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Camelina Intercropping with Pulses a Sustainable Approach for Land Competition between Food and Non-Food Crops

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Abstract: With increasing global attention toward the need for mitigating climate change, the transition to sustainable energy sources has become an essential priority. Introducing alternative oilseed crops, such as camelina (*Camelina sativa* L.), into intercropping systems with staple food crops can mitigate ILUC (indirect land use change) and their negative impact on biofuel production. The present study compared camelina + field pea intercropping (ICw + IP, winter sowing) and camelina + lentil intercropping (ICs + IL, spring sowing) with their respective single crops regarding weed control, soil coverage, yields, and camelina seed quality (1000-seed weight, oil, and fatty acid composition). The comparison between different cropping systems was conducted using a one-way ANOVA. Both intercropping improved weed control at an early stage but no differences in soil coverage were found. Camelina seed yield was negatively affected by the presence of peas, whereas the pulse was unaffected. Conversely, camelina seed yield was not affected when intercropped with lentils while lentils reduced their yield in the intercropping. Furthermore, when camelina was intercropped with lentils, a significant increase was reported in 1000-seed weight and α -linolenic acid (C18:3) compared with the sole-camelina. However, both intercropping systems had a land equivalent ratio (LER, based on total seed yield at maturity) higher than one. Defining the best combination of crops and the optimal sowing and harvesting settings remain key to increasing the adoption of intercropping systems by farmers.

Keywords: intercropping; organic farming; camelina; oilseed crop; pulses; climate change; multiple feedstocks; indirect land use change

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1. Introduction

With increasing global attention to the need for mitigating climate change, the transition to sustainable energy sources has become an essential priority. The Conference of the Parties (COP28) has played a crucial role in shaping the direction of global environmental and energy policies. In this urgent context, oilseed crops have emerged as a key component of the transition towards a low-carbon society. Notably, while oilseed crops can be used to produce renewable diesel, numerous studies have specifically explored their utilization in creating aviation biofuels [1–5]. However, the environmental benefits of Sustainable Aviation Fuels (SAFs) derived from conventional food crops may be compromised by indirect land use changes (ILUCs). To address this, integrating oilseed cover crops with major crops into the rotation or intercropping can mitigate ILUCs and their negative impact on biofuel production, leading to savings in the need for additional cropland. This approach can lead to savings in the need for additional cropland. Camelina (*Camelina sativa* L. Crantz), a minor oilseed crop belonging to the Brassicaceae family, holds great promise as a sustainable and eco-friendly alternative in the renewable energy landscape. This renewed interest is driven by its advantageous industrial and agronomic characteristics [6,7], including its ability to adapt to various environments and its resistance to biotic and abiotic stresses [6,8,9]. In many studies, camelina has shown tolerance to some common pests and diseases of the Brassicaceae family [10–12]. Camelina is a short lifecycle crop and has both winter and spring biotypes [9,13], and its elevated seed oil content ranges from 30 to 42%. It also boasts high levels of polyunsaturated fatty acids (PUFAs) exceeding 50% and monounsaturated fatty acids (MUFAs) at approximately 30% [14]. Weeds are a major problem for growing camelina [6,15,16]. Research on herbicide-free weed control approaches in oilseed crops, including camelina, is limited, but some studies have explored mechanical methods [17] and intercropping techniques [15,18,19]. Introducing a third competitor into the crop–weed system can alter the resource usage (i.e., water, light, soil, nutrients, etc.), potentially enhancing the competitive advantage of crops against weeds [20]. Yet, there is still a need to better understand the potential yields of camelina within various intercropping systems. The advantages of the intercropping system include enhanced resource utilization [21], as diverse crops with different nutrient requirements are planted together [22]. Pulses, for instance, are often included in intercrops because of their ability to fix atmospheric nitrogen, increasing its bioavailability in the soil and also benefiting the companion plants [22–25]. In organic farming systems, where chemical inputs are forbidden, finding sustainable strategies that improve yields and resource efficiency is extremely crucial. Intercropping could improve soil fertility [26,27], promote natural pest control [28,29], and reduce the risk of complete crop failure, contributing to a resilient and sustainable agricultural ecosystem [30]. Additionally, intercropping systems often increase overall yields and provide economic benefits by diversifying agricultural production and income sources for farmers [31]. However, farmers interested in diversifying their cropping systems often cite a lack of appropriate machinery and equipment as a significant barrier [32].

Integrating camelina into existing traditional food/feed cropping systems successfully hinges on understanding the effects of these new intercropping systems on seed yield and quality. Therefore, the objectives of this study were to assess the effects of camelina–field pea (*Pisum sativum*) and camelina–lentil (*Lens culinaris)* intercropping on (i) weed competition, (ii) seed yields and land use productivity, and (iii) fatty acid composition. We hypothesized that the intercropping system would increase total seed yield compared with the respective monoculture, due to greater soil coverage, improved weed control, and better resource sharing. Additionally, we expected that the inclusion of camelina would not negatively impact the yields of the main crop, and vice versa. Furthermore, the seed quality of camelina would remain high, maintaining its appeal for the biofuel industry.

