agronomy

MDPI

Article

Intercropping as a Strategy for Weed Management in Faba Bean (*Vicia faba* L.)

Ángel M. Villegas-Fernández [1,*], Ahmed A. Amarna [1], Juan Moral [2] and Diego Rubiales [1]

[1] Institute for Sustainable Agriculture, Spanish National Research Council (CSIC), 14004 Cordoba, Spain; a.alashqar@yahoo.com (A.A.A.); diego.rubiales@ias.csic.es (D.R.)
[2] Department of Agronomy, University of Córdoba, 14071 Cordoba, Spain; juan.moral@uco.es
* Correspondence: avillegas@ias.csic.es

Abstract: Faba bean is an important legume crop worldwide, which is grown both for food and feed. As for many legume crops, postemergence weed control is difficult. The aim of this work was to assess the potential of intercropping in weed management by assessing the effect of mixing faba bean with different crops (wheat, barley, and pea) on weeds in the South of Spain. Four field trials were conducted over four consecutive seasons, and the results found that the addition of alternate intercropping of faba bean and barley achieved high levels of weed control, both for coverage and biomass (92.7% and 76.6%, respectively). Intercropping with wheat did not reduce weed coverage but did decrease weed biomass by 46.1% as compared with the faba bean monocrop. Intercropping with pea did not provide significant reductions in weed coverage or weed biomass. The diversity of the weed community was not altered by the different crop combinations tested. Additional experiments under controlled conditions were carried out to determine the possible role of barley allelopathy in weed suppression. A strong allelopathic effect entailing a reduction in the number of plants and biomass was detected for four weeds including *Sinapis arvensis*, *Polypogon monspeliensis*, *Matricaria camomilla*, and *Medicago truncatula*. It can be concluded that intercropping faba bean with barley is an excellent strategy for weed control in Southern Spain.

Keywords: allelopathy; faba bean; replacement intercropping; addition intercropping; weed control

check for updates

Citation: Villegas-Fernández, Á.M.; Amarna, A.A.; Moral, J.; Rubiales, D. Intercropping as a Strategy for Weed Management in Faba Bean (*Vicia faba* L.). *Agronomy* **2024**, *14*, 1170. https://doi.org/10.3390/agronomy14061170

Academic Editor: Andrea Peruzzi

Received: 16 April 2024
Revised: 22 May 2024
Accepted: 23 May 2024
Published: 30 May 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Legume crops are an essential component of sustainable agriculture, given the ecological services they provide, especially their ability to fix atmospheric nitrogen [1]. However, legume cultivation is hampered by biotic and abiotic stresses, which can seriously affect yield [2]. One of these is the competition of weeds, which is a serious challenge for managing these crops. Weeds may not only reduce crop yields, but they may also affect the quality of the grain [3], serve as alternative hosts for diseases and pests [4,5], or even hinder harvesting. In general, weed control methods must be implemented for legume crops since they are inefficient competitors [6]. Herbicides are the most widely used weed management method but present several drawbacks, such as high costs for the farmer, environmental damage, and the eventual appearance of weed resistance to the active ingredients. These resistances may be especially problematic, as no herbicides with new modes of action have appeared in recent years [7]. Other strategies are mechanical control and management of the spatial arrangement of crops [8,9].

Faba bean (*Vicia faba* L.) stands out as one of the most cultivated legumes worldwide for use in both animal feed and human consumption [10]. Weeds are one of the major biological constraints for faba bean, reducing yields by up to 50%, although they appear more competitive with weeds than other legumes [11].

Intercropping is the practice of growing two or more crop species simultaneously in one field. It may help in the control of weeds in many crops [12], complementing

herbicides if necessary [13], thus becoming a very valuable tool for organic and sustainable agriculture [14–16]. In the case of legumes, weed reduction has been reported when combined with diverse crops, such as corn, wheat, oat, barley, or rape [17–23]. There are different types of intercropping methods depending on the arrangement and sowing densities of the combined crops. Arrangement types include mixed intercropping, when plants are completely mixed, and alternate intercropping, when rows of each crop alternate regularly [24]. In addition intercropping, all crops are sown at their normal densities, while in replacement intercropping, the densities are adjusted for the presence of the other crop(s) [25].

Different mechanisms explain the smothering of weeds in intercropping systems. The most common is the competition between crops and weeds for natural resources such as light, water, or nitrogen [21]. Another one is allelopathy, which is a characteristic of plants that may be exploited for weed control [26]. Allelopathy is defined as the capability of plants to exert positive or negative influence in the surrounding area by releasing chemicals [27]. It has been known for a long time that several crops present allelopathic activity, such as oat, wheat, barley, and sorghum [28].

The main objective of this work was to determine if it is possible to control weeds in faba bean by intercropping and, if possible, the best crop combination. To this effect, field trials were performed across different years. Additionally, experiments under controlled conditions were carried out to investigate the possible role of allelopathy in weed control in intercrops of faba bean. This work was included in the Ph.D. Thesis "Diversificación de cultivos para el control de estreses bióticos en leguminosas" by Ahmed Amarna [29].

2. Materials and Methods

2.1. Field Trials

Five field trials (Table 1) were carried out to assess the effect of different crop combinations on the control of weeds in faba bean from 2014 to 2018 in the experimental station at the Institute for Sustainable Agriculture (CSIC) in Córdoba (South of Spain). The soil type in all cases was silt loam, and the previous crops were monocrops of wheat or various legumes. Ploughing was made at a depth of 30 cm, with the help of a chisel, a harrow, and a cultivator. Detailed temperature and precipitation per month for each trial are shown in Figure 1. The combinations tested were faba bean/wheat, faba bean/barley, and faba bean/pea as well as monocrops of the four crops and a monocrop of faba bean at 50% of the sowing density (doubling the distance between rows) to check the effect of density on weed infestation. The cultivars used were 'Muchamiel' (faba bean), 'Califa' (wheat), 'Henley' (barley), and 'Messire' (pea). Sowing densities were 80 seeds/m^2 for legumes and 200 seeds/m^2 for cereals. Sowing was performed by hand on furrows previously ploughed in the soil. Two different intercropping systems were evaluated including alternate with replacement at 50%, where rows of each crop were alternated, giving a final sowing rate of 50/50, i.e., half of the normal density of each crop, and alternate with addition, where rows were also alternated but to a final rate of 100/100, i.e., the normal density of each crop. Replacement intercropping was evaluated in trials Córdoba-15-r and Córdoba-16-r, and addition intercropping was evaluated in trials Córdoba-16-a, Córdoba-17-a, and Córdoba-18-a. The experimental plots (Figure 2) had a length of 3 m and comprised eight rows with a 35 cm distance between them in the case of monocrops and replacement intercropping and 16 rows at 17.5 cm in the case of addition intercropping (making a total plot size of 8.4 m^2). The monocrop of faba bean at 50% had four rows at 70 cm per plot (Figure 2). For each trial, the experiment was designed as a randomized complete block with four replications.

