Mechanical Harvesting and Irrigation Strategy Responses on 'Arbequina' Olive Oil Quality

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SUMMARY. This study describes the effects of mechanical harvesting and irrigation on quality in 'Arbequina' olive oil (*Olea europaea* L.). Irrigation treatments included a control, deficit irrigation (DI) during pit hardening, and subsurface deficit irrigation (SDI). Results showed that mechanical harvesting damaged the olives and reduced olive oil quality by increasing free fatty acids (FFAs) and peroxide value, and by decreasing fruitiness, stability, bitterness, and pungency. DI resulted in increased fruit dry weight and oil content, which could be explained by their reduced crop load (9.3% of crop reduction for DI and 23.9% for SDI). DI did not affect olive oil characteristics, whereas SDI increased stability, fruitiness, and bitterness, and decreased polyunsaturated fatty acid (PUFAs). In conclusion, mechanical harvesting tended to damage the fruit, resulting in lower quality olive oil, the DI strategy neither affected fruit nor olive oil characteristics, whereas the SDI strategy positively affected oil quality when greater water restrictions were applied.

In recent years, the increasing consumption of olive oil has boosted the planting of intensive and superintensive orchard systems to achieve competitive production costs (Arbonés et al., 2014). Continuous mechanical harvesting is a key management practice in intensive and superintensive groves. Some studies have shown that this mechanical operation may cause internal fruit damage, leading to a fast reduction of quality in several varieties (Dag et al., 2008; Morales-Sillero and García, 2015; Yousfi et al., 2012). However, other researchers have reported that early harvesting and improving fruit management through mechanization

result in a better oil quality (Campos et al., 2013).

The success of superhigh-density orchards relies on the availability of the required amount of irrigation water, which is a scarce resource in many areas. In terms of crop management, DI strategies have demonstrated their feasibility for yield improvement in arid and semiarid areas (Gómez-del-Campo et al., 2014; Palese et al., 2010). Emerging irrigation technologies such as subsurface irrigation can also optimize water efficiency by reducing soil evaporation—a promising water-saving strategy (Rufat et al., 2014). Nevertheless, the optimal degree of water restriction should be assessed carefully to avoid an impairment of yield and quality (Girona

et al., 2002) or even a reduction in the following year's blooming (Alegre et al., 2002).

It is well known that irrigation modulates plant water stress and affects olive fruit ripening as well as oil yield and quality. Hernández et al. (2009) reported that fatty acid composition of 'Arbequina' and 'Picual' depends on the expression of three genes that are related to external factors, including water supply. In addition, Vossen et al. (2008), working on an irrigation trial with 'Arbequina' in California, reported an increase of PUFAs and a reduction in monounsaturated fatty acids (MUFAs) when irrigation increased, which is in agreement with the results of Tovar et al. (2001) who studied 'Arbequina' under different irrigation conditions in Catalonia. However, this was not observed in 'Frantoio', which was irrigated using a subsurface system at any of the irrigation doses used (Caruso et al., 2014).

Several studies suggest that olive oil composition depends on both irrigation and the ripening process. In this sense, total polyphenol content is related to such factors, increasing olive oil bitterness and oil stability (Motilva et al., 2000; Tovar et al., 2001) as well as flavor composition (Caporaso, 2016). Caruso et al. (2014), analyzed the effects of irrigation on the lipoxygenase pathway compounds and reported a significant increase of alcohol and ester volatiles in greater irrigation doses, suggesting a clear effect on sensory characteristics of olive oil, although no sensory analysis was performed to confirm that possibility.

Currently, there are few published studies that combine the effect of irrigation regime and harvest

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
29.5735	fl oz	mL	0.0338
0.3048	ft	m	3.2808
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg·ha ⁻¹	0.8922
0.0179	lb/inch	kg·mm ⁻¹	55.9974
1	mmho/cm	dS·m ⁻¹	1
28.3495	oz	g	0.0353
1	ppm	mg·kg ⁻¹	1
(°F - 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

method as key techniques for production and quality management of superintensive crop growth of olive oil orchards in semiarid conditions. Therefore, this work aimed to study the impact of several of the most widespread irrigation strategies on 'Arbequina' olive oil quality, as well as the effects caused by mechanical harvesting in irrigated superintensive crop-growing conditions.