2. Materials and Methods

2.1. Experimental Layout of the Trials

The field experiment was carried out during two growing seasons 2021–2022 and 2022–2023 at the organic experimental farm of the University of Bologna in Ozzano dell'Emilia (44°26′2.6″ N; 11°28′46.3″ E). Soil samples were taken each year before sowing to assess the physical and chemical condition of the soil. The soil was characterized as clay loam, with average N and P content, as reported in Table 1.

Table 1. Main soil physical/chemical properties of the experimental trials in the two considered years.

Years	Location	Texture	pH in KCl	Organic C [g/kg] [33]	N tot [g/kg] [33]	Available Nutrients [mg/kg of Soil]	
						P [33]	K [33]
2021–2022	Ozzano dell'Emilia	clay loam	7.75	13.44	1.41	101	454
2022–2023			6.91	9.51	1.24	132	213

The experiment consisted of two distinct trials defined as follows: (i) winter trial: camelina–field pea intercropping (ICw + IP) compared with sole-camelina (SCw) and sole-field pea, (SP); (ii) spring trial: camelina–lentil intercropping (ICs + IL) compared with sole-camelina (SCs) and sole-lentil (SL). The experimental design for both trials was a completely randomized block design with four replicates, with an individual plot size of 18 m^2.

The camelina cultivar Cypress, provided by Smart Earth Camelina, Saskatoon, Canada, was used in both winter and spring trials. Field pea variety Navarro, supplied by Società Italiana Sementi, S.I.S., Bologna, Italy, and the lentil variety Itaca, supplied by Società Produttori Sementi, ISEA, Rome, Italy, were employed in the intercropping experiment. Sole-camelina (SCw, sown in winter, and SCs, sown in spring), sole-field pea (SP), and sole-lentil (SL) were sown at 8 kg ha^{-1}, 200 kg ha^{-1}, and 160 kg ha^{-1}, respectively. In the intercropping systems, these rates were halved (50:50). Sole crops were row-seeded, while in the intercropping system, camelina (ICw and ICs) was broadcasted onto the row-seeded pulses (i.e., IP and IL) (Figure 1). This spatial organization of the experiment was chosen as the most easily acceptable by local organic farmers interviewed within the SCOOP project.

Figure 1. Neighborhood model to assess the spatial arrangement (50:50) of broadcasted camelina (yellow flowers) into the row-seeded pulse plants (green plants) in the intercropping systems.

In both trials, the interrow distance was maintained at 0.17 m, regardless of the crops. The sowing depths were 50 mm for field peas, 30 mm for lentils, and 5 mm for camelina. Sowing occurred at the end of October for the winter trial and between the end of February and the beginning of March for the spring one (Table 2). Winter wheat (*Triticum aestivum*) was always the preceding crop. Prior to sowing, the soil was plowed and harrowed. All the trials were conducted without fertilization. In the first year, emergency irrigation was applied due to prolonged drought following the spring trial sowing, which prevented the establishment of the crops.

Table 2. Main dates and growing cycle characteristics in terms of temperatures (minimum and maximum) and precipitation of the two intercropping systems in the two study seasons.

Year	Intercropping System	Sowing Date	Harvest Date	Cycle Length (d) *	Mean Minimum Temperature (°C) *	Mean Maximum Temperature (°C) *	Cumulative Precipitation (mm) *
2021–2022	Camelina + field pea	26/10/2021	14/06/2022	231	5.2	14.3	554
	Camelina + lentil	25/02/2022	04/04/2022	129	10	21.8	311
2022–2023	Camelina + field pea	27/10/2022	08/06/2023	224	6	14.7	741
	Camelina + lentil	09/03/2023	29/06/2023	112	10.8	23	476

* Calculated from sowing to harvest of each system.

2.2. Meteorological Data

Main daily meteorological data (minimum and maximum temperature, and precipitation) were recorded from the meteorological station located at the experimental farm (Table 2). The experimental site has a typical Mediterranean climate with mild and wet winters and hot and dry summers. Nevertheless, the two study years deviated from the historical average (last 10-year mean), especially regarding precipitation. The first growing season (from 1 November 2021 to 31 October 2022) recorded a mean temperature of 0.5 °C higher and a cumulative precipitation of 22 mm lower compared with the long-term averages. In the second season (from 1 November 2022 to 31 October 2023), the mean temperature was 1.4 °C higher, and the cumulative precipitation was 115 mm lower than long-term averages. In particular, February 2022 was hot (+1.8 °C) and dry (−99 mm), so an emergency irrigation after spring trial sowing was necessary. Nevertheless, April 2022 and May 2023 were characterized by heavy rainy events that exceeded the long-term average precipitation of 95 and 189 mm, respectively. In April 2022 both winter and spring-sown crops were at the flowering stage during these events, while in May 2023 the winter-sown crops were developing pods and seeds, and the spring ones were at the end of flowering. This excess of rain caused, especially in the second year, the lodging of plants and waterlogging, resulting in a negative impact on all crop yields, especially on the sole crops which had not established bivalent support as in the intercropping.

2.3. Agronomic Surveys

Weed competition at the early stages (BBCH 104–106) was observed in the winter trial in both years and only in the second year for the spring one. In each plot, weed flora was visually surveyed in three randomly placed 0.3 × 0.3 m squares. Soil coverage was measured at the rosette stage using a precision agriculture smartphone application called Canopeo (http://www.canopeoapp.com, 30 October 2021) by taking three photos at 0.60 m from the soil for each plot.