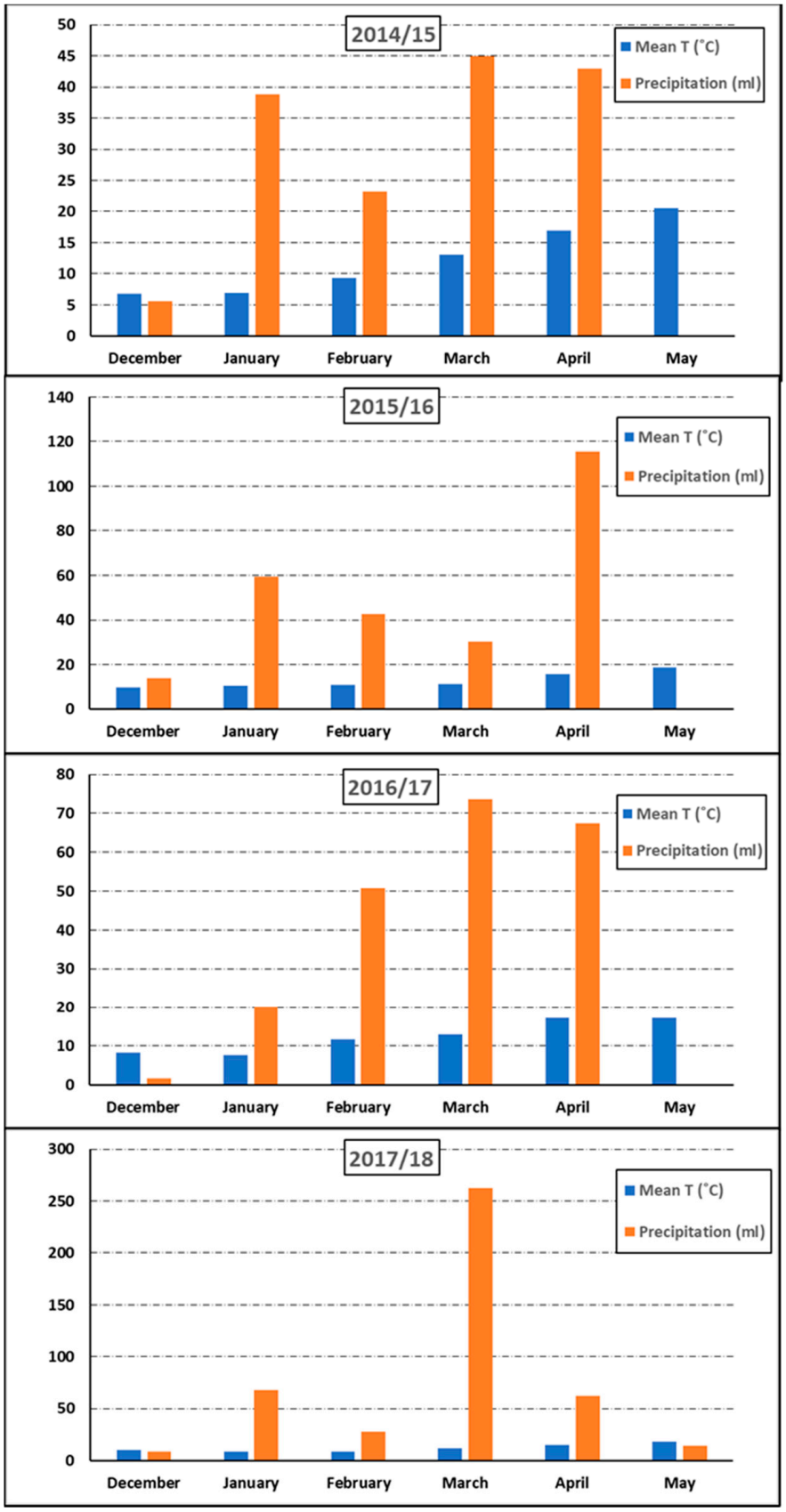

Figure 1. Mean temperature (°C) and precipitation (mL) per month in the seasons when the different trials were carried out.