Materials and methods

EXPERIMENTAL SITE AND MANAGEMENT. The trial was conducted on a commercial adult 'Arbequina' olive plot in Torres de Segre (Lleida, Spain) during three consecutive years: 2010, 2011, and 2012. The climate is a continental Mediterranean-type, with an average rainfall of 350 mm/year, distributed irregularly. The trees were planted in Summer 2002 at 4.5×2.2 m, resulting in a density of 1010 trees/ha. The soil was moderately deep, calcareous with a pH of 8, and had an organic matter content of 1.5%, with a medium texture (loamy) and an electrical conductivity (1:5) of $2.82 \text{ dS}\cdot\text{m}^{-1}$ (resulting from the presence of gypsum). The irrigation system consisted of auto-compensated drip emitters every 60 cm and a water flow rate of $2.3 \text{ L}\cdot\text{h}^{-1}$, used for both surface and subsurface systems. Irrigation water came from the Segre River. Water conductivity was, on average, $0.9 \text{ dS}\cdot\text{m}^{-1}$, with chloride at $2.25 \text{ meq}\cdot\text{L}^{-1}$, sodium at $2.14 \text{ meq}\cdot\text{L}^{-1}$, boron less than 0.15 ppm, and nitrate less than 9 ppm.

The trial consisted of three replicates distributed in randomized blocks. Each elementary plot had 18 trees distributed in three adjacent rows, in which the four central trees were monitored.

HARVESTING AND SAMPLING. Mechanical harvesting was carried out by means of an over-the-row harvester (model G140 SW; Gregoire®, Chateaubernard, France). The harvester passed over the four olive trees and the fruit were collected into a bin. Manual harvesting of samples were taken randomly the day before mechanical harvesting from the same four-tree plots. Sample size was 3 kg of fruit per plot and harvesting method. Fruit were transported just after harvest, stored in a cold room (5°C), and processed within the 12 h after harvest. Harvest dates were 25 Nov. 2010, 28 Nov. 2011, and 30 Nov. 2012.

IRRIGATION TREATMENTS. Three irrigation treatments were tested. The control treatment trees were fully irrigated during the whole season, according to the FAO methodology, based on the water balance (Allen et al., 1998). Trees under the DI strategy were irrigated as the control trees from March to June, but only 25% of the dose was subsequently applied to the control group during pit hardening (beginning of July until the beginning of September), followed by full irrigation from the beginning of September to the end of October. The SDI strategy consisted of applying 70% of control requirements from March to June, 25% from July to the beginning of September, and again 70% of total requirements until the end of October because of less soil evaporation. More details are reported in Rufat et al. (2014). All plots were fertilized weekly from May to October using $50 \text{ kg}\cdot\text{ha}^{-1}$ nitrogen (N) with N-32 solution (16% amide, 8% ammonium, 8% nitrate; Compo Expert Spain, Barcelona, Spain) and $100 \text{ kg}\cdot\text{ha}^{-1}$ potassium (K_2O) per year.

OLIVE OIL EXTRACTION. Fruit were processed using an Abencor system (MC2; Ingenierias y Sistemas, Seville, Spain). This method reproduces the industrial process at a laboratory scale, including a metallic hammer mill (6-mm crusher sieve), a thermo-beater at room temperature (20°C) for 30 min, a pulp centrifuge, an oil vertical centrifuge at 2000 rpm, and a natural decanter. Olive oil samples were put into dark glass bottles and split into two groups; one was preserved at 4°C before sensory analysis (1 week after extraction) and the other was stored at -20°C until chemical analysis (1 month later).