2.4. Productive Surveys

The winter trial harvest took place at the beginning of June, while for the spring trial, it occurred at the end of June or at the beginning of July (Table 2). Upon reaching full maturity, all plants within a central 4 m^2 area of each plot were manually cut at soil level and weighed to determine plant and weed total biomass (PTB and WTB). Two different strategies were employed for threshing the samples: for the sole crops, a plot combine was utilized (Classic ST, Wintersteiger, Ried im Innkreis, Austria), while for the intercropping systems, both crops were threshed together using a laboratory thresher (LD 180, Wintersteiger, Ried im Innkreis, Austria), and followed by a process in which the seeds of the two species were separated using sieves. Residual moisture content in the total biomass, straw, and seed was measured by weighing and oven drying representative sub-samples of 10 g for each replicate at 105 °C until constant weight. Furthermore, the harvest index (HI) was calculated as the ratio of seed to total shoot dry matter.

2.5. Estimation of the Competition Indices for the Intercropping Systems

2.5.1. Land Equivalent Ratio

The land equivalent ratio (LER) quantifies the additional land area required for sole cropping to achieve the equivalent agricultural output of an intercropping system. LER suggests that intercropping is more efficient in utilizing ecosystem resources compared with cultivating a sole crop [34]. The LER values were calculated as follows:

$$LER = LER_{camelina} + LER_{pulse} \quad (1)$$

$$LER_{camelina} = \frac{Yic}{Ysc} \quad (2)$$

$$LER_{pulse} = \frac{Yip}{Ysp} \quad (3)$$

where

Yic = yield of camelina in the intercropping system.

Ysc = yield of sole-camelina.

Yil = yield of pulse in the intercropping system.

Ys = yield of the sole pulse.

If the LER value is >1, intercropping is more efficient than monoculture. Conversely, when LER is <1, intercropping negatively affects the growth and yield of plants in mixtures.

2.5.2. Competitive Ratio

The competitive ratio (CR), introduced by [35], assesses the competitive ability of different species in intercropping systems, specifically focusing on camelina relative to the companion crop. The competitive ratio was calculated as follows:

$$CR\ camelina = \left(\frac{LER\ camelina}{LER\ pulse} \times \frac{Zpc}{Zcp}\right) \quad (4)$$

$$CR\ pulse = \left(\frac{LER\ pulse}{LER\ camelina} \times \frac{Zcp}{Zpc}\right) \quad (5)$$

where

Zpc = sown portion of camelina to pulse.

Zcp = sown portion of pulse to camelina.

If $CR_{camelina} > 1$, it indicates that the competitive ability of camelina is higher than that of pulse in the intercropping system, and if $CR_{camelina} < 1$, then camelina is less competitive than pulse.

2.5.3. Aggressivity Index

Aggressivity (A) is a competitive index, which is a measure of how much the relative yield of one crop component is greater than that of another [36]. Aggressivity is expressed as follows:

$$A_{camelina} = LER_{camelina} - LER_{pulse} \quad (6)$$

$$A_{pulse} = LER_{pulse} - LER_{camelina} \quad (7)$$

If $A_{camelina}$ or $A_{pulse} = 0$, both crops are equally competitive. When $A_{camelina}$ is positive then camelina is dominant and when it is negative then pulse is the dominating species.

2.5.4. Relative Crowding Coefficient

Another coefficient utilized was the relative crowding coefficient (RCC or K), which measures the relative dominance of one species over another within a mixture [37].

$$K = K_{camelina} \times K_{pulse} \tag{8}$$

$$K\ camelina = \left(\frac{Yic}{(Ysc - Yic)} \times \frac{Zpc}{Zcp} \right) \tag{9}$$

$$K\ pulse = \left(\frac{Yip}{(Ysp - Yip)} \times \frac{Zcp}{Zpc} \right) \tag{10}$$

When the product of the two coefficients ($K_{camelina} \times K_{pulse}$) is greater than 1, there is a yield advantage, when K is equal to 1 there is no yield advantage, and when it is less than 1 there is a disadvantage.

2.5.5. Monetary Advantage Index (MAI)

The economic viability of intercropping compared to sole cropping was assessed through the monetary advantage index (MAI). MAI serves as an indicator for determining the economic feasibility of intercropping. This calculation, as outlined by Ghosh, 2004 [38], follows the below equation:

$$MAI = \frac{[(Pc \times Yic) + (Pp \times Yip))] \times (LER - 1)}{LER}$$

where P_c = price of camelina; Y_{ic} yield of camelina in intercropping; P_p = price of pulse; Y_{ip} = yield of pulse in intercropping; and LER = land equivalent ratio. The average prices of the component crops were derived from typical Italian market prices for organic products, provided by AIAB (Italian Association for Organic Farming) as follows: camelina 900 EUR/Mg, lentil 800 EUR/Mg, field pea 270 EUR/Mg. A positive MAI value indicates a profitable cropping system [38], and the higher the MAI the better it is.

