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Deliverable 3.2

Report of the chemical profile of almonds and intercrops

VALMEDALM: Valorization of **Med**iterranean **Alm**ond orchards through the use of intercropping integrated strategies

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1. Executive Summary

This report presents the results of the chemical characterisation of almonds and associated intercrop species cultivated across the countries participating in the VALMEDALM project, namely Italy, Portugal, Croatia, Israel, and Morocco. The chemical profile was evaluated through the determination of organic acids by ultra-fast liquid chromatography coupled with a diode array detector (UFLC-DAD), fatty acids by gas chromatography with flame ionisation detection (GC-FID), and sugars by high-performance liquid chromatography coupled with a refractive index detector (HPLC-RI).

These analyses were performed on almond samples collected from the different intercropping systems established in each participating country, including *Medicago* spp. and *Sulla coronaria* in Italy, chickpea and clover in Portugal, different almond cultivars in Croatia, cover crop and non-cover crop systems in Israel, and lentil and faba bean intercropping systems in Morocco. In addition, the chemical composition of the intercropped lentil and faba bean samples from Morocco was also characterised.

The report compiles the results obtained during the baseline (control) year, where available, together with those from the subsequent intercropping seasons, providing a comprehensive overview of the organic acid, fatty acid, and sugar composition of almonds and associated intercrop species grown under contrasting Mediterranean agroecological conditions.

Deviation: Almond samples corresponding to the second year of production at the Croatian experimental site and chickpea samples corresponding to the third year of production at the Portuguese experimental site could not be collected or analysed, as there was no agricultural production at those sites in the respective years. Since these are field trials, annual production is inherently dependent on environmental and agronomic conditions, which can significantly affect crop yields or even make production unfeasible, constituting a factor beyond the control of the project team. Consequently, the characterization of these crops focused exclusively on the production years for which it was possible to obtain representative samples.

2. Italy

Control Year Results

The chemical composition was obtained by quantifying the fatty acid content through Gas Chromatography coupled to a Flame Ionization Detector (GC-FID, the organic acids by a UFLC-DAD system and the sugar content by HPLC coupled to a refraction index. Four organic acids and sugar content were determined in the three baseline control samples from the Italian trial site (Table 1). Succinic acid was the dominant organic acid, ranging from 0.329 ± 0.001 g/100 g fw (AIC7) to 0.48 ± 0.01 g/100 g fw (AIC1), followed by oxalic acid (0.169–0.311 g/100 g fw). Malic acid was detected only at trace levels in all samples, while fumaric acid was consistently present at very low concentrations. Total organic acid content ranged from 0.428 ± 0.001 g/100 g fw (AIC7) to 0.73 ± 0.01 g/100 g fw (AIC1), with AIC1 presenting the highest values across all organic acid fractions. Sugar content was highly consistent across the three blocks, ranging from 5.2 ± 0.4 g/100 g fw (AIC1) to 5.4 ± 0.1 g/100 g fw (AIC7), indicating negligible within-site variability in carbohydrate content at baseline. These values provide a reference point against which the effect of intercropping on almond organic acid and sugar composition can be assessed in subsequent production years.

Table 1. Organic acid and sugar composition (g/100 g fw) of almond samples collected in the baseline year at the Italian VALMEDALM trial site (mean ± SD). tr.: traces.

	Oxalic acid (g/100 g fw)	Malic acid (g/100 g fw)	Succinic Acid (g/100 g fw)	Fumaric Acids (g/100 g fw)	Total Organic Acids (g/100 g fw)	Sucrose (g/100 g fw)
AIC1	0.311±0.004	tr.	.48±0.01	0.0023±0.0001	0.73±0.01	5.2±0.4
AIC5	0.2397±0.0002	tr.	.34±0.04	0.002332±0.00005	0.45±0.03	5.3±0.3
AIC7	0.169±0.003	tr.	329±0.001	0.00262±0.00004	0.428±0.001	5.4±0.1

Five fatty acids were identified in the three baseline control samples from the Italian trial site: palmitic acid (C16:0), palmitoleic acid (C16:1), stearic acid (C18:0), oleic acid (C18:1n9c) and linoleic acid (C18:2n6c) (Table 2). Oleic acid was the dominant constituent across all three blocks, ranging from 74.5 ± 0.2% (AIC7) to 76.33 ± 0.05% (AIC5), followed by linoleic acid (13.0–14.6%) and palmitic acid (8.1–8.5%). In terms of fatty acid classes, MUFA was predominant (75.2–77.0%), followed by PUFA (13.0–14.6%) and SFA (10.0–10.4%). The composition was highly uniform across the three blocks, with no meaningful differences in any individual fatty acid or lipid class, confirming the homogeneity of the baseline almond lipid profile at this trial site.

Table 2. Fatty acid composition (%) of almond samples collected in the baseline year at the Italian demo site (mean ± SD).

Fatty acid (%)	AIC1	AIC5	AIC7
C16:0	8.502±0.004	8.1±0.1	8.3±0.1
C16:1	0.781 ±0.001	0.71±0.01	0.77±0.01
C18:0	1.94±0.01	1.8485±0.0004	1.90±0.02
C18:1n9c	75.522±0.005	76.33±0.05	74.5±0.2
C18:2n6c	13.26± 0.03	13.0±0.2	14.6±0.5
ΣSFA	10.44±0.02	10.0±0.1	10.2± 0.1
ΣMUFA	76.30±0.01	77.0±0.1	75.2± 0.4
ΣPUFA	13.26±0.03	13.0±0.2	14.6±0.5

Values are expressed as mean ± standard deviation (n = 2). ΣSFA: total saturated fatty acids; ΣMUFA: total monounsaturated fatty acids; ΣPUFA: total polyunsaturated fatty acids.

Year 1 and 2 Intercropping Results

Four organic acids were identified in almond samples from the first year of the Italian intercropping trial: oxalic, malic, succinic and fumaric acids, with succinic acid as the dominant constituent across all plots (Table 3).

Total organic acid content was higher in control plots in Year 1 (2 ± 1 g/100 g fw) than in Sulla coronaria (1.44 ± 0.54 g/100 g fw) and Medicago spp. (1.9 ± 0.1 g/100 g fw) intercropped plots, with succinic acid as the main driver of this difference. However, the high variability observed within the control treatment indicates that this difference should be interpreted with caution rather than as a clear effect of intercropping. In Year 2, total organic acid content was similar across treatments (1.7 to 1.8 g/100 g fw), with no clear distinction between control and intercropped plots.

Malic acid remained at low concentrations across all treatments and years, while fumaric acid was consistently detected only at trace levels.

Table 3. Organic acid composition (g/100 g fw) of almond kernels (*Prunus dulcis* Mill.) from Licata, Sicily (Italy) under control, *Sulla coronaria* and *Medicago* spp. intercropping systems across two consecutive harvest years.

Organic acid (g/100 g fw)	Year 1			Year 2		
	Control	***Sulla***	***Medicago***	***Control***	***Sulla***	***Medicago***
Oxalic acid	0.6 ± 0.2	0.5 ± 0.2	0.7 ± 0.1	0.57 ± 0.01	0.57 ± 0.04	0.59 ± 0.04
Malic acid	0.2 ± 0.1	traces	0.10 ± 0.01	0.09 ± 0.06	0.14 ± 0.05	0.13 ± 0.04
Succinic acid	1.70 ± 0.70	0.95 ± 0.35	1.10 ± 0.03	1.04 ± 0.10	1.13 ± 0.11	1.08 ± 0.07
Fumaric acid	0.005 ± 0.003	0.003 ± 0.001	0.003 ± 0.001	0.0030 ± 0.0001	0.003 ± 0.001	0.0031 ± 0.0003
Total	2 ± 1	1.44 ± 0.54	1.9 ± 0.1	1.7 ± 0.1	1.8 ± 0.2	1.8 ± 0.1

Values are expressed as mean ± standard deviation (n = 3 plots).