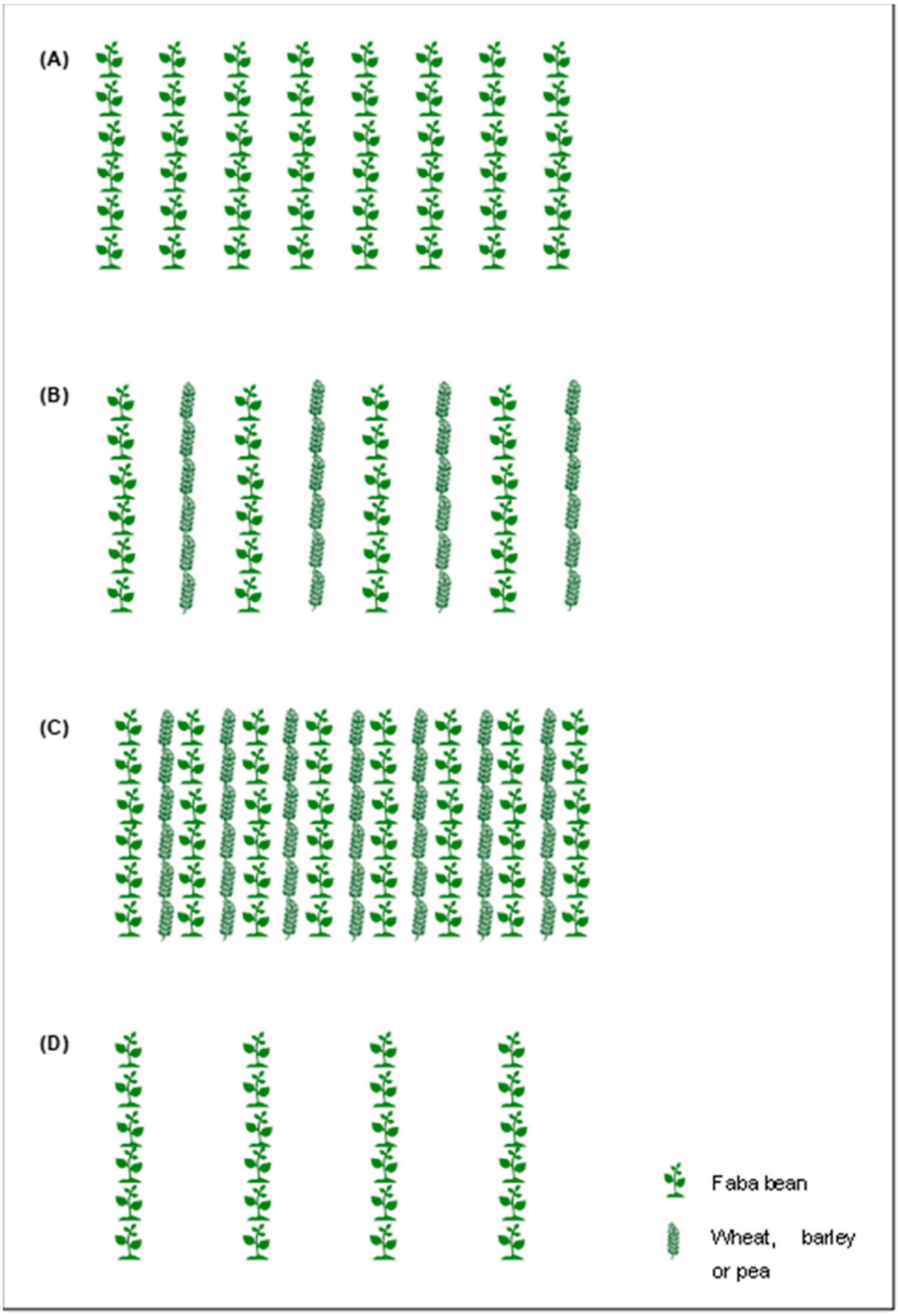

Figure 2. Different cropping systems evaluated in the field trials. (**A**): Faba bean monocrop. (**B**): Alternate replacement intercropping. (**C**): Alternate addition intercropping. (**D**): Faba bean monocrop at 50% of the sowing density. Row distances in (**A**,**B**) were 35 cm, in (**C**) were 17.5 cm, and in (**D**) were 70 cm.

Table 1. Field trials carried out to study the control of weeds in faba bean by intercropping.

Trial	Córdoba-15-r	Córdoba-16-r	Córdoba-16-a	Córdoba-17-a	Córdoba-18-a
Season	2014/15	2015/16	2015/16	2016/17	2017/18
Intercropping system	Replacement	Replacement	Addition	Addition	Addition
Maximum T (°C)	35.3	31.7	31.7	32.2	29.7
Minimum T (°C)	−3.3	−2.3	−2.3	−3.4	−3.4
Mean T (°C)	12.3	12.6	12.6	14.3	12.0
Precipitation (mL)	150	336	336	143.8	444.6

Two areas of 0.7 m^2 were randomly evaluated in the central part of each plot at the faba bean maturity stage to assess weed infestation. The weeds were counted and classified by botanic families. Two diversification indices were calculated in trials Córdoba-16-a, Córdoba-17-a, and Córdoba-18-a as follows:

Richness (R) and *Relative density* (D):

$$R = nF_i / nF_T$$

where R: richness; nF_i: number of weed families present in a given plot (i); and nF_T: total number of weed families found in the whole trial.

$$D_{ji} = (N_{ji} / N_{Ti}) \times 100$$

where D_{ij}: relative density of weed family j in plot i; N_{ji}: number of plants of weed family j present in plot i; and N_{Ti}: total number of weed plants in plot i.

Additionally, two evaluators visually estimated weed coverage as a percentage of the area covered by weeds. At the end of the experiment, in trials Córdoba-16-a and Córdoba-17-a, the weeds in a central area of 2 m^2 in each plot were harvested, and their biomass was determined by drying them in an oven at 60 °C for three days and subsequently weighing them.

2.2. Controlled-Condition Experiments

Two experiments were carried out under controlled conditions to investigate the possible allelopathic effect of barley. Thus, four weeds that grew in the field trials were selected for this: *Polypogon monspeliensis* (L.) Desf., *Matricaria camomilla* L., *Sinapis arvensis* L., and *Medicago truncatula* Gaertm, which belong to the botanical families Poaceae, Asteraceae, Cruciferae, and Fabaceae, respectively. In the first experiment, 10 seeds of barley were sown in plastic pots (5 × 5 × 10 cm) filled with a mixture of sand and peat at a 1:3 rate (*v*:*v*) and grown in a growth chamber with a photoperiod of 12 h of visible light (150 μmol m^{-2} s^{-1} photon flux density) at 25 °C and 12 h of darkness at 20 °C. Two weeks later, the barley plants were removed, and 20 seeds of the same weed species were sown in the same pots maintaining the substrate. The weed plants were counted every two weeks for 42 days. Then, the weed plants were removed, dried in an oven at 60 °C for three days, and weighed to obtain their biomass. A treatment control was used, in which weeds were sown in pots where barley was not previously grown. All this was performed in separate pots for each of the four weeds. The second experiment was carried out in the same way as in the first one, but the barley plants remained in the pots when the weeds were sown, and they grew together until the end of the experiment. The design in the two cases was randomized with seven replications. Each of these experiments was performed twice.

2.3. Statistical Analysis

Considering the type of data, generalized linear models (GLMs) were performed to study the influence of the treatment on weed coverage and biomass in field trials, following the model:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 \times X_2 + \varepsilon$$

where Y is the dependent variable, β_0, β_1, and β_3 denote the estimated parameters (weights), and ε is the residual. Model fits were evaluated through residual plots. Subsequently, we assessed the contribution of treatment, year, and treatment × year according to Cohen's f factor [30].

Given that the treatment × year interactions were significant (Cohen's f > 0.4) for both coverage and biomass, and since this study's main objective was to compare the intercropping treatments independently of the year × crop interaction, a Friedman nonparametric two-way analysis of variance was used. Subsequently, Dunn's test was performed to compare the treatment mean ranks at $p \leq 0.05$. Additional ANOVA analyses were carried out to study the effect of the treatment on weed richness and weed relative density in each experiment.

In the experiments under controlled conditions, the Poisson regression procedure was applied using the maximum likelihood estimation method to study how the plant counts depended on the presence or absence of barley plants. Thus, the data were fitted to the following equation:

$$Y = Exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2)$$

where Y is the number of plants, β_0 is the independent term, and β_1 and β_2 are the estimates associated with the treatment (presence or not of barley). The difference between treatments was evaluated according to the p-value of the Poisson regression. Additionally, a t-test was performed to calculate the effect of barley presence on the biomass of weed species and compare the proportion of reduction of weed plants and weed biomass between the two types of experiments. Finally, the proportion of weed plants and biomass reduction among weed species was assessed by ANOVA analysis.