FRUIT CHARACTERISTICS, OLIVE OIL CONTENT, AND QUALITY ANALYSIS. Fruit maturity index (MI) was measured as proposed by Frías et al. (1991), moisture was analyzed in an oven (105°C), and oil content was determined on the dried sample by nuclear magnetic resonance (Mars60; Oxford Instruments, Abingdon, UK) and referred on the basis of dry fruit weight. Olive oil physicochemical analyses (FFAs, peroxide value, ultraviolet absorption characteristics at 232 and 270 nm, and oil stability) were performed according to official methods (European Union Standard

Methods, 1991). The results are expressed as percentage of oleic acid, milliequivalents of active oxygen (O_2) per kilogram oil, and specific extinction coefficient at 232 and 270 nm (K_{232} and K_{270} , respectively). Stability was expressed as the oxidation induction time (in hours) measured according to Laubli and Bruttel (1986) using the Rancimat method (model Rancimat-679; Metrohm Co., Basel, Switzerland), analyzing 2.5 g of olive oil sample at 120°C with an air flow of 20 L/h. Fatty acid composition was determined by gas chromatography as fatty acid methyl esters, according to European Union Standard Methods (1991). Total phenol content was obtained using the method described by Vázquez-Roncero et al. (1973). An oil sample (10 g) was dissolved in 50 mL hexane and extracted with methanol/water (60:40 v/v, $3 \times 10 \text{ mL}$). The aqueous fractions were collected in a volumetric flask. Total phenols were measured colorimetrically at 725 nm after adding the Folin-Ciocalteu reagent to the extract.

The sensory analysis was carried out by the Official Tasting Panel of Virgin Olive Oils of Catalonia according to European Union Standard Methods (1991). This panel relies on ISO (International Organization for Standardization) 17025 accreditation and is recognized by the International Olive Oil Council. Each oil sample was analyzed by eight tasters who scored the official sensory descriptors using a 10-cm open scale anchored on zero. In addition, the presence of secondary sensory attributes was determined by the percentage of panelists able to perceive each odor note using an open generic profile (Guerrero et al., 2001; Romero-Aroca et al., 1999).

DATA ANALYSIS. The data were subjected to analysis of variance, multivariate analysis of variance, mixed-model analysis, and principal component analysis (PCA) using SAS software (version 9.2; SAS Institute, Cary, NC).

Results

APPLIED WATER AND EVAPOTRANSPIRATION REPOSITION BY IRRIGATION. The seasonal irrigation water for each irrigation treatment during the three crop seasons is shown in Table 1. Irrigation in the control treatment ranged from 338 mm in 2010 to 475 mm in 2011, whereas

Table 1. Total water applied in 2010, 2011 and 2012 cropping seasons and olive and oil yield for each irrigation treatment: control, deficit irrigation (DI), and subsurface deficit irrigation (SDI).

Irrigation treatment	Water applied (mm/yr) ^z			Olive yield (kg/tree) ^z			Oil yield (kg/tree)		
	2010	2011	2012	2010	2011	2012	2010	2011	2012
Control	338	475	422	6.43 a ^y	12.84 a	5.67 b	1.56 a	3.27 a	1.19 a
DI	193	303	240	4.39 b	11.34 a	6.93 a	1.16 ab	2.61 ab	1.46 ab
SDI	118	260	221	4.72 b	8.71 b	5.56 b	1.31 b	2.15 b	1.26 b
ETo (mm)	953.5	1,006.1	1,012.4						
Seasonal rainfall Apr.–Oct. (mm)	280.1	165.1	243.8						
Kca Control	0.45	0.53	0.50						
Kca DI	0.30	0.36	0.32						
Kca SDI	0.22	0.31	0.30						
Kca DI/Control	0.66	0.68	0.64						
Kca SDI/Control	0.49	0.59	0.60						

^z1 mm = 0.0394 inch, 1 kg = 2.2046 lb.

^yMeans within a column followed by the same letter are not significantly different by Tukey's honest significant difference test at $P \leq 0.05$.

ETo = reference evapotranspiration; Kca = actual crop coefficient.

Table 2. Significance of repeated-measurements model (multivariate analysis of variance) for olive production parameters and fruit characteristics (probability values), considering year as a repeated factor.