Oleic and linoleic acids were the dominant fatty acids in almond kernels from Licata in both years, followed by palmitic and stearic acids, consistent with the typical *Prunus dulcis* profile (Table 4). In Year 1, oleic acid was slightly higher in intercropped plots, particularly *Medicago spp.* (60 ± 6), than in control plots (55 ± 8), with the opposite trend observed for linoleic acid, reflected in a lower oleic to linoleic ratio in control plots (1.5 ± 0.5) compared with the intercropped treatments (2 ± 1). The high variability within treatments, however, limits this as a clear intercropping effect. In Year 2, oleic acid increased across all treatments (64 to 68%), with a corresponding decrease in linoleic acid and a higher oleic to linoleic ratio (2.6 to 3) than in Year 1, consistently across control and intercropped plots, pointing to a year effect rather than a treatment effect. Saturated fatty acid content was slightly higher in Year 2 than in Year 1 but remained similar between control and intercropped plots within each year.

Table 4. Fatty acid composition (%) of almond kernels (*Prunus dulcis* Mill.) from Licata (Italy) under control, *Sulla coronaria* and *Medicago* spp. intercropping systems across two consecutive harvest years.

Fatty acid (%)	**Year 1**			**Year 2**		
	Control	***Sulla***	***Medicago***	***Control***	***Sulla***	***Medicago***
C16:0	5.7 ± 0.4	7 ± 1	7 ± 3	7 ± 2	7.6 ± 2.1	8 ± 1
C18:0	2.2 ± 0.2	3 ± 1	2.0 ± 0.4	3.0 ± 0.3	4 ± 1	3 ± 1
C18:1	55 ± 8	59 ± 10	60 ± 6	68 ± 4	64 ± 3	68 ± 5
C18:2	37 ± 8	31 ± 10	31 ± 10	22 ± 5	25 ± 1	21 ± 6
ΣSFA	8 ± 1	10 ± 2	9.3 ± 3.8	10.4 ± 1.4	11.2 ± 3.1	10.9 ± 0.2
ΣMUFA	55 ± 8	59 ± 10	60 ± 6	68 ± 4	64 ± 3	68 ± 5
ΣPUFA	37 ± 8	31 ± 10	31 ± 10	22 ± 5	25 ± 1	21 ± 6
O/L ratio	1.5 ± 0.5	2 ± 1	2 ± 1	3 ± 1	2.6 ± 0.2	3 ± 1

Values are expressed as mean ± standard deviation (n = 3 plots). ΣSFA: total saturated fatty acids (C16:0 + C18:0); ΣMUFA: total monounsaturated fatty acids (C18:1); ΣPUFA: total polyunsaturated fatty acids (C18:2); O/L ratio: oleic to linoleic acid ratio.

Sucrose content showed a consistent pattern across treatments, with significantly higher values recorded in the first production year compared to the second, regardless of the intercropping system applied (Figure 1). This interannual variation likely reflects differences in climatic conditions, particularly water availability and temperature during kernel filling, which are known to influence soluble sugar accumulation in almonds. In contrast, no significant differences were observed between treatments within the same year, suggesting that intercropping with Sulla coronaria or Medicago spp. did not negatively affect sucrose accumulation relative to the control. These findings indicate that the year of production exerted a stronger influence on sucrose content than the intercropping system itself, supporting the suitability of these consociations as a sustainable alternative without compromising this aspect of almond quality.

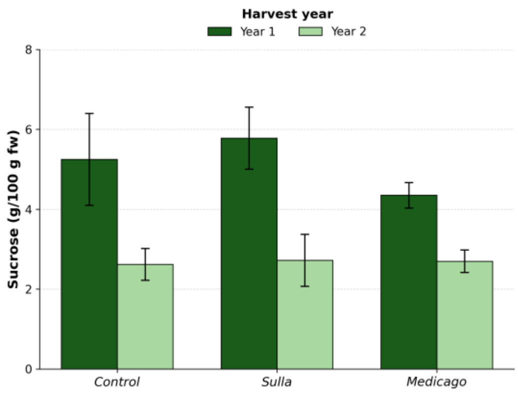

Figure 1. Sucrose content (g/100 g fw) of almond kernels (*Prunus dulcis* Mill.) under control, *Sulla coronaria* and *Medicago* spp. intercropping systems across two consecutive harvest years at Licata, Sicily. Bars represent mean ± standard deviation (n = 3 plots).

3. Portugal

For the organic acids, the samples collected from the dry almond grove showed higher content of oxalic and malic acid (Table 6), which can be explained by the stress conditions to which the plant was subjected. Regarding the sugar content, no significant difference was detected between the two samples

Table 6. Organic acids and sugar content for both analyzed almond samples.

	Oxalic Acid (g/100 g fw)	Malic Acid (g/100 g fw)	Succinic Acid (g/100 g fw)	Total Organic Acids (g/100 g fw)	Sacarose (g/100 g fw)
AES	0.38±0.02	0.288±0.002	0.79±0.03	1.46±0.05	5.3±0.1
ADR	0.343±0.003	0.205±0.003	0.82±0.02	1.37±0.03	5.4±0.1

The fatty acid composition of almond samples from the two production systems is presented in Table 7. Five fatty acids were identified in both samples, palmitic acid (C16:0), palmitoleic acid (C16:1), stearic acid (C18:0), oleic acid (C18:1n9c) and linoleic acid (C18:2n6c), with oleic acid as the dominant constituent, accounting for 71.06 ± 0.01% (AES) and 70.2 ± 0.2% (ADR) of total fatty acids. Linoleic acid was the second most abundant fatty acid (≈18% in both samples), followed by palmitic acid (7.65–8.47%). In terms of fatty acid classes, monounsaturated fatty acids (MUFA) were predominant (71.73% and 70.9%), followed by polyunsaturated fatty acids (PUFA, ≈18%) and saturated fatty acids (SFA, ≈10%). No significant differences were observed between the two samples in any fatty acid or lipid class, confirming the homogeneity of the almond lipid profile regardless of the intercropping condition applied at this site.

Table 7. Fatty acid content of almonds produced under different conditions by intercropping systems.

	AES	ADR
C16:0	7.65±0.03	8.47±0.01
C16:1	0.668±0.004	0.698±0.002
C18:0	2.60±0.01	2.47±0.01
C18:1n9c	71.06±0.01	70.2±0.2
C18:2n6c	18.03±0.03	18.2±0.2
ΣSFA	10.24±0.04	10.939±0.001
ΣMUFA	71.73±0.01	70.9±0.2
ΣPUFA	18.03±0.03	18.2±0.2

SFA: saturated fatty acids; MUFA: Monounsaturated fatty acids; PUFA: Polyunsaturated Fatty Acids.

Four organic acids were identified in almond kernels across all treatments and production years: oxalic, malic, succinic and fumaric acids (Table 8). Succinic acid was consistently the dominant organic acid, ranging from 0.38 ± 0.04 g/100 g fw (Rainfed Control, Year 1) to 1.0 ± 0.1 g/100 g fw (Rainfed Control, Year 3), followed by oxalic acid (0.23–0.50 g/100 g fw). Malic acid was absent in several treatments, particularly under irrigated conditions, while fumaric acid was detected at trace levels in all samples. Total organic acid content tended to be higher in rainfed than irrigated treatments across all years, which may reflect a stress-induced accumulation response under water-limited conditions.

Intercropping with chickpea generally yielded higher total organic acids compared to clover intercropping and control plots, though this trend was not consistent across all years. No clear progressive pattern across production years was observed, suggesting that organic acid accumulation in almond kernels is more strongly influenced by irrigation regime than by intercropping system or year of production.

Table 8. Organic acid composition (g/100 g fw) in almond kernels as affected by irrigation regime, intercropping system, and production year.