Data were analyzed using Statistix software (Version 10; Statistix, Tallahassee, FL, USA) and the R statistical software package (RStudio 2023.12.1 + 402).

3. Results

3.1. Field Trials

A high level of weed infestation was present in all field trials.

3.1.1. Field Trials—Replacement System

In the experiments where the replacement intercropping system was used, there was no difference in weed coverage between any intercropping treatment and the faba bean monocrop (Supplementary Data Table S1). In these trials, faba bean at 50% density presented the highest level of weed infestation (not statistically different from the wheat and pea monocrops in the case of Córdoba-16-r). That is, intercropping was ineffective in controlling weeds in faba bean when rows of faba bean plants were replaced with rows of other crops (pea, wheat, or barley).

3.1.2. Field Trials—Addition System

Clear differences were found among treatments according to weed infestation values for the addition system. In general, pea and faba bean at 50% density presented the highest levels of weed infestation in all trials, both for weed coverage and weed biomass. The combined analysis of the experiments found the lowest weed coverage for the combination of faba bean with barley, with a reduction of 92.7% compared with the faba bean monocrop (Figure 3). For weed biomass, the combinations of faba bean with barley and faba bean with wheat showed the lowest values, which were not significantly different from those

of barley as a sole crop, getting decreases in comparison with monocropped faba bean of 76.6% and 46.1%, respectively (Figure 4).

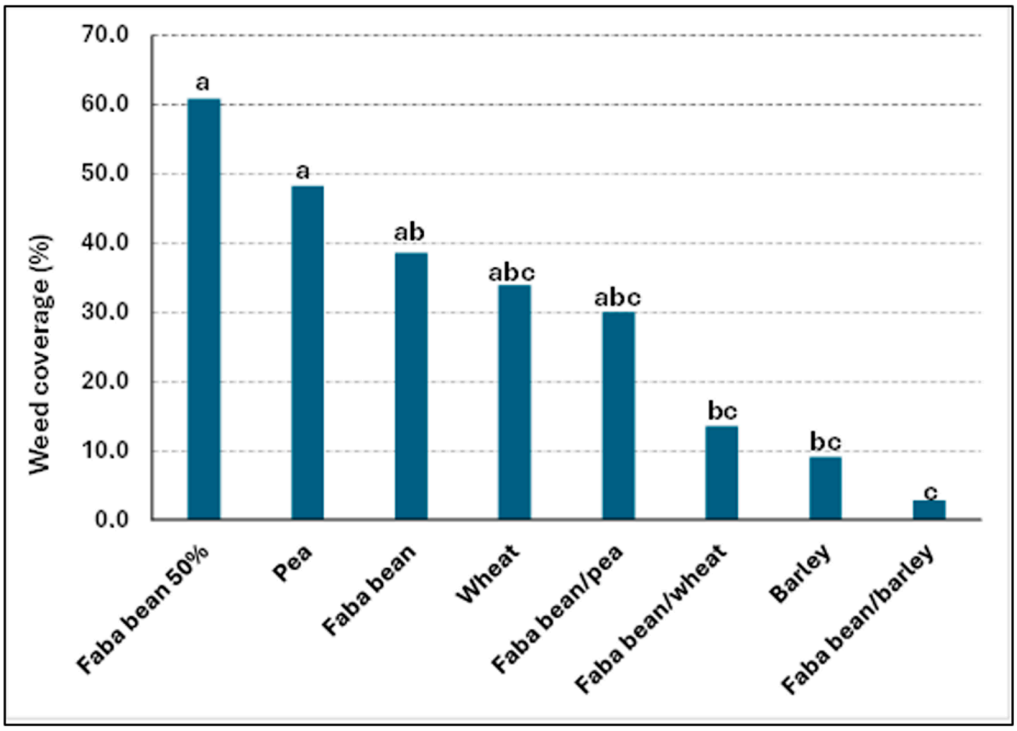

Figure 3. Weed coverage in the different treatments evaluated across the three intercropping field trials where addition alternate intercropping was tested. Different letters mean significant differences according to Dunn's test at $p \leq 0.05$.

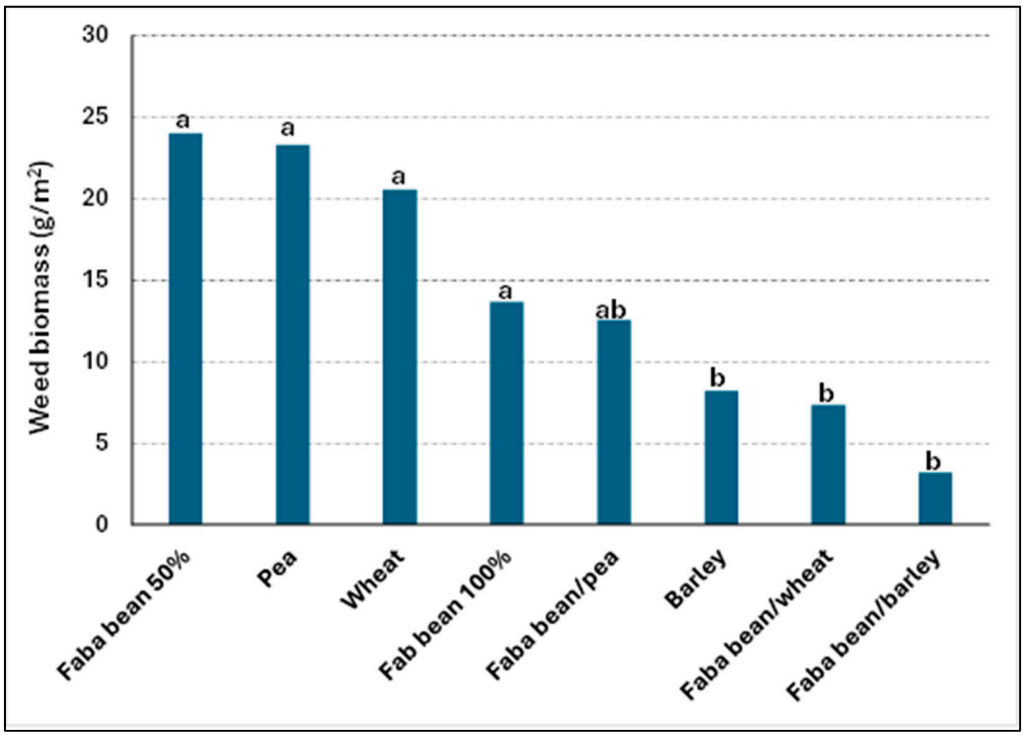

Figure 4. Weed biomass (g/m^2) in the different treatments evaluated across the two intercropping field trials where addition alternate intercropping was tested. Different letters mean significant differences according to the Least Significant Difference (LSD) test at $p \leq 0.05$.