	Irrigation ^z ($P > F$)	Block ^z ($P > F$)	Year ($P > F$)	Year $\times$ irrigation ^y ($P > F$)	Year $\times$ block ^y ($P > F$)
Olive yield	<0.001*	0.696	<0.001*	0.148	0.274
Oil yield	0.004*	0.777	<0.001*	0.392	0.301
Maturity index	0.332	0.319	0.011*	0.028*	0.233
Fruit fresh weight	0.254	0.121	0.034*	0.076	0.395
Fruit dry weight	0.001*	0.019*	0.002*	0.181	0.074
Pit weight	0.220	0.395	0.001*	0.024*	0.296
Flesh/pit ratio	0.119	0.074	0.191	0.139	0.206
Oil content	0.002*	0.380	0.001*	0.166	0.458
Fruit water content	0.738	0.437	0.007*	0.343	0.402

^zAccording to the F test.

^yAccording to Roy's max root criteria.

*Denotes a significant effect or interaction at $P \leq 0.05$.

Table 3. Average olive yield, oil content, and fruit characteristics related to irrigation treatments: control, deficit irrigation (DI), and subsurface deficit irrigation (SDI).

	Irrigation treatment		
	Control	DI	SDI
	(mean $\pm$ SD)		
Olive yield (kg/tree) ^z	9.26 $\pm$ 4.22 a ^y	9.14 $\pm$ 2.99 a	7.14 $\pm$ 2.50 b
Oil yield (kg/tree)	2.14 $\pm$ 1.10 a	2.13 $\pm$ 1.11 b	1.76 $\pm$ 1.07 b
Oil content (% dry basis)	48.00 $\pm$ 0.59 b	49.30 $\pm$ 0.67 ab	51.10 $\pm$ 0.43 a
Maturity index	2.07 $\pm$ 0.36	1.95 $\pm$ 0.16	2.15 $\pm$ 0.56
Fruit fresh weight (g) ^z	1.70 $\pm$ 0.10	1.78 $\pm$ 0.10	1.84 $\pm$ 0.11
Fruit dry weight (g)	0.82 $\pm$ 0.04 b	0.84 $\pm$ 0.05 ab	0.89 $\pm$ 0.04 a
Pit weight (g)	0.41 $\pm$ 0.03	0.46 $\pm$ 0.03	0.44 $\pm$ 0.02
Flesh/pit ratio (g·g ⁻¹)	4.16 $\pm$ 0.14	3.90 $\pm$ 0.11	4.22 $\pm$ 0.15
Fruit water content (%)	51.60 $\pm$ 1.69	52.50 $\pm$ 1.98	50.80 $\pm$ 1.83

^z1 kg = 2.2046 lb, 1 g = 0.0353 oz.

^yMeans within a column followed by the same letter are not significantly different by Tukey's honest significant difference test at $P \leq 0.05$.

irrigation decreased to 64% and 68% in the DI treatment, and to 49% and 60% in the SDI treatment for the same 2 years in comparison with control trees. Seasonal rainfall was scarce (165 to 250 mm) and effective rainfall was negligible compared with reference

evapotranspiration (ETo; effective rainfall range, 55–90 mm). Actual crop coefficient (Kca) was calculated as (Irrigation + Effective rainfall)/ETo, reaching maximum values for the control treatment (about 0.5) and descending to 0.30 and 0.36

for DI, and even lower for SDI (0.22 and 0.31). Water savings were obtained using the deficit irrigation strategies: 35% in DI and 44% in SDI.

FRUIT TRAITS AND YIELD COMPONENTS. The multivariate analysis of variance on repeated measurements (when year was the repeated factor) showed significant differences as the result of irrigation treatment and year effects on global fruit traits (Table 2). Deficit irrigation strategies tended to produce larger fruit that were richer in oil than those from the control treatment (Table 3). Pit weight, flesh-to-pit ratio, and fruit water content showed no significant differences between irrigation strategies. Within years, fruit were harvested at the same MI, without significant differences between treatments. However, when yield was greater (year 2011), fruit of deficit irrigation strategies exhibited a greater MI than control fruit. On the other hand, total crop load correlated inversely to fruit weight ($r = -0.631$,

$P = 0.001$), pit weight ($r = -0.717$, $P < 0.001$), dry fruit weight ($r = -0.692$, $P < 0.001$), and MI ($r = -0.60$, $P = 0.001$).