Treatment	Year	Oxalic	Malic	Succinic	Fumaric	Total
Irrigated Control	1	0.31 ± 0.01	nd	0.65 ± 0.03	0.0024 ± 0.0001	0.89 ± 0.03
Rainfed Control	1	0.251 ± 0.001	nd	0.38 ± 0.04	0.00243 ± 0.00002	0.56 ± 0.04
Irrigated Chickpea	1	0.509 ± 0.001	nd	0.92 ± 0.01	0.00237 ± 0.00003	1.416 ± 0.004
Rainfed Chickpea	1	0.407 ± 0.001	0.022 ± 0.004	0.78 ± 0.03	0.002615 ± 0.000004	1.21 ± 0.03
Irrigated Clover	1	0.227 ± 0.002	nd	0.52 ± 0.02	0.0023 ± 0.0001	0.61 ± 0.01
Rainfed Clover	1	0.3708 ± 0.0003	0.16 ± 0.02	0.90 ± 0.01	0.0031 ± 0.0001	1.43 ± 0.03
Irrigated Control	2	0.45 ± 0.01	0.03 ± 0.01	0.77 ± 0.02	0.0032 ± 0.0001	1.24 ± 0.02
Rainfed Control	2	0.327 ± 0.003	0.09 ± 0.02	0.449 ± 0.005	0.0056 ± 0.00001	0.87 ± 0.01
Irrigated Chickpea	2	0.47 ± 0.01	0.26 ± 0.02	0.91 ± 0.02	0.0054 ± 0.0001	1.64 ± 0.05
Rainfed Chickpea	2	0.41 ± 0.01	0.10 ± 0.01	0.88 ± 0.05	0.0064 ± 0.0001	1.40 ± 0.05
Irrigated Clover	2	0.2690 ± 0.0005	nd	0.44 ± 0.03	0.0067 ± 0.0001	0.55 ± 0.03
Rainfed Clover	2	0.41 ± 0.01	0.32 ± 0.01	0.792 ± 0.002	0.0081 ± 0.0002	1.515 ± 0.001
Irrigated Control	3	0.32 ± 0.01	nd	0.70 ± 0.01	0.004 ± 0.004	0.926 ± 0.001
Rainfed Control	3	0.50 ± 0.04	0.26 ± 0.03	1.0 ± 0.1	0.0070 ± 0.0005	1.8 ± 0.1
Irrigated Chickpea	3	0.30 ± 0.05	nd	0.80 ± 0.02	0.0030 ± 0.0001	0.97 ± 0.05
Rainfed Chickpea	3	0.44 ± 0.03	0.287 ± 0.002	0.8 ± 0.1	0.0029 ± 0.0001	1.56 ± 0.03
Irrigated Clover	3	0.30 ± 0.05	nd	0.79 ± 0.03	0.0031 ± 0.0001	0.99 ± 0.05
Rainfed Clover	3	0.43 ± 0.05	0.34 ± 0.05	0.8 ± 0.1	0.0059 ± 0.0002	1.6 ± 0.2

Values are presented as mean ± standard deviation (n = 2). nd: not detected.

Three sugars were identified in almond kernels across all treatments and years: fructose, glucose and sucrose, with sucrose as the overwhelmingly dominant constituent, accounting for over 85% of total sugars in all samples (Table 9). Total sugar content showed considerable variation across treatments and years, ranging from 5.1 ± 0.1 g/100 g fw (Rainfed Chickpea, Year 1) to 9.0 ± 0.3 g/100 g fw (Rainfed Clover, Year 3). Rainfed treatments consistently presented higher total sugars than their irrigated counterparts, most notably in Year 3, where Rainfed Control (8.9 ± 0.2 g/100 g fw) and Rainfed Clover (9.0 ± 0.3 g/100 g fw) were markedly higher than the corresponding irrigated treatments (6.8 and 5.0 g/100 g fw, respectively). This pattern is consistent with osmotic adjustment mechanisms under mild water deficit, whereby sugar accumulation contributes to cellular protection. Sucrose content in irrigated treatments remained relatively stable across years (4.7–6.5 g/100 g fw), while rainfed treatments showed a progressive increase from Years 1 to 3, suggesting a cumulative effect of the irrigation regime on carbohydrate partitioning over successive production years.

Table 9. Sugar composition (g/100 g fw) of almond kernels under different irrigation regimes and intercropping systems across three consecutive production years.

Treatment	Fructose	Glucose	Sucrose	Total sugars
1st Year				
Irrigated Control	0.059 ± 0.002	0.157 ± 0.004	5.52 ± 0.04	5.74 ± 0.05
Rainfed Control	0.114 ± 0.003	0.26 ± 0.01	4.78 ± 0.01	5.16 ± 0.03
Irrigated Chickpea	0.101 ± 0.001	0.219 ± 0.004	6.407 ± 0.001	6.73 ± 0.01
Rainfed Chickpea	0.087 ± 0.003	0.36 ± 0.04	4.65 ± 0.02	5.1 ± 0.1
Irrigated Clover	0.121 ± 0.002	0.25 ± 0.01	5.8 ± 0.1	6.2 ± 0.1
Rainfed Clover	0.084 ± 0.002	0.27 ± 0.03	5.2 ± 0.1	5.5 ± 0.2
2nd Year				
Treatment	**Fructose**	**Glucose**	**Sucrose**	**Total sugars**
Irrigated Control	0.18 ± 0.01	0.42 ± 0.01	6.22 ± 0.03	6.81 ± 0.04
Rainfed Control	0.36 ± 0.01	0.50 ± 0.02	4.5 ± 0.1	5.4 ± 0.1
Irrigated Chickpea	0.31 ± 0.01	0.49 ± 0.02	5.4 ± 0.3	5.8 ± 0.3
Rainfed Chickpea	0.35 ± 0.01	0.47 ± 0.01	5.5 ± 0.1	6.3 ± 0.1
Irrigated Clover	0.16 ± 0.01	0.33 ± 0.02	6.5 ± 0.1	7.0 ± 0.1
Rainfed Clover	0.3395 ± 0.0003	0.46 ± 0.01	4.85 ± 0.01	5.64 ± 0.02
3rd Year				
Treatment	**Fructose**	**Glucose**	**Sucrose**	**Total sugars**
Irrigated Control	0.10 ± 0.01	0.35 ± 0.02	6.3 ± 0.3	6.80 ± 0.31
Rainfed Control	0.16 ± 0.03	0.6 ± 0.1	8.1 ± 0.4	8.9 ± 0.2
Irrigated Chickpea	0.052 ± 0.001	0.27 ± 0.02	5.4 ± 0.3	5.7 ± 0.3
Rainfed Chickpea	0.09 ± 0.01	0.32 ± 0.01	7 ± 1	7.4 ± 0.8
Irrigated Clover	0.06 ± 0.01	0.291 ± 0.002	4.7 ± 0.2	5.0 ± 0.2
Rainfed Clover	0.16 ± 0.02	0.46 ± 0.01	8.4 ± 0.3	9.0 ± 0.3

Values are mean ± standard deviation.

The fatty acid profiles of almond kernels were characterised across three production years under irrigated and rainfed conditions with and without intercropping (Tables 10-12). Four fatty acids were consistently identified in all samples: palmitic acid (C16:0), stearic acid (C18:0), oleic acid (C18:1) and linoleic acid (C18:2), with oleic acid as the dominant constituent across all treatments and years (66-75%), followed by linoleic acid (13-19%), palmitic acid (8-11%) and stearic acid (2-3.4%).

In Year 1, fatty acid composition was highly uniform across all treatments, with no meaningful differences between irrigated and rainfed plots or between intercropping systems, consistent with the stable lipid profiles reported for this cultivar. In Year 2, a slight increase in SFA content was observed relative to Year 1 (12-13% *vs* 10-11%), alongside a reduction in PUFA (13.7-16.6% vs 17.7–19%), though these differences remained within a narrow range and showed no consistent intercropping effect.

Year 3 showed the greatest inter-treatment variability, with oleic acid ranging from 66 ± 1% (Irrigated Control) to 75 ± 2% (Rainfed Chickpea), and a corresponding inverse trend in linoleic acid (14-19%). Rainfed treatments consistently presented higher MUFA and lower PUFA than irrigated treatments in Years 2 and 3, suggesting that water deficit favours oleic acid accumulation at the expense of linoleic acid, a pattern well documented in almond and other tree nut species. No consistent effect of intercropping system on fatty acid composition was observed across any of the three years.

Table 10. Fatty acid composition (%) of almond kernels as affected by irrigation regime and cropping systems during the first production year.