2.6. Assessment of Seed Quality

2.6.1. Determination of 1000-Seed Weight (TKW) of Camelina Seeds

On harvested camelina seeds, 1000-seed weight was surveyed on a representative seed sample for each replicate. Samples were carefully cleaned by means of a lab blower, then 1000 seeds were counted with an automatic seed counter (DataCount S25, Data Technologies, Tsor'a, Israel), and their weight was determined by means of a precision balance (WLC, Radwag, Radom, Poland). Camelina seed oil content and FA profile were determined in the laboratories of Bologna University, located in Cesena (Italy).

2.6.2. Determination of Camelina Seed Oil Content

Oil was extracted from camelina seeds and gravimetrically determined according to the procedure described by [39]. Briefly, oil extraction was carried out for 2 h on 1.5 g of ground seeds in an in-line Soxhlet extraction unit, using 60 mL of n-hexane as organic solvent. After drying the extract over anhydrous sodium sulfate, solvent was removed under reduced pressure in a rotary evaporator. The residual oil was weighed and stored at −18 °C in n-hexane/i-propanol 4/1 (*v*/*v*) for further analyses. For full details, see the before-mentioned study by [39].

2.6.3. Determination of Fatty Acids by Gas Chromatography (GC)

Bound fatty acids (FAs) were derivatized and then analyzed by GC as fatty acid methyl esters (FAMEs) after a cold transmethylation procedure (Christopherson and Glass, 1969) was performed on 20 mg of oil. A gas chromatograph (mod. 7820A) from Agilent Technologies (Santa Clara, CA, USA) equipped with a flame ionization detector (FID) was used. Compound separation was carried out on a polar capillary column BPX70 (30 m × 0.25 mm i.d.; film thickness: 0.25 µm; stationary phase: 70% cyanopropyl polysilphenylene-siloxane) from SGE Analytical Science (Ringwood, Australia). Fatty acids were identified by matching peak retention times with those of a FAME standard mixture. The relative amount of each fatty acid was determined from the ratio of its peak area to the sum of the peak areas of all FAs identified in the GC trace. For full details about FA transmethylation and GC operating conditions, see the study by [40].

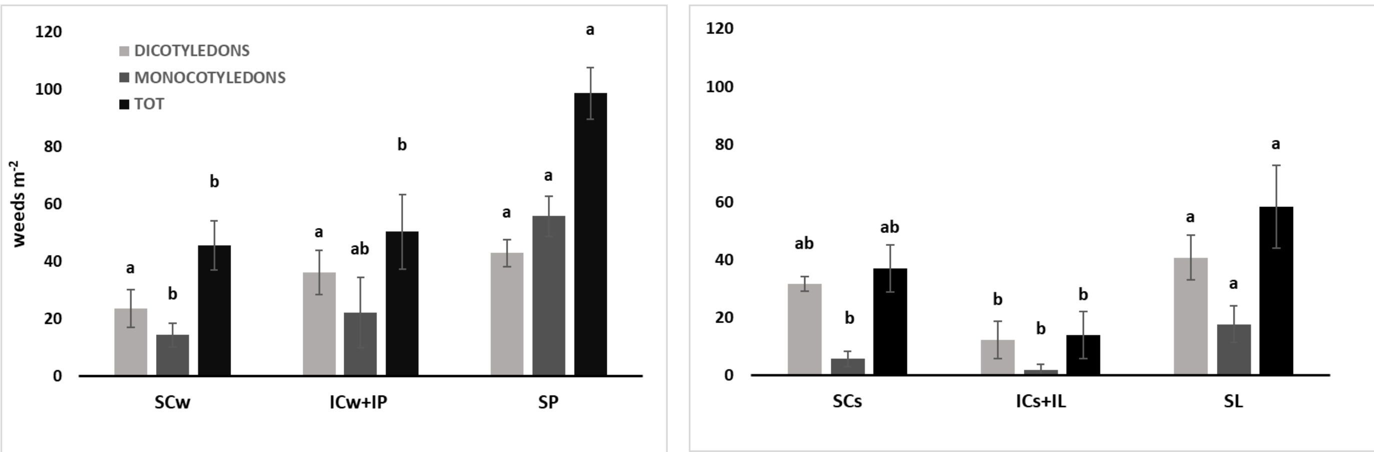
2.7. Statistical Analysis

Prior to analysis of variance (ANOVA), the homoscedasticity of data was verified by performing Barlett's Test ($p \leq 0.05$). All the surveyed parameters for each trial were subjected to a one-way ANOVA to determine the effects of treatments using STATGRAPHICS Centurion 19 (Centurion, Statpoint, Herndon, VA, USA). One-way ANOVA was chosen as the most appropriate way to analyze the data, since "year" was considered a random effect, so it was not included as a fixed factor in the analysis. Statistical differences between the means were assessed using the least significant difference (LSD) test with a significance level of 5%.

3. Results

3.1. Agronomic Results

Concerning the winter trial, the total weed presence, surveyed at BBCH 104–106, was significantly higher in SP compared with SCw and ICw + IP, particularly in relation to the higher presence of monocot weeds (Figure 2a). Nevertheless, soil coverage, expressed as a percentage, did not significantly differ among treatments, reporting an average value of 47%. The spring trial showed similar results regarding weed population at an early stage (Figure 2b). The synergy between camelina and lentil facilitated the competition against weeds in comparison to SL, where lentil plants were greatly suffering from weed pressure. Also, the soil coverage did not show significant differences among treatments, with an average percentage of 42%, although it varied between the two study years due to different weather conditions. In the first year, the plants reached an average soil cover of 10% at 43 DAS (Days After Sowing), while in the second one, it was already around 70% at a similar growth stage (49 DAS).