FATTY ACID COMPOSITION. The irrigation strategies affected the fatty acid composition of the olive oil (Table 4). Average PUFAs were significantly less using the SDI strategy (11.9% vs. 13.2% in DI and 12.9% in control), affecting both linoleic (C18:2) and linolenic (C18:3) acids. MUFAs showed no significant differences between treatments, because oleic acid (C18:1) averaged 65% in all treatments, whereas palmitoleic acid (C16:1) was 1.4% in SDI, 1.6% in DI, and 1.8% in control treatments. No significant interaction between irrigation strategy and year was observed with respect to fatty acids composition (Table 4).

OLIVE OIL PHYSICOCHEMICAL CHARACTERISTICS. FFAs were related significantly to harvesting system and year particularities (Table 4), without significant changes resulting from irrigation strategies. Mechanical harvesting increased FFAs from 0.12% to 0.18% on average (Table 5), although such a variation is not relevant from the official regulation point of view (COI/T.15/NC No 3/REV.10–Trade Standard Applying to Olive Oils and Olive-Pomace oils. 2015). In addition, peroxide value did not change between irrigation strategies, but significant differences were observed with respect to harvesting method and year (Table 4). In fact, mechanical harvesting increased peroxides by at least 2 meq·kg⁻¹ O₂ compared with the manual system (Table 5). Polyphenol content was also affected by harvesting method and irrigation, decreasing when olives were harvested mechanically and when irrigation rate increased. Year effect on polyphenols was related to changes in MI (1.8 in 2011 and 2.6 in 2012), suggesting other complementary effects that could be related to annual variations in crop load and Kca. Olive oil stability was affected by harvesting system, irrigation, and year conditions, without significant interactions among these factors (Table 4). Mechanical harvesting resulted in a significant reduction of stability from 11.9 to 8.3 h, which is a relevant variation for quality in ‘Arbequina’ oil. As for irrigation, the SDI strategy promoted greater stability (45% more) than the other treatments (SDI scored

12.9 h; DI, 8.6 h; and control, 8.9 h) (Table 5).

SENSORY CHARACTERISTICS. Harvesting method strongly affected sensory characteristics. Mechanical harvesting resulted in olive oil lower in fruitiness, cut grass perception, bitterness, pungency, and astringency, whereas sweetness was always greater (Table 5). In addition, a significant harvest system-by-year interaction was observed for all descriptors (Table 6). This can be explained as the result of crop load and MI, with increasing susceptibility to damage when fruit were larger and more mature. In 2012, which demonstrated a low fruit yield (Table 1), fruit were larger and riper, and the differences resulting from the harvesting systems were greatest. Irrigation treatment affected the sensory profile significantly (Table 6). Deficit irrigation strategies resulted in oils more pungent, bitter, and astringent than control oil (Table 5). This response is in accordance with a significant increase in total phenols when irrigation was restricted. Also, olfactory attributes changed significantly between irrigation treatments, with oils with more fruitiness and cut grass perception obtained when deficit irrigation was applied. However, the irrigation-by-year effect was significant for fruitiness and cut grass perception in the sense that differences in intensity of these attributes between control and deficit treatments were greater in the year with a lesser water supply, as would be expected. On the other hand, the irrigation-by-harvest system interaction was only significant for the cut grass attribute, with a greater reduction in the control irrigation level.

Discussion

Interpretation of the effects of the treatments (harvest method, irrigation strategy, and year) on the studied variables was carried out by PCA. After a preliminary analysis, the most relevant variables in the first two PCA components were closely related to harvest method and irrigation strategies—namely, the oil sensory characteristics, peroxides, polyphenols, fatty acid composition, and, to a lesser extent, yield and MI. The biplot of loadings, in the space defined by the first two principal components, explains 67.4% of the overall variance of results (Fig. 1). The first

Table 4. Results of significance of analysis of variance mixed model ($P > F$) for olive oil physicochemical parameters.