Fatty acid (%)	Irrigated Control	Irrigated Clover	Irrigated Chickpea	Rainfed Control	Rainfed Clover	Rainfed Chickpea
C16:0	8 ± 1	7.5 ± 0.5	7.9 ± 0.3	7.8 ± 0.1	8.0 ± 0.2	7.7 ± 0.1
C18:0	2.9 ± 0.2	2.3 ± 0.2	2.6 ± 0.4	2.5 ± 0.03	2.0 ± 0.2	2.5 ± 0.3
C18:1	71± 1	72 ± 1	70 ± 1	72.3 ± 0.1	71.6 ± 0.5	72 ± 1
C18:2	17.7 ± 0.3	18.3 ± 1.2	19 ± 1	17.7 ± 0.4	18.3 ± 0.1	18.2 ± 0.4
ΣSFA	11 ± 1	9.8 ± 0.3	11 ± 1	10.29 ± 0.02	10.0 ± 0.4	10.2 ± 0.4
ΣMUFA	71 ± 1	72 ± 1	70 ± 1	72.3 ± 0.1	71.6 ± 0.5	72 ± 1
ΣPUFA	17.7 ± 0.3	18 ± 1	19 ± 1	17.7 ± 0.4	18.3 ± 0.1	18.2 ± 0.4

Values are expressed as mean ± standard deviation (n = 2). ΣSFA: total saturated fatty acids; ΣMUFA: total monounsaturated fatty acids; ΣPUFA: total polyunsaturated fatty acids.

Table 11. Fatty acid composition (%) of almond kernels as affected by irrigation regime and cropping systems during the second production year.

Fatty acid (%)	Irrigated Control	Irrigated Clover	Irrigated Chickpea	Rainfed Control	Rainfed Clover	Rainfed Chickpea
C16:0	10 ± 1	9.8 ± 0.1	9.6 ± 0.1	9.7 ± 0.1	8.67 ± 0.03	9.0 ± 0.3
C18:0	3.18 ± 0.04	3.4 ± 0.1	3.09 ± 0.03	2.86 ± 0.03	2.92 ± 0.03	3.38 ± 0.03
C18:1	71 ± 1	70.11 ± 0.05	71.8 ± 0.1	73.1 ± 0.2	74.67 ± 0.05	71.7 ± 0.3
C18:2	15.44 ± 0.10	16.62 ± 0.02	15.49 ± 0.03	14.3 ± 0.1	13.7 ± 0.1	16.0 ± 0.1
ΣSFA	13 ± 1	13.27 ± 0.03	12.7 ± 0.1	12.6 ± 0.1	11.592 ± 0.003	12.4 ± 0.4
ΣMUFA	71 ± 1	70.11 ± 0.05	71.8 ± 0.1	73.1 ± 0.2	74.67 ± 0.05	71.7 ± 0.3
ΣPUFA	15.44 ± 0.10	16.62 ± 0.02	15.49 ± 0.03	14.3 ± 0.1	13.7 ± 0.1	16.0 ± 0.1

Values are expressed as mean ± standard deviation (n = 2). ΣSFA: total saturated fatty acids; ΣMUFA: total monounsaturated fatty acids; ΣPUFA: total polyunsaturated fatty acids.

Table 12. Fatty acid composition (%) of almond kernels as affected by irrigation regime and cropping systems during the third production year.

Fatty acid (%)	Irrigated Control	Irrigated Clover	Irrigated Chickpea	Rainfed Control	Rainfed Clover	Rainfed Chickpea
C16:0	11.1 ± 0.2	10 ± 1	9.3 ± 0.2	9 ± 1	8.4 ± 0.5	8 ± 1
C18:0	3.1 ± 0.3	3.2 ± 0.2	2.5 ± 0.5	2.7 ± 0.3	3 ± 1	2 ± 1
C18:1	66 ± 1	68 ± 1	71 ± 1	73 ± 4	75 ± 1	75 ± 2
C18:2	19.4 ± 0.5	18.51 ± 0.46	17 ± 1	16 ± 3	14 ± 1	14 ± 1
ΣSFA	14.2 ± 0.2	13 ± 1	12 ± 1	11 ± 1	11 ± 1	11 ± 1
ΣMUFA	66 ± 1	68 ± 1	71 ± 1	73 ± 4	75 ± 1	75 ± 2
ΣPUFA	19.4 ± 0.5	18.5 ± 0.5	17 ± 1	16 ± 3	14 ± 1	14 ± 1

Values are expressed as mean ± standard deviation (n = 2). ΣSFA: total saturated fatty acids; ΣMUFA: total monounsaturated fatty acids; ΣPUFA: total polyunsaturated fatty acids.

Sucrose was the only sugar detected and quantified in chickpea samples from the first year of production at the Portuguese trial site (Table 13). Values ranged from 2.2 ± 0.3 g/100 g fw (A3, control irrigated) to 3.0 ± 0.3 g/100 g fw (C1-3, non-irrigated intercropped) and 3.0 ± 0.1 g/100 g fw (C2-1, irrigated intercropped). Overall, sucrose content was comparable across the three treatment groups, with control irrigated samples averaging 2.49–2.66 g/100 g fw, non-irrigated intercropped samples 2.49–3.0 g/100 g fw and irrigated intercropped samples 2.5–3.0 g/100 g fw. The variability within each group, particularly in the non-irrigated intercropped treatment, precludes clear conclusions regarding the effect of intercropping or irrigation regime on sucrose accumulation in chickpea at this production stage.

Table 13. Sucrose composition (g/100 g fw) of chickpea samples from the first year of production at the Portuguese demo site, control irrigated (A1-A3), non-irrigated intercropped (C1-1-C1-3) and irrigated intercropped (C2-1-C2-3), (mean ± SD).

	Sucrose (g/100 g fw)
A1	2.56±0.04
A2	2.66±0.03
A3	2.2±0.3
C1-1	2.491±0.004
C1-2	2.6±0.1
C1-3	3.0±0.3
C2-1	3.0±0.1
C2-2	2.7±0.2
C2-3	2.5±0.1

The fatty acid composition of chickpea seeds as analyzed under three management systems during the second year of intercropping: GBC2 (control), GBI2 (intercropped with irrigation), and GBNI2 (intercropped without irrigation) (Table 14). The results demonstrate notable differences in the proportions of saturated (SFA), monounsaturated (MUFA), and polyunsaturated (PUFA) fatty acids among the treatments.

Palmitic acid (C16:0) was the predominant saturated fatty acid in all samples, with values ranging from 12.73% in the control (GBC2) to 14.78% in the irrigated intercropping treatment (GBI2). Stearic acid (C18:0) levels remained relatively consistent across treatments, varying slightly between 4.72% and 5.73%. Among the monounsaturated fatty acids, oleic acid (C18:1n9c) showed the highest concentration in the control treatment (27.3%) and lower values in intercropped samples, particularly GBI2 (23.5%). This indicates a decrease in MUFA under intercropping conditions, especially when irrigation was applied.

Linoleic acid (C18:2n6c), the major polyunsaturated fatty acid, increased with intercropping, reaching 46.34% in GBI2, followed by 44.4% in GBNI2 and 43.22% in the control. Alpha-linolenic acid (C18:3n3), though present in smaller amounts, also followed a similar trend, with higher values in GBI2 (5.1%) compared to GBC2 (4.18%). Total SFA content was similar across treatments, slightly higher in the control (25.3%) and marginally lower in GBNI2 (24.6%). MUFA levels were highest in GBC2 (27.3%) and decreased in GBI2 (23.5%). On the other hand, PUFA levels were enhanced under intercropping, particularly in the irrigated system (GBI2), which reached 51.4%, compared to 47.4% in the control. These results suggest that intercropping, especially under irrigation, contributes to an improved fatty acid profile in chickpeas by increasing the proportion of essential polyunsaturated fatty acids, which are beneficial for human health. Conversely, the decrease in MUFA under intercropping may reflect changes in lipid metabolism associated with environmental and agronomic factors.

Table 14. Fatty acid content of almonds produced under different conditions by intercropping systems.