The weeds found were classified into 10 different botanical families along the trials Córdoba-16, Córdoba-17, and Córdoba-18 (Table 2). No difference was found for Richness (R) between the faba bean monocrop and any of the intercropping mixtures in any of the three trials where it was calculated (Table 3). Equally, no significant differences in Relative density (D) of any of the 10 botanical families of weeds were detected for the different treatments tested ($p > 0.05$, ANOVA test; Supplementary Data Table S2).

Table 2. Presence of the different botanical families to which the weeds identified belonged in the field trials Córdoba-16, Córdoba-17, and Córdoba-18. Taken from Amarna (2023) [29].

	Córdoba-16	**Córdoba-17**	**Córdoba-18**
AMARANTACEAE		x	x
ASTERACEAE	x		
CONVOLVULACEAE	x	x	x
CRUCIFERAE	x		x
CYPERACEAE		x	
FABACEAE	x	x	x
PAPAVERACEAE		x	x
POACEAE	x		x
POLYGONACEAE	x	x	x
QUENOPODIACEAE	x		

Table 3. Weed richness (R) for the different treatments tested in three field trials (Córdoba-16, Córdoba-17, and Córdoba-18). Different letters mean significant differences for each trial (Tukey test, $p < 0.05$). Richness was not measured for barley, wheat and pea monocrops in Cordoba-16. Taken from Amarna (2023) [29].

	Richness (R)		
	Córdoba-16	**Córdoba-17**	**Córdoba-18**
Faba bean 100%	35.7 a	78.6 ab	76.2 ab
Faba bean/barley	25.0 a	50.0 ab	42.3 a
Faba bean/wheat	25.0 a	46.4 a	61.9 ab
Faba bean/ea	50.0 a	64.3 ab	85.7 b
Faba bean 50%	46.4 a	75.0 ab	85.7 b
Barley 100%		83.3 b	76.2 ab
Wheat 100%		75.0 ab	95.0 b
Pea 100%		83.3 b	80.9 ab

3.2. Controlled-Condition Experiments

The number of emerged weed plants was significantly lower ($p < 0.05$) in the pots where barley was grown previously (either removed or maintained when weed seeds were sown) than in the pots used as control. The number of plants did not vary as the experiments progressed, so the counts for the three time points were very similar. The results for the final count of plants are shown in Table 4, both for the experiment where barley was removed before sowing the seeds of weeds and for the experiment where barley remained in the pots after the seeds of weeds were sown. The biomass of weeds at the end of the experiments was significantly lower in the pots with barley than in the control ones (Table 5).

Table 4. Number of weed plants per pot for each treatment in the two experiments under controlled conditions: where barley was removed before sowing the weeds and where barley was not removed after sowing the weeds. Different letters mean significant differences for each weed in each type of experiment, i.e., with barley removed or not removed. Differences were significant in all cases according to Poisson's *p*-value at $p \leq 0.05$. Taken from Amarna (2023) [29].

	Barley Removed		**Barley Not Removed**	
	Control	**Barley Sown**	**Control**	**Barley Sown**
Polypogon monspeliensis	19.9 a	5.0 b	19.7 a	4.6 b
Matricaria chamomilla	18.9 a	5.9 b	18.6 a	5.1 b
Sinapis arvensis	11.1 a	3.8 b	11.9 a	2.7 b
Medicago truncatula	5.2 a	1.4 b	7.8 a	1.4 b

Table 5. Biomass of weed plants per pot (mg) for each treatment in the two experiments under controlled conditions: where barley was removed before sowing the weeds and where barley was not removed after sowing the weeds. Different letters mean significant differences for each weed in each type of experiment, i.e., with barley removed or not removed, according to the t-student test at $p \leq 0.05$. Taken from Amarna (2023) [29].

	Barley Removed		**Barley Not Removed**	
	Control	**Barley Sown**	**Control**	**Barley Sown**
Polypogon monspeliensis	39.9 a	20.2 b	55.5 a	24.9 b
Matricaria chamomilla	115.4 a	49.0 b	131.6 a	25.6 b
Sinapis arvensis	70.6 a	41.7 b	104.6 a	10.1 b
Medicago truncatula	16.3 a	10.6 b	35.0 a	4.8 b

The proportion of reduction in the number of weed plants and weed biomass per pot compared to the control (considered as the average of all the control pots for that weed) was calculated in both experiments (removing barley before sowing the weeds and not removing it). There were no significant differences in the proportion of the number of plants for the two types of experiments. On the contrary, there were differences in weed biomass per pot for *Matricaria chamomilla* and *Sinapis arvensis*: the final weed biomass was lower when barley remained in the pots until the end of the experiment (Table 6).

Table 6. Proportion of the number of weed plants and biomass per pot as compared to the control for both types of experiments under controlled conditions (removing barley and not removing it just prior to sowing the weeds). Different letters mean significant differences for each weed and parameter: number and biomass of weeds (according to the t-student test at $p \leq 0.05$). Taken from Amarna (2023) [29].

	No. of Weeds (%)		**Biomass of Weeds (%)**	
	Barley Removed	**Barley Not Removed**	**Barley Removed**	**Barley Not Removed**
Polypogon monspeliensis	25.2 a	23.6 a	70.1 a	61.9 a
Matricaria chamomilla	31.1 a	27.3 a	65.5 a	43.7 b
Sinapis arvensis	32.1 a	23.0 a	77.0 a	29.3 b
Medicago truncatula	24.9 a	18.4 a	58.9 a	31.9 a

Additionally, the proportion of reduction in the number of weed plants and weed biomass per pot compared to the control was compared among the four weed species in the experiment where barley was removed, to investigate if any of them were more affected

by barley than the others. No significant differences were found among them (ANOVA, $p > 0.05$).

4. Discussion

In this work, intercropping was evaluated as a tool to control weeds in faba bean in the South of Spain. The level of control attained was very high, reaching reductions of 92.7% in weed coverage when combined with barley and 76.6% and 46.1% in weed biomass when mixed with barley and wheat, respectively. The mixture of faba bean and barley, then, might be effective enough to dispense with the application of herbicides in this agroecosystem.