Effects	FFA ($P > F$)	PV ($P > F$)	K ₂₃₂ ($P > F$)	K ₂₇₀ ($P > F$)	Stability ($P > F$)	Polyphenols ($P > F$)	SAT ($P > F$)	MUFA ($P > F$)	PUFA ($P > F$)
Fixed									
Harvest	0.018	0.014	0.606	0.007	0.001	<0.001	0.323	0.183	0.103
Irrigation	0.579	0.164	0.889	0.370	0.004	0.001	0.654	0.320	0.006
Random									
Year	<0.001	0.027	0.255	<0.001	0.014	<0.001	<0.001	0.002	<0.001
Harvest × Irrigation	0.146	0.708	0.934	0.769	0.786	0.456	0.447	0.392	0.399
Harvest × Year	0.023	0.230	0.456	0.345	0.231	0.657	0.426	0.176	0.265
Irrigation × Year	0.579	0.331	0.342	0.624	0.113	0.213	0.303	0.281	0.256
Block	0.758	0.179	0.932	0.436	0.092	0.541	0.730	0.524	0.006

FFA = free fatty acids; PV = peroxide value; K₂₃₂ = ultraviolet absorption at 232 nm; K₂₇₀ = ultraviolet absorption at 270 nm; SAT = saturated fatty acids; MUFA = monounsaturated fatty acids; PUFA = polyunsaturated fatty acids.

Table 5. Physicochemical characteristics of olive oil and sensory scores of oil related to irrigation [control, deficit irrigation (DI), and subsurface deficit irrigation (SDI)] and harvesting method treatments.

Physicochemical characteristic	Irrigation					
	Control		DI		SDI	
	Harvesting					
	Manual	Mechanical	Manual	Mechanical	Manual	Mechanical
	(mean ± SD)					
FFA (% oleic acid)	0.13 ± 0.02	0.18 ± 0.02	0.12 ± 0.02	0.18 ± 0.02	0.15 ± 0.02	0.17 ± 0.02
Palmitic acid C16:0 (%)	19.59 ± 3.22	16.24 ± 1.61	19.26 ± 4.19	17.61 ± 2.26	20.01 ± 4.09	17.03 ± 1.49
Palmitoleic acid C16:1 (%)	1.75 ± 0.50	1.86 ± 0.31	1.51 ± 0.35	1.59 ± 0.29	1.35 ± 0.32	1.38 ± 0.25
Stearic acid C18:0 (%)	1.75 ± 0.38	1.66 ± 0.36	1.66 ± 0.29	1.73 ± 0.25	2 ± 0.27	1.89 ± 0.24
Oleic acid C18:1 (%)	63.82 ± 1.29	66.07 ± 1.59	64.3 ± 1.83	65.02 ± 1.00	64.42 ± 2.23	66.82 ± 1.08
Linoleic acid C18:2 (%)	11.69 ± 1.99	12.82 ± 1.13	12.42 ± 1.99	12.55 ± 1.48	11.25 ± 1.54	11.49 ± 0.99
Linolenic acid C18:3 (%)	0.62 ± 0.19	0.69 ± 0.15	0.72 ± 0.18	0.7 ± 0.14	0.57 ± 0.15	0.58 ± 0.09
Saturated	21.62 ± 3.59	18.13 ± 1.81	21.15 ± 4.41	19.60 ± 2.37	18.58 ± 9.16	18.98 ± 1.72
MUFA	65.83 ± 1.70	67.92 ± 1.56	65.92 ± 2.08	66.62 ± 1.17	65.75 ± 2.46	68.22 ± 1.19
PUFA	12.30 ± 2.20	13.53 ± 1.27	13.13 ± 2.16	13.23 ± 1.64	11.80 ± 1.69	12.07 ± 1.07
Peroxide value [O ₂ (meq·kg ⁻¹)] ^z	5.00 ± 0.89	7.83 ± 0.60	6.00 ± 1.03	8.10 ± 0.78	5.00 ± 0.93	7.07 ± 0.48
K ₂₃₂	1.52 ± 0.08	1.74 ± 0.04	1.59 ± 0.08	1.67 ± 0.07	1.52 ± 0.08	1.67 ± 0.06
K ₂₇₀	0.10 ± 0.00	0.10 ± 0.01	0.10 ± 0.00	0.09 ± 0.01	0.12 ± 0.01	0.10 ± 0.01
Stability (h at 120 °C)	10.8 ± 0.56 Ba ^y	7.00 ± 0.89 b	10.40 ± 0.55 Ba	6.87 ± 0.97 b	14.64 ± 1.04 Aa	11.12 ± 1.46 b
Polyphenols (mg·kg ⁻¹) ^z	108.2 ± 17.3 Ba	95.2 ± 12.3 b	130.9 ± 16.4 Ba	106 ± 18.3 b	126 ± 17.1 Aa	110.2 ± 15.7 b
Fruitiness	5.73 ± 0.15 Ba	4.57 ± 0.56 b	5.84 ± 0.24 Ba	4.75 ± 0.52 b	6.18 ± 0.09 Aa	5.75 ± 0.25 b
Bitterness	3.70 ± 0.16 Ba	2.67 ± 0.37 b	3.72 ± 0.21 Ba	2.98 ± 0.35 b	4.72 ± 0.27 Aa	4.32 ± 0.35 b
Pungency	4.21 ± 0.10 Ba	3.55 ± 0.48 b	4.84 ± 0.22 ABa	4.05 ± 0.42 b	5.22 ± 0.18 Aa	4.92 ± 0.24 b
Astringency	2.06 ± 0.17 Ba	1.18 ± 0.46 b	2.31 ± 0.15 Ba	1.33 ± 0.37 b	2.83 ± 0.29 Aa	2.65 ± 0.29 b
Cut grass	3.54 ± 0.13	1.92 ± 0.73	3.58 ± 0.22	2.16 ± 0.60	3.94 ± 0.12	3.48 ± 0.22
Sweetness	4.63 ± 0.18 Ab	4.90 ± 0.15 a	4.55 ± 0.13 Ab	5.03 ± 0.15 a	4.27 ± 0.19 B	4.28 ± 0.19