	GBC2	GBI2	GBNI2
C14:0	0.206±0.001	0.327±0.001	0.24±0.01
C16:0	12.73±0.03	14.78±0.01	13.7±0.2
C18:0	5.726±0.002	4.72±0.03	4.81±0.02
C18:1n9c	27.3±0.1	23.5±0,2	26.0±0.1
C18:2n6c	43.22±0.03	46.34±0.05	44.4±0.1
C18:3n3	4.179±0.004	5.1±0.1	4.978±0.001
C20:0	6.60±0.03	5.271±0.002	5.8±0.1
ΣSFA	25.3±0.1	25.10±0.02	24.6±0.1
ΣMUFA	27.3±0.2	23.5±0.2	26.0±0.1
ΣPUFA	47.4±0.1	51.4±0.2	49.4±0.1

SFA: saturated fatty acids; MUFA: Monounsaturated fatty acids; PUFA: Polyunsaturated Fatty Acids.

In the chickpea treatments from the second year of the Portuguese trial, oxalic acid was clearly the dominant organic acid across all samples, accounting for the majority of the total organic acid content, while malic acid was present at comparatively low concentrations and fumaric acid was not detected in any of the treatments (Table 15). Total organic acid content was lowest in the control plots and increased under intercropping, with the rainfed chickpea treatment showing marginally higher values than the irrigated treatment, suggesting a possible influence of water regime on organic acid accumulation, although the modest magnitude of these differences warrants a cautious interpretation rather than a clear intercropping effect.

Table 15. Organic acid composition (g/100 g fw) of almond kernels (*Prunus dulcis* Mill.) from the second year of production in Portugal, under control, irrigated, and rainfed chickpea intercropping conditions (mean ± SD).

Treatment	Year	Oxalic	Malic	Fumaric	Total
Chickpea Control	2	4.76±0.04	0.203 ± 0.001	nd	4.96 ± 0.04
Irrigated Chickpea	2	5.9±0.2	0.22±0.01	nd	6.1 ± 0.2
Rainfed Chickpea	2	5.96 ± 0.01	0.28±0.01	nd	6.24 ± 0.02

4. Croatia

Sucrose was the only sugar detected in Croatian almond samples, ranging from 3.421 ± 0.003 g/100 g fw (Texas, ACT) to 4.3 ± 0.1 g/100 g fw (AI, ACAI), with Ferragnes (ACFG, 4.2 ± 0.3 g/100 g fw) and Ferraduel (ACFD, 3.9 ± 0.1 g/100 g fw) showing intermediate values (Table 16). Overall, sucrose content was relatively consistent across cultivars, with no pronounced cultivar-dependent trend.

Table 16. Sucrose composition (g/100 g fw) of almond samples from the first year of production at the Croatian VALMEDALM demonstration site (mean ± SD).

	Sucrose (g/100 g fw)
ACT	3.421±0.003
ACFG	4.2±0.3
ACFD	3.9±0.1
ACAI	4.3±0.1

The fatty acid profile was dominated by oleic acid (C18:1n9c) in all four cultivars, ranging from 71.43 ± 0.02% (ACT) to 78.285 ± 0.004% (ACFG), followed by linoleic acid (C18:2n6c, 10.90–16.36%) and palmitic acid (C16:0, 6.8–8.70%) (Table 17). ACT stood out with the lowest oleic acid content and the highest linoleic acid (16.36 ± 0.03%) and stearic acid (C18:0, 4.97 ± 0.02%), resulting in a markedly higher PUFA content (16.4%) relative to the other cultivars (10.9–13.6%). ACFG presented the highest MUFA content (78.89 ± 0.03%) and the lowest PUFA (10.90%), consistent with its elevated oleic acid. These inter-cultivar differences in fatty acid composition are likely primarily genetically determined, as all samples were collected from the same Croatian site under identical growing conditions.

Table 17. Fatty acid composition (%) of almond samples from the first year of production at the Croatian VALMEDALM demonstration site (mean ± SD). ΣSFA: total saturated fatty acids; ΣMUFA: total monounsaturated fatty acids; ΣPUFA: total polyunsaturated fatty acids.

Fatty acid (%)	**ACAI**	**ACFG**	**ACT**	**AFD**
C16:0	8.70±0.01	7.5305±0.0004	6.8±01	7.849±0.001
C16:1	0.62±0.01	0.61±0.02	0.472±0.004	0.602±0.002
C18:0	3.31±0.01	2.679±0.001	4.97±0.02	2.8±0.1
C18:1n9c	75.319±0.002	78.285±0.004	71.43±0.02	75.2±0.3
C18:2n6c	12.05±0.01	10.90±0.01	16.36±0.03	13.6±0.2
ΣSFA	12.012±0.03	10.210±0.002	11.7±0.1	10.7±0.1
ΣMUFA	75.94±0.01	78.89±0.03	71.90±0.04	76±1
ΣPUFA	12.05±0.02	10.90±0.03	16.4±0.1	13.6±0.4

5. Israel

Four organic acids were identified and quantified in the Israeli almond samples: oxalic acid, malic acid, succinic acid and fumaric acid, the latter detected only at trace levels in all samples (Table 19). Succinic acid was the dominant organic acid across all samples, ranging from 0.65 ± 0.02 g/100 g fw (CCF2R3) to 2.3 ± 0.1 g/100 g fw (CCF2R4) in cover crop plots, and from 0.76 ± 0.03 g/100 g fw (NCCF2R1) to 1.24 ± 0.03 g/100 g fw (NCCF1R5) in non-cover crop plots. Oxalic acid was the second most abundant acid, contributing 0.274–0.890 g/100 g fw across all samples, while malic acid was present at lower concentrations (0.04–0.488 g/100 g fw).

Total organic acid content varied considerably within both groups. Cover crop samples ranged from 1.11 ± 0.04 g/100 g fw (CCF2R3) to 3.7 ± 0.1 g/100 g fw (CCF2R4), while non-cover crop samples showed a narrower range (1.10 ± 0.04 to 1.87 ± 0.04 g/100 g fw), suggesting greater variability in the CCF group, likely reflecting differences between plots and replications rather than a consistent intercropping effect. No clear systematic difference in total organic acid content was observed between CCF and NCCF groups overall, though CCF2R4 stood out as an outlier with notably elevated succinic acid (2.3 ± 0.1 g/100 g fw) and oxalic acid (0.89 ± 0.01 g/100 g fw) concentrations relative to all other samples.

Table 19. Organic acid composition (g/100 g fw) of almond samples collected from cover crop (CCF) and non-cover crop (NCCF) plots in Israel (mean ± SD). tr.: traces.

	Oxalic Acid (g/100 g fw)	Malic Acid (g/100 g fw)	Succinic Acid (g/100 g fw)	Fumaric Acids (g/100 g fw)	Total Organic Acids (g/100 g fw)
CCF1R1	0.502±0.002	0.08±0.02	1.10±0.02	tr.	1.69±0.01
CCF1R2	0.619±0.001	0.17±0.03	1.67±0.01	tr.	2.46±0.04
CCF1R3	0.514±0.003	0.132±0.005	1.3±0.1	tr.	1.93±0.05
CCF1R4	0.54±0.02	0.17±0.03	1.3±0.1	tr.	1.99±0.04
CCF1R5	0.584±0.005	0.30±0.05	2.0±0.5	tr.	3±1
CCF2R1	0.493±0.002	0.18±0.02	1.6±0.3	tr.	2.2±0.3
CCF2R2	0.480±0.003	0.1±0.1	0.87±0.03	tr.	1.5±0.1
CCF2R3	0.340±0.04	0.12±0.01	0.65±0.02	tr.	1.11±0.04
CCF2R4	0.89±0.01	0.488±0.004	2.3±0.1	tr.	3.7±0.1
NCCF1R2	0.506±0.001	0.17±0.04	1.188±0.003	tr.	1.87±0.04
NCCF1R3	0.411±0.002	0.20±0.04	1.18±0.02	tr.	1.79±0.02
NCCF1R5	0.48±0.01	0.11±0.03	1.24±0.03	tr.	1.8±0.1
NCCF2R1	0.274±0.003	0.07±0.01	0.76±0.03	tr.	1.10±0.04
NCCF2R2	0.50±0.01	0.17±0.01	1.2±0.1	tr.	1.8±0.1
NCCF2R4	0.482±0.002	0.22±0.01	1.1±0.1	tr.	1.83±0.05
NCCF2R5	0.40±0.01	0.04±0.03	0.88±0.02	tr.	1.32±0.02

6. Morocco

The fatty acid profiles of Moroccan almond and lentil samples were characterised across control and intercropped treatments in the first year of production. In both crop types, four main fatty acids were identified, palmitic acid (C16:0), stearic acid (C18:0), oleic acid (C18:1n9c) and linoleic acid (C18:2n6c), with an additional fatty acid, α-linolenic acid (C18:3n3), detected exclusively in the lentil samples.