(**a**) (**b**)

Figure 2. Weed population density. (**a**) Winter trial: SCw, winter sole-camelina; SP, sole-field pea; ICw + IP, camelina–field pea intercropping. (**b**) Spring trial: SCs, spring sole-camelina; SL, sole-lentil; ICs + IL, camelina–lentil intercropping. Vertical bars: standard error. Different letters: statistically different means for $p \leq 0.05$ (LSD test).

3.2. Productive Results

As expected, camelina concluded its growth cycle in perfect synchrony with peas, whereas lentils were slightly late (approximately 10 d), but thanks to the non-dehiscence of the camelina's siliques, there was no seed loss. The results obtained at harvest for weed biomass (WTB) and plant total biomass (PTB), seed and straw yield, and HI are reported in Table 3.

Table 3. Productive results surveyed at harvest in response to the main effect of the cropping system on plant (PTB) and weed total biomass (WTB), seed and straw yields, and harvest index (HI) in the two considered growing seasons. SP, sole-field pea; SCw, winter sole-camelina; ICw + IP camelina–field pea intercropping; SL sole-lentil; SCs spring sole-camelina; ICs + IL camelina–lentil intercropping. Different letters: statistically different means for $p \leq 0.05$ (LSD test).

Sowing Season	Type of Cropping System	PTB	WTB	Straw Yield	Seed Yield			HI
					Camelina	Pulse	TOT	
		(Mg DM ha^{-1})						
Winter	SP	4.52 [b]	0.55	2.75 [b]	-	1.77	1.77	0.37 [a]
	SCw	4.41 [b]	0.68	3.14 [b]	1.27 [a]	-	1.27	0.23 [b]
	ICw + IP	7.25 [a]	0.48	5.46 [a]	0.62 [b]	1.18	1.79	0.26 [b]
Spring	SL	2.78	0.75	1.67 [ab]	-	0.30 [a]	0.30 [b]	0.17
	SCs	1.99	0.61	1.49 [b]	0.33	-	0.33 [ab]	0.14
	ICs + IL	2.58	0.52	2.45 [a]	0.3	0.16 [b]	0.46 [a]	0.12

In the winter trial, the weed biomass did not significantly differ between sole crops and intercropping systems (grand mean: 0.57 Mg ha^{-1}). Nevertheless, the winter intercropping (ICw + IP) reported a significantly higher straw yield compared with SCw (+42%) and SP (+50%), and the same trend was also evidenced for the total biomass (seed and straw yield, Table 3). The seed yield of camelina in the intercropping (ICw) was negatively affected by the combination with the pulse, with a decrement of 53% compared with the sole crop system (SCw, Table 3). However, field peas did not show significant differences in seed yield in the sole crop (SP) compared with the intercropping (IP, Table 3). Nevertheless, when considering the different cropping systems as a whole (SP vs. SCw vs. ICw + IP), no significant differences were surveyed among seed yields (Table 3). Lastly, when analyzing the HI (harvest index), sole-field pea reported a significantly higher value (0.37) compared with sole-camelina (0.23) and intercropping (0.26).

Analyzing the results for the spring trial, no significant differences were reported for weed and plant total biomass. However, in spring the intercropping system (ICs + IL) showed a significantly higher straw yield compared with SCs, and overall, it produced a higher seed yield compared with SL (Table 3). No significant differences were reported for HI (Table 3). But, when separately analyzing the seed yields of individual crops, lentil significantly reduced its yield by 46% in intercropping (IL) compared with the sole crop (SL), while camelina did not.

3.3. Competition Indices Results

Both intercropping systems (i.e., ICw + IP and ICs + IL) provided yield advantages for camelina and pulses, as evidenced by the LER (based on total seed yield at maturity) exceeding 1.00 (Table 4). However, upon closer examination, the partial LERs were either equivalent or exceeded 0.5. This suggests that each species in the intercropping systems yielded seeds equal to or higher than their respective yields in monoculture. Moreover, the relative crowding coefficient (K) was greater than one in both intercropping systems (Table 4). The higher K value observed in spring intercropping is attributed to the slightly lower yield of SCs compared with ICs. When analyzing the competition indicators (Table 4), peas showed higher competitiveness when grown with camelina ($CR_{camelina} < 1$). Conversely, in spring intercropping, camelina exhibited significantly higher competitiveness compared with lentils ($CR_{camelina} > 1$). The aggressivity index (Table 4) revealed that in winter, aggressiveness slightly favoured peas over camelina (−0.18), whereas in spring, camelina showed high dominance over lentil (+0.47). All the MAI values were both positive due to LER values which were greater than one showing a definite yield advantage of camelina intercropping systems. In particular, the MAI of the spring intercropping was higher in relation to higher prices of the produced seeds in the organic market.