^z1 kg = 2.2046 lb, (1.8 $\times$ °C) + 32 = °F, 1 mg·kg⁻¹ = 1 ppm.

^yUppercase letters indicate differences between irrigation treatments. Lowercase letters indicate differences between harvesting systems according to Tukey's honest significant difference test ($P < 0.05$). When interactions were significant (Table 4), no mean differences test was done for main effects.

FFA = free fatty acids; MUFA = monounsaturated fatty acids; PUFA = polyunsaturated fatty acids; K₂₃₂ = ultraviolet absorption at 232 nm; K₂₇₀ = ultraviolet absorption at 270 nm.

Table 6. Results of significance of analysis of variance mixed model for olive oil sensory attributes.

Model	Fruitiness	Cut grass	Bitterness	Pungency	Sweetness	Astringency
$P > F$	<0.001	<0.001	<0.001	<0.001	0.005	<0.001
R^2	0.831	0.871	0.812	0.831	0.610	0.822
Effects ($P > F$)						
Harvest	<0.001	<0.001	<0.001	0.007	0.036	0.003
Irrigation	0.001	0.006	<0.001	<0.001	0.001	<0.001
Year	<0.001	0.002	<0.001	<0.001	0.395	0.002
Harvest $\times$ Irrigation	0.160	0.047	0.204	0.395	0.276	0.1090
Harvest $\times$ Year	<0.001	<0.001	<0.001	0.005	0.030	0.003
Irrigation $\times$ Year	0.042	0.031	0.204	0.721	0.715	0.476
Block	0.169	0.068	0.006	0.002	0.065	0.007

component (54.2% of total variance) is clearly associated with overlapping effects of harvest method and irrigation strategy. The observed association between irrigation strategies and fruit weight and yield can be explained by the differences in crop load (Fig. 2). In fact, crop load in SDI was less than control, imposing a significant yield limitation. This can be explained in terms of physiologic production cost or oil yield per unit of

water used. Fruit water cost (or water productivity) was less in the control treatment (4.3 kg·mm⁻¹) than in the DI (6.6 kg·mm⁻¹) and SDI treatments (7.6 kg·mm⁻¹), as reported by Rufat et al., (2014), indicating the well-known plant adaptive behavior to water status progressively reducing crop load in response to water reduction. This is in agreement with the results obtained by Serman et al. (2011), who worked on 'Arbequina' in

superhigh-density orchards in Argentina, and with Dabbou et al. (2011), who studied irrigation doses in 'Koroneiki' in Tunisia.