Previously, only one work had studied the effect of the combination of faba bean and barley on weeds. In that study, Dhima et al. [31] reported that alternate replacement intercropping achieved levels of reduction of corn poppy (*Papaver rhoeas* L.) of around 90%. As for other cereals, it was shown that a mixture of faba bean and wheat reduced weed biomass by 60% in alternate and mixed replacement intercropping [32]. Similarly, Boutagayout et al. [33] found that an alternate intercrop of faba bean with wheat and oat decreased weed biomass by around 50%. As far as we know, our work is the first to achieve such a level of weed suppression in faba bean validated across three field experiments. Equally, barley has proved to be successful in reducing broomrape (*Orobanche crenata* Forsk.) infestation in faba bean [34] and also to be effective in controlling rust disease in faba bean [35]. In these cases, the intercropping systems were different from those assessed in this work, so it would be necessary to integrate them in the best way to maximize the benefits of faba bean/barley intercropping. Furthermore, it is remarkable that the combination of faba bean and wheat reduced weed biomass by 64% compared with the wheat monocrop, making this mixture an exciting option for farmers that can be combined with some herbicide applications. Pea, however, has proved to be a poor competitor against weeds, both as a monocrop and in a mixture with faba bean, which is in line with the fact that the combination of grain legumes alone is not a good strategy to control weeds. Actually, these combinations are not found in the literature on weed suppression by intercropping [36].

No differences in weed diversity among all the tested treatments were found. No weeds belonging to a particular botanic family were more affected by any crop combination or monocrop than others. This is in contrast with what has been found in other intercropping systems [37,38], although there are also situations where weed diversity has not been influenced by intercropping [38]. In our case, the weed community proved to be relatively stable regardless of the crop or crops present.

Of the two types of intercropping tested, alternate with replacement and alternate with addition, only the latter was adequate for controlling weeds. The relationship between crops and weeds is based on competition for available resources such as water, nutrients, and light [39,40]. Plant density is one key factor in the improvement of crop competitiveness against weeds [41], and that is precisely the difference between both intercropping systems. In addition, intercropping plant density is doubled in comparison with alternate intercropping. The high weed pressure levels that we observed in the plots with faba bean sown at half density confirm the importance of plant density.

Plant density, however, is not the only mechanism that explains weed suppression in intercropping. If that were the case, similar results would have been observed with barley, wheat, or pea. Weed pressure levels for them as sole crops illustrate that not all crops have the same competitive ability against weeds: barley presents very low weed infestation compared with the other two, with pea ranking the highest. Other factors influence performance in the presence of weeds, such as plant architecture, vigor, and allelopathy [42,43].

Barley has been described as one of the most competitive crops against weeds by different authors [44,45]. The rapid biomass accumulation and high growth rates that barley shows at the beginning of its cycle are some of the reasons for this [45]. Another

reason is the efficiency of barley in taking nitrogen: it has been reported to be more competitive for nitrogen than pea in intercrops, thus depriving weeds of this nutrient. Beyond that, barley is considered a crop with high levels of allelopathy [46], and as many as 44 potential allelochemicals have been identified so far [47]. The two more important are the alkaloids Gramine and Hordeine, which appear in the leaves, roots, and root exudates of barley plants [27,47]. All this has made barley a common partner in crop diversification for weed control [36].

The experiments under controlled conditions aimed at evaluating the role that barley allelopathy might have on our results. Different types of bioassays under controlled conditions may be used to assess the allelopathic ability of a plant species, such as testing extracts from the allelopathic plant [48,49], agar bioassays [44], or pot screenings [50], where plants are grown together in Petri dishes or pots with soil, respectively. We opted for pot screening because it may better reflect the conditions under which allelopathy operates. In addition, our design, in which removing barley plants is compared with the effect of not removing them, allows for discriminating allelopathy from competition effects.

The results from the pots where barley was removed before sowing the weeds showed a substantial allelopathic effect against them. All four weed species presented a decrease in plant emergence and biomass that can only be explained by the presence of chemical compounds in the soil that were previously released by the barley plants. These results also suggest that the main allelopathic effect is related to the first stages of seed germination and seedling development. Remarkably, there were no significant differences between the final number of weed plants in the pots where barley was removed and in those where it remained until the end. As for weed biomass, however, in the case of two species (*Sinapis arvensis* and *Matricaria camomilla*), the decrease was higher when barley remained than when it was removed. This is probably due to additional allelopathic effects, although it is more difficult to separate them from competition effects in this case. Barley allelopathy was previously tested on *Sinapis arvensis* [51,52]. Still, as far as we know, this is the first time it has been assessed on the other three weeds.

The fact that there was no difference in the reduction in emerged plants and biomass between four weeds belonging to such different botanical families points to a global and non-discriminatory effect of barley in our case. These weeds are a sample of the ten families found in our area, and this global effect could explain the lack of differences in the composition of weed communities between the barley intercrops and the monocrops in our field experiments.

5. Conclusions

In conclusion, this research has established that the combination of faba bean and barley has great potential for the control of weeds in the agroclimatic region of the South of Spain. Further work should focus on developing the optimal intercropping strategy to obtain the best advantages from combining these two crops with special attention to the arrangement and densities of crops. It would also be of great interest to identify the allelochemicals behind weed suppression in our experiments and determine their mechanisms of action.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14061170/s1, Table S1. (Global weed coverage for the different treatments tested in field trials Cordoba-15-r and Cordoba-16-r, with alternate replacement intercropping). Table S2 (Relative density (D) of the botanical families of weeds for each of the treatments in the three field trials where addition intercropping was carried out).

Author Contributions: Conceptualization, D.R., Á.M.V.-F. and J.M.; methodology, D.R., Á.M.V.-F. and J.M.; formal analysis, J.M. and Á.M.V.-F.; investigation, A.A.A., Á.M.V.-F. and J.M.; writing—original draft preparation, Á.M.V.-F.; writing—review and editing, Á.M.V.-F., D.R. and J.M.; supervision, D.R.; funding acquisition, D.R. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Spanish projects PID2020-114668RB-I00 and PCI2020-111974 (financed by MICIU/AEI/10.13039/501100011033 and NextGenerationEU/PRTR), the Horizon 2020 EU project H2020-RADIANT GA No. 101000622, and Junta de Andalucía PAIDI 2020 project P20_00986.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy reasons.