Table 4. Land equivalent ratio (LER), competitive ratio (CR), relative crowding coefficient (K), the aggressivity index (A), and the monetary advantage index (MAI) in the intercropping systems: ICw + IP camelina–field pea intercropping; ICs + IL camelina–lentil intercropping.

	LER			K			CR		A		MAI
	Camelina	**Pulse**	**Tot**	**Camelina**	**Pulse**	**Tot**	**Camelina**	**Pulse**	**Camelina**	**Pulse**	**Tot**
ICw + IP	0.49	0.67	1.16	0.95	2.01	1.91	0.73	1.37	−0.18	0.18	121
ICs + IL	0.99	0.52	1.51	114	1.08	122	0.5	0.26	0.47	−0.47	131

3.4. Results on Camelina Seed Quality

Camelina seed quality was surveyed by determining the 1000-seed weight (Figure 3), seed oil content, and fatty acid profile (Table 5).

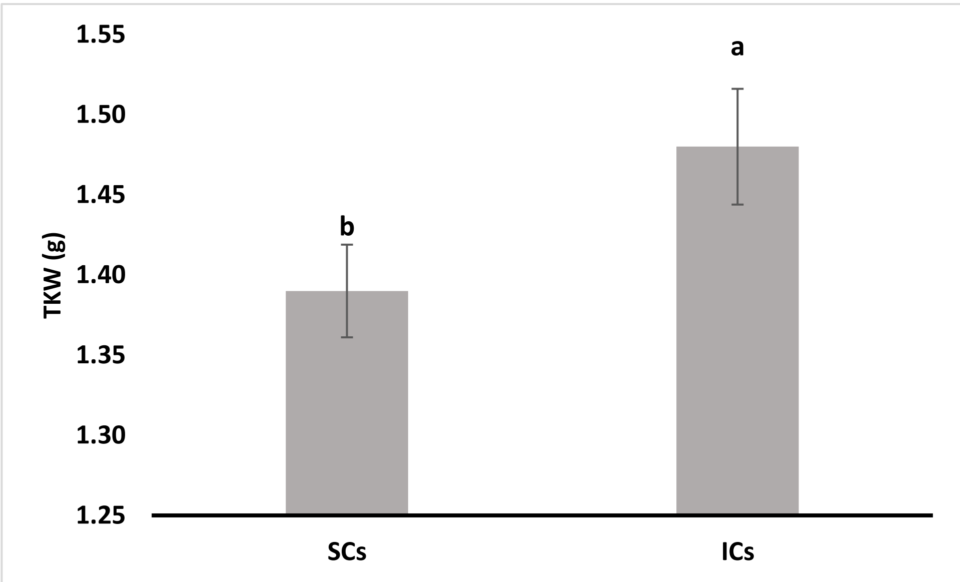


Figure 3. A 1000-seed weight (thousand seed weight, TKW) of camelina intercropped with lentil (ICs) compared with spring sole-camelina (SCs). Vertical bars: standard error. Different letters: statistically different means for $p \leq 0.05$ (LSD test).

Significant differences in 1000-seed weight were observed in the spring trial, with camelina benefiting from intercropping (1.48 vs. 1.39 g, $p \leq 0.05$, in ICs vs. SCs, respectively), while no significant differences were observed in the winter trial (grand mean: 1.49 g).

While no significant effects were observed in seed oil content in either the winter or spring trial (grand mean: 31.7% and 27.8%, respectively), the final oil yield per hectare, mirroring seed yield, was significantly higher in SCw compared to ICw (Figure 4).

Table 5. Camelina seed oil content (%), main FA content (%), i.e., oleic (C18:1), linoleic (18:2), α-linolenic (C18:3), and erucic (C22:1) acid, and FA groups, i.e., SFAs (saturated FAs), MUFAs (monounsaturated FAs), PUFAs (polyunsaturated FAs), in response to the different cropping systems: SCw = winter sole-camelina; ICw = winter intercrop-camelina; SCs = spring sole-camelina; ICs = spring intercrop-camelina. Different letters: statistically different means for $p \leq 0.05$ (LSD test).

	Seed Oil Content	C18:1	C18:2	C18:3	C22:1	SFA	MUFA	PUFA
SCw	30.4	12.96	19.65	32.48	3.56	10.39 [a]	33.40	56.21
ICw	33.0	13.27	18.95	33.38	3.39	10.06 [b]	33.56	56.38
SCs	28.1	12.68	18.98 [a]	33.39 [b]	3.90	10.28 [a]	33.19 [a]	56.54 [b]
ICs	27.5	12.52	18.38 [b]	34.32 [a]	3.88	9.97 [b]	33.08 [b]	56.95 [a]

