2007**, *103*, 1494–1501. [CrossRef]
28. Klonsky, K.; Tourte, L. Organic Agricultural Production in the United States: Debates and Directions. *Am. J. Agric. Econ.* **1998**, *80*, 1119–1124. [CrossRef]
29. Massantini, R.; Frangipane, M.T. Progress in Almond Quality and Sensory Assessment: An Overview. *Agriculture* **2022**, *12*, 710. [CrossRef]
30. Reganold, J.; Wachter, J. Organic agriculture in the twenty-first century. *Nat. Plants* **2016**, *2*, 15221. [CrossRef]
31. Goldhamer, D.A.; Viveros, M. Effects of preharvest irrigation cutoff durations and postharvest water deprivation on almond tree performance. *Irrig. Sci.* **2000**, *19*, 125–131. [CrossRef]
32. López-López, M.; Espadafor, M.; Testi, L.; Lorite, I.J.; Orgaz, F.; Fereres, E. Water use of irrigated almond trees when subjected to water deficits. *Agric. Water Manag.* **2018**, *195*, 84–95. [CrossRef]
33. Karat, F.E. Organic vs conventional almond: Market quality, fattuy acid composition and volatile aroma. *Appl. Ecol. Environ. Res.* **2019**, *17*, 7783–7793. [CrossRef]
34. Bolling, B.W.; Dolnikowski, G.; Blumberg, J.B.; Chen, C.Y.O. Polyphenol content and antioxidant activity of California almonds depend on cultivar and harvest year. *Food Chem.* **2010**, *122*, 819–825. [CrossRef]
35. Dixon, R.A.; Paiva, N.L. Stress-Induced Phenylpropanoid Metabolism. *Plant Cell* **1995**, *7*, 1085–1097. [CrossRef]
36. García-Martínez, M.D.; Esteve Ciudad, P.; Gómez Tenorio, M.Á.; Raigón Jiménez, M.D. Effect of Organic Farming Techniques on the Quality of Almond Fat. *Horticulturae* **2025**, *11*, 135. [CrossRef]
37. López-Bucio, J.; Nieto-Jacobo, M.F.; Ramírez-Rodríguez, V.; Herrera-Estrella, L. Organic acid metabolism in plants: From adaptive physiology to transgenic varieties for cultivation in extreme soils. *Plant Sci.* **2000**, *160*, 1–13. [CrossRef] [PubMed]
38. Venkatachalam, M.; Sathe, S.K. Chemical composition of selected edible nut seeds. *J. Agric. Food Chem.* **2006**, *54*, 4705–4714. [CrossRef] [PubMed]
39. Gutiérrez, G.S.; Durán-Zuazo, V.H.; Hernández-Santana, V.; Ferrera-Gil, F.; García-Escalera, A.; Amores-Agüera, J.J.; García-Tejero, I.F. Cultivar dependent impact on yield and its components of young almond trees under sustained-deficit irrigation in semi-arid environments. *Agronomy* **2020**, *10*, 733. [CrossRef]
40. Lipan, L.; Cano-Lamadrid, M.; Hernández, F.; Sendra, E.; Corell, M.; Vázquez-Araújo, L.; Moriana, A.; Carbonell-Barrachina, Á.A. Long-Term Correlation between Water Deficit and Quality Markers in HydroSOStainable Almonds. *Agronomy* **2020**, *10*, 1470. [CrossRef]
41. Stitt, M.; Zeeman, S.C. Starch turnover: Pathways, regulation and role in growth. *Curr. Opin. Plant Biol.* **2012**, *15*, 282–292. [CrossRef]
42. Lemoine, R.; La Camera, S.; Atanassova, R.; Dédaldéchamp, F.; Allario, T.; Pourtau, N.; Bonnemain, J.L.; Laloi, M.; Coutos-Thévenot, P.; Maurousset, L.; et al. Source-to-sink transport of sugar and regulation by environmental factors. *Front. Plant Sci.* **2013**, *4*, 272. [CrossRef] [PubMed]
43. Rolland, F.; Baena-Gonzalez, E.; Sheen, J. Sugar sensing and signaling in plants: Conserved and novel mechanisms. *Annu. Rev. Plant Biol.* **2006**, *57*, 675–709. [CrossRef]
44. Kodad, O.; Estopañan, G.; Juan, T.; R. Socias i Company. Genetic diversity in an almond germplasm collection: Application of a chemometric approach. *Acta Hortic.* **2013**, *976*, 237–242. [CrossRef]
45. Barreira, J.; Casal, S.; Ferreira, I.; Peres, A.; Pereira, J.; Oliveira, M. Supervised chemical pattern recognition in almond (Prunus dulcis) portuguese PDO cultivars: PCA-and LDA-based triennial study. *J. Agric. Food Chem.* **2012**, *60*, 9697–9704. [CrossRef]
46. Ros, E. Health benefits of nut consumption. *Nutrients* **2010**, *2*, 652–682. [CrossRef]

47. Chen, C.Y.; Lapsley, K.; Blumberg, J. A nutrition and health perspective on almonds. *J. Sci. Food Agric.* **2006**, *86*, 2245–2250. [CrossRef]
48. Kalra, A.; Goel, S.; Elias, A.A. Understanding role of roots in plant response to drought: Way forward to climate-resilient crops. *Plant Genome* **2023**, *17*, e20395. [CrossRef] [PubMed]