Regarding harvest method effects, the increase in FFAs and peroxide value observed in the mechanically harvested fruit suggests significant damage to the olives. The same effect was reported by Yousfi et al. (2012), who compared manual harvesting with mechanical over-the-row harvesting in

Fig. 1. Biplot of two first principal components (PC 1 and PC 2) analysis of selected variables for olive oil physicochemical and sensory analysis. Principal component analysis includes harvest method and irrigation treatments [control, deficit irrigation (DI), and subsurface deficit irrigation (SDI)]. PUFA, polyunsaturated fatty acids; MUFA, monounsaturated fatty acids.

Fig. 2. Olive oil yield for the different irrigation strategies [control, deficit irrigation (DI), and subsurface deficit irrigation (SDI)] and years. Uppercase letters indicate differences between years within each irrigation level ($P < 0.05$). Lowercase letters indicate irrigation effects within each year ($P < 0.05$); 1 kg·ha⁻¹ = 0.8922 lb/acre.

‘Arbequina’ under superhigh-density system conditions. Mechanical harvest caused fruit damage, with the fruit sustaining rapid deterioration, losing polyphenols and stability. These trends are in agreement with the

results obtained by Dag et al. (2012), who reported a shorter shelf life for oils from mechanically harvested fruit. Because of fruit damage, sensory quality was affected too, resulting in oils with lesser fruitiness and

bitterness. Other research (Vichi et al., 2009) reported a similar trend in virgin oil sensory characteristics when fruit were damaged, resulting from microbiologic degradation of olives and the generation of volatile phenols responsible for off flavors.

Sharp changes in virgin oil characteristics were observed between the control and SDI strategies, with a significant olive oil improvement compared with the SDI treatment. However, the DI treatment had a low impact on oil characteristics, which could be explained by the period of imposed water reduction. In fact, the restricted water supply during the summer, followed by recovering the full crop evapotranspiration during the last steps of lipogenesis and during the ripening period, does not provoke important changes compared with full irrigation, as observed by Berenguer et al. (2006). Our experiment therefore corroborates the usefulness of a DI strategy for water-saving purposes without any effects on olive oil quality compared with the more extensively used full irrigation strategy. However, when irrigation was more restricted (SDI) oil stability increased significantly as a result of a greater phenol content, which explains the greater bitterness, pungency, and astringency reported by the panel, as was also reported by Berenguer et al. (2006) and Tovar et al. (2001). In addition, SDI resulted in a different fatty acid composition, with a greater saturated fatty acid content and a lesser unsaturated and polyunsaturated acid content. Similarly, Serman et al. (2011) observed a lesser MUFA-to-PUFA ratio when water was more restricted. However, controversial results appear in the literature in this respect. For example, Berenguer et al. (2006) reported a lesser polyunsaturated acid content with lower irrigation doses. Their results suggest an effect of strong changes on the MI for some treatments related to severe water restrictions. Similarly, this relationship between restricted irrigation and fatty acid composition contradicts that reported by Dabbou et al. (2011), who worked on ‘Koroneiki’ and suggested that fatty acid composition is much more affected by maturity than by irrigation dose. In the current study, irrigation restrictions were designed to take into account

the compromise between oil yield sustainability and quality, and—from this perspective—the effect of changes in MI was negligible.

Conclusions

Mechanical harvesting tended to damage the fruit, resulting in lower quality virgin olive oil in all cases. The DI strategy (reduction of 75% of irrigation water from July to September) neither affected fruit nor olive oil characteristics, whereas the SDI strategy (reduction of 75% from July to September and 30% from March to June and during October) had a significant effect on olive oil characteristics compared with the control. The overall results show no interaction between harvest system and irrigation strategy, and suggest that in low-yield years, the cumulative effect of mechanical harvesting, deficit irrigation, and fruit maturity influenced oil quality and may explain part of its dramatic decrease. Although the increase of polyphenols and MUFAs can be considered positive for olive oil quality, low yields imply the need for optimization of the SDI strategy if no changes in olive oil quality are desired. Fruit degradation processes, related to oxidation effects, were triggered by mechanical damage and took place in the period immediately after harvest. Thus, two key processes need to be considered: an early harvest and a shortening (as much as possible) of the time between harvesting and fruit processing.

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