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

References

1. Ditzler, L.; van Apeldoorn, D.F.; Pellegrini, F.; Antichi, D.; Bàrberi, P.; Rossing, W.A.H. Current research on the ecosystem service potential of legume inclusive cropping systems in Europe. A review. *Agron. Sustain. Dev.* **2021**, *41*, 26. [CrossRef]
2. Rubiales, D.; Fondevilla, S.; Chen, W.D.; Gentzbittel, L.; Higgins, T.J.V.; Castillejo, M.A.; Singh, K.B.; Rispail, N. Achievements and Challenges in Legume Breeding for Pest and Disease Resistance. *Crit. Rev. Plant Sci.* **2015**, *34*, 195–236. [CrossRef]
3. Plaza, M.E.H.; Bastida, F.; Gibson, D.J.; Barro, F.; Giménez, M.J.; Pallavicini, Y.; Izquierdo, J.; González-Andújar, J.L. Grain Quality as Influenced by the Structural Properties of Weed Communities in Mediterranean Wheat Crops. *Agronomy* **2022**, *13*, 49. [CrossRef]
4. Kumar, S.; Bhowmick, M.; Ray, P. Weeds as alternate and alternative hosts of crop pests. *Indian J. Weed Sci.* **2021**, *53*, 14–29. [CrossRef]
5. Dentika, P.; Ozier-Lafontaine, H.; Penet, L. Weeds as Pathogen Hosts and Disease Risk for Crops in the Wake of a Reduced Use of Herbicides: Evidence from Yam (*Dioscorea alata*) Fields and *Colletotrichum* Pathogens in the Tropics. *J. Fungi* **2021**, *7*, 283. [CrossRef] [PubMed]
6. Carton, N.; Naudin, C.; Piva, G.; Baccar, R.; Corre-Hellou, G. Differences for traits associated with early N acquisition in a grain legume and early complementarity in grain legume-triticale mixtures. *Aob Plants* **2018**, *10*, ply001. [CrossRef] [PubMed]
7. Duke, S.O. Why have no new herbicide modes of action appeared in recent years? *Pest Manag. Sci.* **2012**, *68*, 505–512. [CrossRef] [PubMed]
8. Avola, G.; Tuttobene, R.; Gresta, F.; Abbate, V. Weed control strategies for grain legumes. *Agron. Sustain. Dev.* **2008**, *28*, 389–395. [CrossRef]
9. Pannacci, E.; Tei, F.; Guiducci, M. Evaluation of mechanical weed control in legume crops. *Crop Prot.* **2018**, *104*, 52–59. [CrossRef]
10. FAOSTAT. Food and Agriculture Organization of the United Nations. FAOSTAT Statistical Database. 2020. Available online: https://www.fao.org/statistics/es (accessed on 15 December 2023).
11. Karkanis, A.; Ntatsi, G.; Lepse, L.; Fernandez, J.A.; Vagen, I.M.; Rewald, B.; Alsina, I.; Kronberga, A.; Balliu, A.; Olle, M.; et al. Faba Bean Cultivation—Revealing Novel Managing Practices for More Sustainable and Competitive European Cropping Systems. *Front. Plant Sci.* **2018**, *9*, 1115. [CrossRef]
12. Huss, C.P.; Holmes, K.D.; Blubaugh, C.K. Benefits and Risks of Intercropping for Crop Resilience and Pest Management. *J. Econ. Entomol.* **2022**, *115*, 1350–1362. [CrossRef] [PubMed]
13. Weerarathne, L.V.Y.; Marambe, B.; Chauhan, B.S. Does intercropping play a role in alleviating weeds in cassava as a non-chemical tool of weed management?—A review. *Crop Prot.* **2017**, *95*, 81–88. [CrossRef]
14. Belete, T.; Yadete, E. Effect of Mono Cropping on Soil Health and Fertility Management for Sustainable Agriculture Practices: A Review. *J. Plant Sci.* **2023**, *11*, 192–197. [CrossRef]
15. Kumar, K.N.S.S.; Sahoo, S.; Pechetti, B.C.; Upadhyay, H. Organic Weed Management: A Step Forward Towards Sustainability. *Ecol. Environ. Conserv.* **2023**, *29*, 1782–1789. [CrossRef]
16. Abdulkareem, B.M.; Mokhtassi-Bidgoli, A.; Ayyari, M.; Keshtkar, E.; Eyni-Nargeseh, H. Enhancing cotton sustainability: Multi-factorial intercropping, irrigation, and weed effects on productivity, quality and physiology. *Heliyon* **2024**, *10*, e27135. [CrossRef] [PubMed]
17. Flores-Sanchez, D.; Pastor, A.; Lantinga, E.A.; Rossing, W.A.H.; Kropff, M.J. Exploring Maize-Legume Intercropping Systems in Southwest Mexico. *Agroecol. Sustain. Food Syst.* **2013**, *37*, 739–761. [CrossRef]
18. Banik, P.; Midya, A.; Sarkar, B.K.; Ghose, S.S. Wheat and chickpea intercropping systems in an additive series experiment: Advantages and weed smothering. *Eur. J. Agron.* **2006**, *24*, 325–332. [CrossRef]
19. Begna, S.H.; Fielding, D.J.; Tsegaye, T.; Van Veldhuizen, R.; Angadi, S.; Smith, D.L. Intercropping of oat and field pea in Alaska: An alternative approach to quality forage production and weed control. *Acta Agric. Scand. Sect. B-Soil Plant Sci.* **2011**, *61*, 235–244. [CrossRef]
20. Corre-Hellou, G.; Dibet, A.; Hauggaard-Nielsen, H.; Crozat, Y.; Gooding, M.; Ambus, P.; Dahlmann, C.; von Fragstein, P.; Pristeri, A.; Monti, M.; et al. The competitive ability of pea-barley intercrops against weeds and the interactions with crop productivity and soil N availability. *Field Crops Res.* **2011**, *122*, 264–272. [CrossRef]