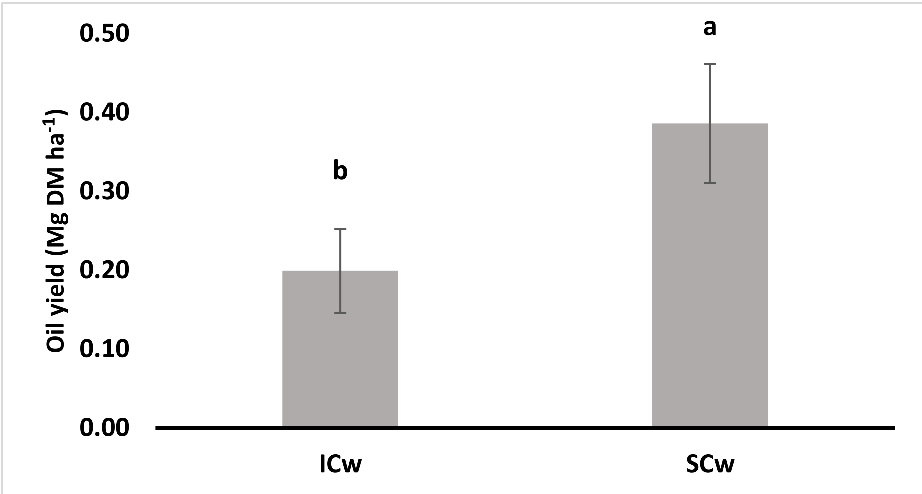


Figure 4. Oil yield (Mg DM ha^{-1}) of camelina intercropped with field pea (ICw) compared with winter sole-camelina (SCw). Vertical bars: standard error. Different letters: statistically different means for $p \leq 0.05$ (LSD test).

In both winter and spring trials, significant but negligible differences in the main FAs characterizing camelina oil were reported in Table 5. Specifically, in the winter trial, significant differences were reported only in SFAs, which were higher in SCw compared to ICw. On the other hand, spring intercropped camelina (ICs) exhibited a significant decrease in linoleic acid (C18:2) and an increase in α -linolenic acid (C18:3) compared with sole-camelina (SCs). Consequently, these changes resulted in significant differences in all main groups of fatty acids (i.e., SFA, MUFA, PUFA, Table 5).

4. Discussion

Cropping system diversification plays a significant role in the transition toward a more sustainable and ecological agriculture [40]. However, there is a lack of information regarding the adaptability of minor oilseed crops, such as camelina, to intercropping systems, particularly those including pulses. Therefore, in the present study, camelina was evaluated in two different intercropping systems, with the aim of demonstrating the feasible production of differentiated feedstocks (food and non-food) from the same piece of land.

According to the obtained results, weed competition was reduced in the winter intercropping system compared with the sole pulse at the early stages of growth. This effect may be related to the allelopathic effects of camelina against weeds, as previously demonstrated by Gilchrist and Trenbath [41] on wild oat and flax. The ability to delay weed germination in agriculture can provide cultivated crops with a competitive edge, allowing them to establish before weed growth occurs. Using allelopathic crops in mulching, intercropping, and rotations is considered a strategic and sustainable measure for weed management. Nevertheless, in the present study, at the end of the growing cycle, all cropping systems were affected by high weed pressure. Conversely, research conducted by Leclére et al. [15] illustrated that increasing camelina seeding rate or practicing intercropping with peas or barley led to a decrease in weed biomass under different agricultural conditions.

In the present study, a 50:50 sowing density ratio was applied in all the intercropping systems compared with the respective monocultures. This configuration presumably did not allow for higher soil coverage throughout the entire growing cycle compared to the sole crop. In contrast, in the study by Saucke et al. [18], camelina significantly contributed to the total crop canopy during the critical establishment period of field pea (beginning of flowering), especially within rows, due to the formation of the characteristic layer of leaves at the rosette stage. Presumably, in the northern Italian conditions, the camelina rosette stage was shorter and the rosette dimension was less expanded than in the German conditions [18]. This difference may be attributed to higher temperatures and lower precipitation amounts, which could have led to a higher weed presence at harvest, even in the studied intercropping systems.

Camelina seed yield was negatively affected by the presence of peas, whereas the latter was unaffected. Conversely, in the camelina–lentil intercropping, camelina seed yield was not affected, but lentil reduced its seed yield. These results could be explained by the differences in the canopy structures of sole and intercrops. On the one hand, sunlight reaching lower canopy layers was likely greater in camelina intercropped with lentil due to the significant difference in height between the two species, thereby reducing self-shading and increasing light interception capacity. On the other hand, the effect was the opposite in the winter trials, as camelina intercropped with vigorous pea plants reduced the interception efficiency compared with sole-camelina. This finding is also supported by the competition indices [i.e., relative crowding coefficient (K), competitive ratio (CR), and aggressivity index (A)]. In fact, camelina was the subordinate component when intercropped with pea, while it dominated when intercropped with lentil.

However, LER was greater than 1 in both studied intercropping systems and ranged from 1.16 in the camelina–field pea intercropping to 1.51 in the camelina–lentil intercropping. This means that for a LER of 1.51, the area allocated to sole crops should be 51% greater than the area dedicated to the intercropping system for the two individual crops to generate an equivalent combined yield. However, the high total LER obtained by the spring intercropping is mainly due to the high partial LER of camelina (0.99). The increased yield observed in the intercropping systems might be partially attributed to the complementary use of resources both in time and space between camelina and pulses, as demonstrated in previous studies [42,43]. For instance, camelina–pea intercropping, studied by Saucke and Ackermann [18], was also successful, but peas were marginally dominant without significantly affecting the performance of camelina. In addition, [44] studied camelina intercropped with other pulses, such as lupin, reporting LER values greater than one. Conversely, when camelina was intercropped with cereals [45], such as barley, the LER was lower than one, confirming the high pressure that the cereal caused on camelina without any clear productive benefits. It is worth mentioning that in the intercropping systems, sowing and post-harvest seed separation operations resulted in increased labor and costs, compared to sole cropping, as they required a two-step process. So, despite the positive and high MAI the real profitability of these systems needs to be thoroughly evaluated, taking into account not only the increased revenues but also the additional operational costs. In the present study, harvesting was carried out in a single step due to the synchronized growth cycle of the intercropped crops, and manual separation of two seeds was done thereafter. The future scale-up of intercropping systems will encompass the need for new equipment reducing human labor and making the seed separation automatized, as in many processing plans where optical devices are used to screen products.