In almonds (Table 20), oleic acid was the dominant constituent across all samples, ranging from 64.3 ± 0.1% (BIAF3) to 68.3 ± 0.3% (BCA3), followed by linoleic acid (20.4-23.0%) and palmitic acid (8.9-10.1%). MUFA was the predominant lipid class (64.3–68.3%), followed by PUFA (20.4-23.0%) and SFA (11.3-12.6%). No consistent trend distinguishing control (BCA) from intercropped plots (BIAF, BIAL) was observed, as values overlapped considerably across treatments. The slightly higher linoleic acid content in BIAL samples (22.0-23.0%) compared to BCA controls (20.4-21.2%) is not sufficient to draw conclusions given the variability within groups.

Table 20. Fatty acid composition (%) of almond samples from the first year of intercropping in Morocco (mean ± SD).

Fatty acid (%)	BCA1	BCA2	BCA3	BIAF1	BIAF2	BIAF3	BIAL1	BIAL2	BIAL3
C16:0	9.0±0.1	9.1±0.1	8.9±0.1	9.12±0.03	9.4±0.1	9.6±0.2	9.4±0.1	9.2±0.1	10.1±0.2
C18:0	2.5±0.1	2.55±0.01	2.4±0.1	2.76±0.04	2.93±0.05	3.1±0.2	2.7±0.1	2.5±0.5	2.3±0.1
C18:1n9c	67.3±0.2	67.66±0.05	68.3±0.3	66.3±0.3	65.3±0.3	64.3±0.1	65,0±0.1	66.14±0.04	66.3±0.2
C18:2n6c	21.18±0.04	20.67±0.03	20.4±0.1	21.8±0.2	22.4±0.2	23.0±0.1	23.0±0.1	22±1	21.26±0.02
ΣSFA	11.5±0.2	11.7±0.1	11.3±0.1	11.9±0.1	12.3±0.1	12.63±0.02	12.05±0.02	12±1	12.4±0.
ΣMUFA	67.3±0.2	67.66±0.05	68.3±0.3	66.3±0.3	65.3±0.3	64.3±0.1	65.0±0.1	66.14±0.04	66.3±0.2
ΣPUFA	21.18±0.04	20.67±0.03	20.4±0.1	21.8±0.2	22.4±0.2	23.0±0.1	23.0±0.1	22±1	21.3±0.02

BCA: Azilal Control Almond; BIAF: Azilal Intercrop Almond with Fava Bean; BIAL: Azilal Intercrop Almond with Lentil. ΣSFA: total saturated fatty acids; ΣMUFA: total monounsaturated fatty acids; ΣPUFA: total polyunsaturated fatty acids. Values are expressed as mean ± SD (n = 2).

Lentil samples (Table 21) presented a markedly different fatty acid profile from almonds, with linoleic acid (C18:2n6c) as the dominant fatty acid, ranging from 37.4 ± 0.4% (TCL1) to 46.5 ± 0.04% (TIL2), followed by oleic acid (22.8-38.7%) and α-linolenic acid (C18:3n3, 8.8-13.4%). PUFA was the predominant lipid class in all lentil samples (46.2–59.2%), reflecting the high combined content of linoleic and α-linolenic acids. A notable trend was observed between control (TCL) and intercropped (TIL) lentils: TIL samples consistently presented lower oleic acid (22.8-25.1%) and higher linoleic acid (44.7-46.5%) than their TCL counterparts (26-38.7% and 37.4-44.0%, respectively), suggesting that intercropping with almonds may influence the fatty acid metabolism of lentils, though the limited number of replicates precludes definitive conclusions.

Table 21. Fatty acid composition (%) of lentil samples from the first year of intercropping in Morocco (mean ± SD).

Fatty acid (%)	TCL1	TCL2	TCL3	TIL1	TIL2	TIL3
C16:0	12.03±0.3	12.8±0.1	14.46±0.01	14.70±0.02	14.58±0.01	15.4±0.3
C18:0	3.05±0.03	2.8±0.1	3.1±0.1	3.11±0.03	3.0±0.1	3.3±0.1
C18:1n9c	38.7±0.5	30.19±0.03	26±1	25.1±0.1	23.19±0.04	22.8±0.1
C18:2n6c	37.4±0.4	42.8±0.1	44.0±0.40	44.72±0.03	46.52±0.04	45.1±0.4
C18:3n3	8.8±0.2	11.48±0.03	12.1±0.3	12.3±0.1	12.7±0.1	13.4±0.1
ΣSFA	15.1±0.3	15.5±0.2	17.6±0.1	17.82±0.05	17.6±0.1	18.7±0.3
ΣMUFA	38.7±0.5	30.19±0.03	26.±1	25.1±0.1	23.19±0.04	22.8±0.1
ΣPUFA	46.2±0.2	54.3±0.1	56±1	57.1±0.1	59.20±0.03	58.5±0.5

TCL: Taoujdate Control Lentil; TIL: Taoujdate Intercrop Lentil. ΣSFA: total saturated fatty acids; ΣMUFA: total monounsaturated fatty acids; ΣPUFA: total polyunsaturated fatty acids. Values are expressed as mean ± SD (n = 2).

The fatty acid profiles of fava bean samples from both the Azilal (BCF, BIF) and Taoujdate (TCF, TIF) sites were dominated by linoleic acid (C18:2n6c) and α-linolenic acid (C18:3n3), with PUFA as the overwhelmingly predominant lipid class across all samples (59.0-61.2% in Azilal; 56.8–60.0% in Taoujdate), consistent with the well-documented high polyunsaturated fatty acid content of fava bean seed lipids.

In the Azilal samples (Table 22), linoleic acid ranged from 47.6 ± 0.04% (BCF2) to 53.4 ± 0.1% (BIF3), followed by oleic acid (14.9–20.2%) and palmitic acid (20.9–23.0%). BCF2 stood out with notably higher oleic acid (20.2 ± 0.1%) and lower SFA (20.8 ± 0.1%) than the other Azilal samples, which clustered around 14.9–15.4% oleic acid and 24–26% SFA. BIF3 presented the lowest α-linolenic acid content (6.6 ± 0.1%), markedly lower than all other Azilal samples (11.0–11.9%), which may reflect a plot-specific effect rather than a consistent intercropping response. No systematic difference between control (BCF) and intercropped (BIF) samples was evident overall.

Table 22. Fatty acid composition (%) of fava bean samples from the first year of intercropping in Morocco (mean ± SD).