21. Sharma, G.; Shrestha, S.; Kunwar, S.; Tseng, T. Crop Diversification for Improved Weed Management: A Review. *Agriculture* **2021**, *11*, 461. [CrossRef]
22. Kemper, R.; Rinke, N.; Gerhards, R.; Böhm, H. Weed suppression and crop yield performance in sole and intercrops of common vetch and spring wheat depending on seed density ratio in organic farming. *J. Kult.* **2020**, *72*, 12–24. [CrossRef]
23. Leoni, F.; Carlesi, S.; Triacca, A.; Koskey, G.; Croceri, G.; Antichi, D.; Moonen, A.-C. A three-stage approach for co-designing diversified cropping systems with farmers: The case study of lentil-wheat intercropping. *Ital. J. Agron.* **2023**, *18*. [CrossRef]
24. Lithourgidis, A.S.; Dordas, C.A.; Damalas, C.A.; Vlachostergios, D.N. Annual intercrops: An alternative pathway for sustainable agriculture. *Aust. J. Crop Sci.* **2011**, *5*, 396–410.
25. Boudreau, M.A. Diseases in Intercropping Systems. *Annu. Rev. Phytopathol.* **2013**, *51*, 499–519. [CrossRef] [PubMed]
26. Khamare, Y.; Chen, J.J.; Marble, S.C. Allelopathy and its application as a weed management tool: A review. *Front. Plant Sci.* **2022**, *13*, 1034649. [CrossRef] [PubMed]
27. Maver, M.; Miras-Moreno, B.; Lucini, L.; Trevisan, M.; Pii, Y.; Cesco, S.; Mimmo, T. New insights in the allelopathic traits of different barley genotypes: Middle Eastern and Tibetan wild-relative accessions vs. cultivated modern barley. *PLoS ONE* **2020**, *15*, e0231976. [CrossRef] [PubMed]
28. Belz, R.G. Allelopathy in crop/weed interactions—An update. *Pest Manag. Sci.* **2007**, *63*, 308–326. [CrossRef] [PubMed]
29. Amarna, A. Diversificación de Cultivos para el Control de Estreses Bióticos en Leguminosas. Ph.D. Thesis, Universidad de Córdoba, Córdoba, Spain, 2023.
30. Cohen, J. *Statistical Power Analysis for the Behavioral Sciences*, 2nd ed.; Lawrence Erlbaum Associates, Inc.: Mahwah, NJ, USA, 1988.
31. Dhima, K.; Vasilakoglou, I.; Gatsis, T.; Gougoulias, N. Faba bean-barley intercrops for high productivity and corn poppy suppression. *Exp. Agric.* **2016**, *54*, 163–180. [CrossRef]
32. Eskandari, H. Intercropping of wheat (*Triticum aestivum*) and bean (*Vicia faba*): Effects of complementarity and competition of intercrop components in resource consumption on dry matter production and weed growth. *Afr. J. Biotechnol.* **2011**, *10*, 17755–17762. [CrossRef]
33. Boutagayout, A.; Belmalha, S.; Nassiri, L.; el Alami, N.; Jiang, Y.; Lahlali, R.; Bouiamrine, E.H. Weed competition, land equivalent ratio and yield potential of faba bean (*Vicia faba* L.)-cereals (*Triticum aestivum* L. and/or *Avena sativa* L.) intercropping under low-input conditions in Meknes region, Morocco. *Vegetos* **2023**. [CrossRef]
34. Fernandez-Aparicio, M.; Sillero, J.C.; Rubiales, D. Intercropping with cereals reduces infection by *Orobanche crenata* in legumes. *Crop Prot.* **2007**, *26*, 1166–1172. [CrossRef]
35. Villegas-Fernandez, A.M.; Amarna, A.A.; Moral, J.; Rubiales, D. Crop Diversification to Control Rust in Faba Bean Caused by *Uromyces viciae-fabae*. *J. Fungi* **2023**, *9*, 344. [CrossRef] [PubMed]
36. Gu, C.; Bastiaans, L.; Anten, N.P.R.; Makowski, D.; van der Werf, W. Annual intercropping suppresses weeds: A meta-analysis. *Agric. Ecosyst. Environ.* **2021**, *322*, 107658. [CrossRef]
37. Poggio, S.L.; Satorre, E.H.; de la Fuente, E.B. Structure of weed communities occurring in pea and wheat crops in the Rolling Pampa (Argentina). *Agric. Ecosyst. Environ.* **2004**, *103*, 225–235. [CrossRef]
38. Stefan, L.; Engbersen, N.; Schöb, C. Crop–weed relationships are context-dependent and cannot fully explain the positive effects of intercropping on yield. *Ecol. Appl.* **2021**, *31*, e2311. [CrossRef] [PubMed]
39. Swanton, C.; Ondoua, R.; Blackshaw, R.E. Experimental methods for crop-weed competition studies. *Weed Sci.* **2015**, *63*, 2–11. [CrossRef]
40. Singh, M.; Kukal, M.S.; Irmak, S.; Jhala, A.J. Water Use Characteristics of Weeds: A Global Review, Best Practices, and Future Directions. *Front. Plant Sci.* **2022**, *12*, 794090. [CrossRef] [PubMed]
41. Lemerle, D.; Cousens, R.; Gill, G.; Peltzer, S.; Moerkerk, M.; Murphy, C.; Collins, D.; Cullis, B. Reliability of higher seeding rates of wheat for increased competitiveness with weeds in low rainfall environments. *J. Agric. Sci.* **2004**, *142*, 395–409. [CrossRef]
42. Korav, S.; Dhaka, A.; Singh, R.; Reddy, G. A study on crop weed competition in field crops. *J. Pharmacogn. Phytochem.* **2018**, *7*, 3235–3240.
43. Jha, P.; Kumar, V.; Godara, R.; Chauhan, B. Weed management using crop competition in the United States: A review. *Crop Prot.* **2017**, *95*, 31–37. [CrossRef]
44. Bertholdsson, N.O. Early vigour and allelopathy—Two useful traits for enhanced barley and wheat competitiveness against weeds. *Weed Res.* **2005**, *45*, 94–102. [CrossRef]
45. Dhima, K.; Vasilakoglou, I.; Gatsis, T.; Eleftherohorinos, I. Competitive interactions of fifty barley cultivars with *Avena sterilis* and *Asperugo procumbens*. *Field Crops Res.* **2010**, *117*, 90–100. [CrossRef]
46. Jabran, K.; Mahajan, G.; Sardana, V.; Chauhan, B.S. Allelopathy for weed control in agricultural systems. *Crop Prot.* **2015**, *72*, 57–65. [CrossRef]
47. Kremer, R.; Ben-Hammouda, M. Allelopathic Plants. 19. Barley (*Hordeum vulgare* L.). *Allelopath. J.* **2009**, *24*, 225–242.
48. Asghari, J.; Tewari, J.P. Allelopathic Potentials of Eight Barley Cultivars on *Brassica jucea* (L.) Czern. and *Setaria viridis* (L.) p. Beauv. *J. Agric. Sci. Technol.* **2007**, *9*, 165–176.
49. Copaja, S.; López, M.; Bravo, H. Dynamic of indole alkaloids in a soil and its relationships with allelopathic properties. *J. Chil. Chem. Soc.* **2023**, *68*, 5787–5795. [CrossRef]
50. Wu, H.; Pratley, J.; Lemerle, D.; Haig, T.; An, M. Screening methods for the evaluation of crop allelopathic potential. *Bot. Rev.* **2001**, *67*, 403–415. [CrossRef]

51. Vasilakoglou, I.; Dhima, K.; Lithourgidis, A.; Eleftherohorinos, I. Allelopathic potential of 50 barley cultivars and the herbicidal effects of barley extract. *Allelopath. J.* **2009**, *24*, 309–319.
52. Modhej, A.; Rafatjoo, A.; Behdarvandi, B. Allelopathic inhibitory potential of some crop species (wheat, barley, canola, and safflower) and wild mustard (*Sinapis arvensis*). *Int. J. Biosci. (IJB)* **2013**, *3*, 212–220.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.