From a qualitative point of view, the 1000-seed weight of camelina is consistent with the available literature for the same variety [46,47]. However, intercropping had an effect on seed weight for spring-sown camelina, where the seed weight was greater in the intercropping. Czarnic et al. and Kakabouki et al. [48,49] showed a significant increase in the weight of 1000 seeds as the amount of nitrogen in the fertilizer increased. Nevertheless, determining the mechanism of resource usage in camelina (e.g., transfer of symbiotically fixed N_2 to camelina) was not the aim of our study. Therefore, we are unable to determine whether N availability affected the observed increase in 1000-seed weight. Nevertheless, many studies reported that pulses increase overall nitrogen use efficiency in intercropping systems in relation to their ability for symbiotic nitrogen fixation and minimize competition for soil nitrogen [50–53]. Part of the nitrogen fixed by the legume is deposited into the soil, making it available for absorption by the roots of the non-fixing component [54–58]. In a legume–oilseed intercrop, as much as 10% of the early nitrogen accumulation in the oilseed component can originate directly from the legume [58,59]

Camelina seed oil content ranged from 27.5 to 33.0% in spring and winter trials, respectively, and the concurrent growth with another species did not affect this trait. However, the reported seed oil content was lower than in previous studies [6,7,60]. Oil yield exhibited the same trend as seed yield, as reported by Zanetti et al. [61], and it was higher when camelina was sown in winter and alone (0.39 Mg DM ha^{-1}). As far as the authors know, published data on camelina oil content in an intercropping system are very limited. The present results were in line with the study conducted by Chandra et al. [61] in India where camelina was inter-seeded within a jatropha (*Jatropha curcas*) plantation. Conversely, the present data were lower than the oil yield obtained in the intercropping with peas by Lèclere et al. [15]. Gesch et al. [62] studied the effect of camelina in relay cropping systems with soybean compared to the sole crop without obtaining significant differences between the two systems. The oil yield ranged from 0.41 to 0.45 Mg DM ha^{-1}.

Generally, fatty acid composition is under genetic control, but other factors like soil quality, climate, and weather conditions might also impact camelina oil composition [63,64]. Additionally, as many studies have reported [7,65,66], sowing date could significantly affect seed oil content and fatty acid composition of camelina oil. In the present study, some statistical differences among main fatty acids were observed, but they could have a negligible impact on camelina oil quality. One reliable hypothesis could be that the intercropping systems significantly affected camelina phenological development, resulting in non-contemporaneous flowering and seed-filling stages between the sole crop and intercropping. Consequently, the oil composition was affected by different climatic conditions, but only in the spring trials. In detail, intercropping systems would have anticipated the flowering phase in camelina, occurring earlier in the season when temperatures were presumably lower. This could lead to an increase in linolenic acid (C18:3) and a decrease in linoleic acid (C18:2), as already demonstrated by Righini et al. [67] and Walia et al. [68], These results should be carefully evaluated since it appears evident that not only intercropping systems could affect seed and oil yield, but also oil quality, which might have relevant consequences on the final end-uses of the produced feedstocks.

5. Conclusions

The new EU policy is pushing toward the adoption of sustainable intensification systems capable of providing multiple feedstocks from the same piece of land, without negatively impacting food production in accordance with the principle of ILUC mitigation. Therefore, the integration of a multi-purpose oilseed crop such as camelina should provide additional benefits to food crop production, with little to no repercussions. In light of the obtained results, the intercropping system in which camelina did not negatively affect the food crop seed yield was the one with field pea. Although camelina yield was reduced, this effect can be mitigated in the future by increasing the seeding rate of camelina. This measure, besides bringing a greater surplus to the final production, could also have a beneficial impact on soil coverage and weed control. Defining the best combination of crops and the optimal seeding settings remains crucial in increasing the adoption of intercropping systems. The combination of camelina and pulses represented a promising example in this direction, consistently achieving LER values exceeding one. Furthermore, this study, like many others, demonstrates the agronomic feasibility of intercropping systems but not their practical feasibility in terms of the optimization of equipment and mechanization systems needed. With rising labor costs, the need for mechanization techniques in intercropping systems is becoming urgent to reduce production costs and enhance the competitiveness of agricultural production. Therefore, future research should focus on developing and implementing mechanization solutions to fully realize the benefits of intercropping systems.

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Abbreviations

ICw + IP = winter inter-camelina + inter-field pea. ICs + IL = spring inter-camelina + inter-lentil. SCw = winter sole-camelina. SCs = spring sole-camelina. SP = sole-field pea. SL = sole-lentil.

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