Fatty acid (%)	BCF1	BCF2	BCF3	BIF1	BIF2	BIF3
C16:0	23.0±0.3	17.6±0.2	22.2±0.1	21.9±0.2	20.9±0.1	21.6±0.2
C18:0	3.0±0.1	3.17±0.03	2.80±0.01	2.49±0.01	2.5±0.1	3.06±0.03
C18:1n9c	14.94±0.02	20.2±0.1	15.06±0.05	15.22±0.01	15.4±0.1	15.4±0.2
C18:2n6c	48.1±0.2	47.60±0.04	48.1±0.2	49.2±0.1	49.4±0.4	53.4±0.1
C18:3n3	11.0±0.2	11.446±0.001	11.9±0.3	11.2±0.1	11.8±0.2	6.6±0.1
ΣSFA	26,0±0.4	20.8±0.1	25.0±0.2	24.4±0.2	23.4±0.1	24.7±0.1
ΣMUFA	14.94±0.02	20.2±0.1	15.06±0.05	15.22±0.01	15.4±0.1	15.4±0.2
ΣPUFA	59.1±0.4	59.05±0.04	60.0±0.1	60.4±0.2	61.2±0.2	59.93±0.03

BCF: Azilal Control Fava Bean; BIF: Azilal Intercrop Fava Bean; TCF: Taoujdate Control Fava Bean; TIF: Taoujdate Intercrop Fava Bean. ΣSFA: total saturated fatty acids; ΣMUFA: total monounsaturated fatty acids; ΣPUFA: total polyunsaturated fatty acids. Values are expressed as mean ± SD.

In the Taoujdate samples (Table 23), the fatty acid profile was more uniform across treatments, with oleic acid ranging from 20 ± 1% (TCF1) to 23.17 ± 0.04% (TIF3), linoleic acid from 43.4 ± 0.2% (TIF1) to 46.5 ± 0.01% (TCF2), and α-linolenic acid from 11.3 ± 0.1% (TIF2) to 13.4 ± 0.3% (TCF1 and TIF1). TIF samples tended to present slightly higher oleic acid (22.6–23.2%) compared to TCF controls (20–20.6%), suggesting a possible effect of almond intercropping on MUFA accumulation in fava beans at this site, though the difference is modest. Comparing the two sites, Taoujdate fava beans presented consistently higher oleic acid and lower palmitic acid than Azilal samples, indicating a site-dependent influence on fatty acid composition that may reflect differences in soil type, climate or cultivar between the two locations.

Table 23. Fatty acid composition (%) of fava bean samples from the first year of intercropping in Morocco (mean ± SD).

Fatty acid (%)	TCF1	TCF2	TCF3	TIF1	TIF2	TIF3
C16:0	16.7±0.2	17.3±0.1	17.1±0.2	17.08±0.04	16.2±0.3	16.14±0.02
C18:0	3.29±0.01	3.1±0.1	3.40±0.04	3.47±0.04	3.25±0.05	3.43±0.02
C18:1n9c	20±1	20.6±0.1	20.6±0.2	22.6±0.2	23.0±0.2	23.17±0.04
C18:2n6c	46±0.3	46.50±0.01	45.8±0.5	43.4±0.2	46.3±0.4	45.25±0.01
C18:3n3	13.4±0.3	12.6±0.3	13±1	13.4±0.4	11.3±0.1	12.02±0.01
ΣSFA	20.0±0.2	20.4±0.2	20.5±0.2	20.55±0.01	19.4±0.3	19.6±0.04
ΣMUFA	20±1	20.6±0.1	20.6±0.2	22.6±0.2	23±0.2	23.17±0.04
ΣPUFA	60±1	59.1±0.3	58.8±0.4	56.8±0.2	57.6±0.4	57.269±0.001

Four organic acids were identified in almond samples from the first year of intercropping in Morocco: oxalic, malic, succinic and fumaric acids (Table 24). Succinic acid was the dominant organic acid across all samples, ranging from 0.69 ± 0.02 g/100 g fw (BIAL2) to 1.801 ± 0.004 g/100 g fw (BCA3), followed by oxalic acid (0.354–0.654 g/100 g fw). Malic acid was detected only in BCA3 (0.06 ± 0.01 g/100 g fw) and BIAF3 (0.033 ± 0.005 g/100 g fw), while fumaric acid was present only at trace levels in all samples.

Total organic acid content varied considerably among plots, ranging from 0.87 ± 0.03 g/100 g fw (BIAL2) to 2.49 ± 0.01 g/100 g fw (BCA3). Within the control group (BCA), total organic acid content increased progressively from Block 1 to Block 3 (1.40, 1.97 and 2.49 g/100 g fw, respectively), suggesting notable within-site variability. Among intercropped samples, BIAF3 (1.83 ± 0.05 g/100 g fw) and BIAL3 (2.01 ± 0.01 g/100 g fw) presented higher total organic acid contents than the corresponding Block 1 and Block 2 samples, a pattern also observed in the control group and likely reflecting block-level soil or microclimate differences rather than a consistent intercropping effect. No systematic difference between fava bean (BIAF) and lentil (BIAL) intercropping treatments was observed in either succinic or total organic acid content.

Table 24. Organic acid composition (g/100 g fw) of almond samples from the first year of intercropping in Morocco (mean ± SD).

Organic acid (g/100 g fw)	BCA1	BCA2	BCA3	BIAF1	BIAF2	BIAF3	BIAL1	BIAL2	BIAL3
Oxalic acid	0.43±0.01	0.619±0.003	0.623±0.003	0.360±0.003	0.372±0.001	0.537±0.001	0.609±0.002	0.354±0.002	0.65±0.01
Malic acid	nd	nd	0.06±0.01	nd	nd	0.033±0.005	nd	nd	nd
Succinic acid	1.01±0.01	1.372±0.005	1.801±0.004	0.98±0.01	0.89±0.04	1.24±0.04	1.034±0.001	0.69±0.02	1.41±0.04
Fumaric acid	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.
Total	1.40±0.01	1.97±0.01	2.49±0.01	1.26±0.01	1.22±0.05	1.83±0.05	1.5500±0.0001	0.87±0.03	2.01±0.01

BCA: Azilal Control Almond; BIAF: Azilal Intercrop Almond with Fava Bean; BIAL: Azilal Intercrop Almond with Lentil. Values are expressed as mean ± SD (n = 2). nd: not detected; tr.: traces.

The fatty acid profiles of lentil samples from the second year of intercropping in Morocco are presented in Table 25, comprising five fatty acids, palmitic acid (C16:0), stearic acid (C18:0), oleic acid (C18:1n9c), linoleic acid (C18:2n6c) and α-linolenic acid (C18:3n3), with PUFA as the dominant lipid class in all samples (49–57%).

Among control lentils (TCL), TCL1 stood out with a notably higher oleic acid content (30 ± 1%) compared to TCL2 and TCL3 (23.5 ± 0.2% and 24.0 ± 0.2%, respectively), and correspondingly lower linoleic acid (36.15 ± 0.04%) and lower PUFA (49 ± 1%). TCL2 and TCL3 showed more similar profiles, with linoleic acid as the dominant fatty acid (42.6% and 41.96%), higher PUFA (56.1% and 54.9%) and lower MUFA. Among intercropped lentils (TIL), TIL1 and TIL2 presented profiles comparable to TCL2 and TCL3, while TIL3 showed the highest linoleic acid content (47.6 ± 0.1%) and the lowest α-linolenic acid (9.2 ± 0.3%) of all Year 2 samples, a marked divergence from the other TIL samples (13.4-13.5%) that may reflect plot-specific variability rather than a consistent intercropping effect. Comparing Year 2 with Year 1 results, the overall fatty acid profiles were broadly similar, with PUFA dominance maintained throughout, though the high oleic acid content of TCL1 in Year 2 (30 ± 1%) contrasts with the more uniform distribution observed across Year 1 control samples.

Table 25. Fatty acid composition (%) of lentil samples from the second year of intercropping in Morocco, Taoujdate control (TCL) and intercropped with almond (TIL), (mean ± SD).

Fatty acid (%)	TCL1	TCL2	TCL3	TIL1	TIL2	TIL3
C16:0	16.9±0.1	17.06±0.04	17.67±0.02	17.7±0.3	17.25±0.02	19.6±0.3
C18:0	4.2±0.2	3.262±0.002	3.3±0.1	3.0±0.1	2.612±0.004	3.40±0.05
C18:1n9c	30±1	23.5±0.2	24.0±0.2	23±0.1	23.3±0.2	20.3±0.1
C18:2n6c	36.15±0.04	42.6±0.3	41.96±0.03	42.4±0.2	43.5±0.1	47.6±0.1
C18:3n3	12.5±0.5	13.5±0.1	13.0±0.1	13.5±0.2	13.37±0.02	9.2±0.3
ΣSFA	21.1±0.3	20.32±0.04	21.01±0.1	20.7±0.2	19.86±0.03	23.0±0.4
ΣMUFA	30±1	23.5±0.2	24.0±0.2	23±1	23.3±0.2	20.3±0.1
ΣPUFA	49±1	56.1±0.2	54.9±0.1	55.9±0.3	56.8±0.1	56.7±0.2

TCL: Taoujdate Control Lentil; TIL: Taoujdate Intercrop Lentil with Almond. ΣSFA: total saturated fatty acids; ΣMUFA: total monounsaturated fatty acids; ΣPUFA: total polyunsaturated fatty acids. Values are expressed as mean ± SD (n = 2).

The sucrose contents measured in both years are consistent with published reference ranges for lentil seeds, with values falling within or slightly below the expected range when expressed on a fresh weight basis, consistent with the approximately 10% seed moisture content recorded (Figure 2).

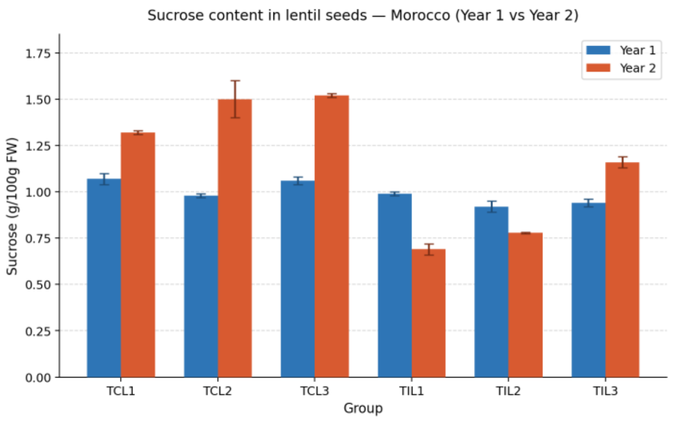

Figure 2. Sucrose content (g/100g FW, mean ± SD) in lentil seeds from conventional (TCL) and intercropping (TIL) groups, Year 1 and Year 2, Morocco.

A clear inter-annual increase was observed in the conventional groups (TCL), rising from approximately 0.98–1.07 g/100g FW in Year 1 to 1.32–1.52 g/100g FW in Year 2, likely reflecting greater sensitivity to temperature and drought stress during grain filling. In contrast, intercropping groups (TIL) showed heterogeneous responses, with TIL1 and TIL2 decreasing and TIL3 increasing in Year 2, suggesting that spatial variability in resource competition within intercropping plots influences carbon partitioning to seeds differently across replicates.

The elevated sucrose levels in TCL groups in Year 2 may also imply increased RFO accumulation, with consequences for both stress tolerance and nutritional quality. The low coefficients of variation (< 4%) across all groups confirm the analytical reliability of the HPLC method. Overall, cropping system and growing season interact to modulate sucrose accumulation under Moroccan field conditions. Sucrose was consistently identified as the majority sugar in the almond kernels and fava bean samples from Morocco, across both production years and all treatments (Figure 3 and 4).

In almond, sucrose content was generally higher in the first year of production than in the second, with control samples ranging from 4.03–4.93 g/100 g fw in Year 1 to 4.14–4.16 g/100 g fw in Year 2. No consistent effect of intercropping was observed: fava bean intercropping was associated with a slightly higher sucrose content relative to the control in Year 1, but with a marked decrease in Year 2, while lentil intercropping showed the opposite pattern, with lower and more variable sucrose content in both years. This inconsistency, together with the high variability recorded within the lentil-intercropped almonds in Year 1, points to plot-level and interannual variability as the main drivers of sucrose accumulation rather than a systematic effect of the intercropping system, consistent with the pattern already observed for phenolic compounds and bioactivity at this trial site.

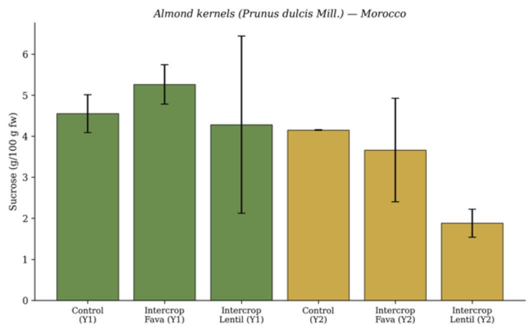

Figure 3. Sucrose content (g/100 g fw, mean ± SD) in almond kernels (*Prunus dulcis* Mill.) from control and intercropped (fava bean, lentil) plots at the Azilal and Ain-Taoujdate demo sites, Year 1 and Year 2, Morocco.

In fava bean, sucrose content was comparable between control and intercropped plots at the Azilal site in Year 1 (2.53 and 2.52 g/100 g fw, respectively), while at Taoujdate the intercropped samples showed lower sucrose content in Year 1 but higher and more variable content in Year 2, exceeding the corresponding control. The intercropped samples presented the highest sucrose content recorded among fava bean treatments (5.34 g/100 g fw), although this estimate should be interpreted with some caution given the data limitations described below.

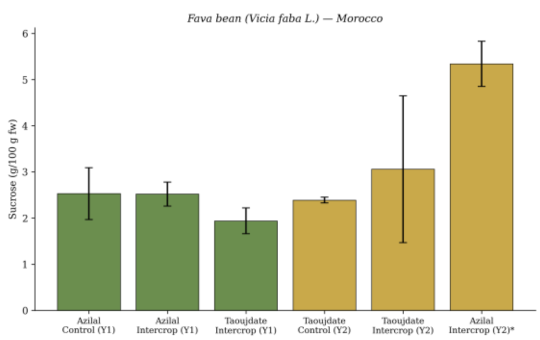

Figure 4. Sucrose content (g/100 g fw, mean ± SD) in fava bean (*Vicia faba* L.) samples from control and intercropped plots at the Azilal and Ain-Taoujdate demo sites, Year 1 and Year 2, Morocco.

7. Conclusions

The chemical characterisation of almonds and intercrop species across the five VALMEDALM trial sites revealed that organic acid, fatty acid and sugar profiles were primarily shaped by site-specific conditions, irrigation regime and production year, rather than by the intercropping systems themselves. Across all countries, succinic acid consistently emerged as the dominant organic acid in almond kernels, while sucrose was confirmed as the principal sugar fraction, accounting for the large majority of total carbohydrate content wherever sugar profiling was performed. The fatty acid composition of almonds followed the typical *Prunus dulcis* pattern in every trial site, with oleic acid as the predominant constituent, followed by linoleic and palmitic acids, and this overall lipid signature remained stable irrespective of the associated cropping system.

Where significant variation was detected, it was most frequently attributable to interannual differences or to water availability rather than to the presence of a companion crop, as observed in Portugal, where rainfed conditions consistently promoted higher sugar and organic acid accumulation than irrigated conditions, and in Italy, where sucrose content declined markedly between the first and second harvest years across all treatments. Genetic and cultivar-related factors also played a relevant role, as seen in Croatia, where fatty acid composition differed mainly according to almond cultivar rather than management practice, and direct intercropping effects on the almond chemical profile were, in most cases, modest or inconsistent, with treatment differences generally falling within the range of natural plot-to-plot variability. Nonetheless, some indications of an intercropping influence were observed in the associated legume species, namely in the fatty acid profile of chickpea and lentil in Portugal and Morocco, where companion cropping with almond appeared to shift the relative proportions of oleic and linoleic acids, and in the sucrose dynamics of lentil seeds in Morocco, which responded differently to intercropping depending on the production year.

Overall, these results suggest that the legume and aromatic plant intercropping systems evaluated within VALMEDALM can be integrated into Mediterranean almond orchards without compromising the chemical quality of the almond kernel, while potentially conferring agronomic and environmental co-benefits associated with these consociations. The variability observed across countries and years underscores the importance of site-specific and multi-year monitoring when assessing the impact of intercropping strategies on tree nut composition and reinforces the value of the broader VALMEDALM dataset in capturing this complexity across contrasting Mediterranean conditions.