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Effect of Swathing or Direct Combining on Yield, Seed Losses and Costs of Camelina

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Abstract: Camelina is an interesting crop and producers must adopt cultural practices to achieve the highest yield and oil content possible. Considering the size of the seed, the harvesting phase is crucial to reduce losses and maximize income. Furthermore, in recent years, with the worsening of climatic conditions due to global warming, crop management can no longer follow the classic seasonality but must adapt to new climatic conditions. The possibility of double cropping, that is the process of producing two crops in a single season, allows multiple advantages such as weed control, greater remuneration, and less exposure to bare soil which determine greater resilience of the production system. To enable this, especially in recent years, even a few days of difference in the cultivation phases can guarantee the success of double cropping. For these reasons, the authors compared two different harvesting strategies: direct combining at full maturity (DC); swathing + combining at full maturity (SW). The working performance, cost, and seed losses associated with each harvesting method were calculated. The results highlighted how SW reduced the crop cycle length by 11 days, did not influence seed losses and crop yield but showed lower performance and higher cost with respect to DC.

Keywords: direct combining; swathing; crop cycle; seed loss; double cropping

Citation: Pari, L.; Cozzolino, L.; Marsac, S.; Hermet, L.; Bergonzoli, S. Effect of Swathing or Direct Combining on Yield, Seed Losses and Costs of Camelina. *Agronomy* **2024**, *14*, 325. https://doi.org/10.3390/agronomy14020325

Academic Editor: Hengyou Zhang

Received: 9 January 2024
Revised: 26 January 2024
Accepted: 31 January 2024
Published: 1 February 2024

1. Introduction

Camelina [*Camelina sativa* (L.) Crantz] is becoming increasingly attractive to agriculture and industrial sectors due to the wide possibility of exploitation of its seeds [1,2]. It is one of the most representative biofuel crops for cultivation on marginal lands and can also be integrated into different crop rotation and intercropping systems [3,4].

In the past, other Brassicaceae species such as rapeseed, were extensively studied both as a main crop and in more complex rotations [5–7], but they are very sensitive to low rainfall and undrained soil. On the contrary, camelina, considering its adaptability to different climatic and soil conditions, can contribute to increase the resilience of agricultural systems [8–10]. For that reason, camelina is currently cultivated in many regions of the world in European, Asian, and American continents proving its high suitability to be included in agricultural contexts of different climate regions [11]. Indeed, crop rotations and intercropping improve biodiversity with positive effects on local farming as well as on the environment [12]. In fact, poor biodiversity farming systems on the one hand could be more efficient and productive, but on the other hand they are more susceptible to fluctuations of the weather and market conditions. Consequently, the high sensitiveness to external conditions poses a serious threat for farmers' economic sustainability [13]. According to Dardonville et al. [14], farmers that choose biodiversity-based agroecosystems would experience an increase in natural capital and tend to record stable performances.

Moreover, Jalli et al. [15] proved a lower disease index and higher wheat yield in diversified crop rotation systems in comparison with monoculture.

Camelina oil can be used both as a food source for the human diet [16,17] and also for industrial purposes as follows: technical oil, biodiesel, jet-fuel production, lubricants, plasticizer, and several other applications [18–22]. In addition, in cold press meal, the oil and protein contents still account for up to 14% and 40% *w*/*w*, respectively, which makes camelina press cake a good competitor of soybean press cake in the animal feeding sector [23,24]. Moreover, reporting high oil contents in seeds, achieving up to 45% [4], camelina is a rich source of linolenic acid- (n−3 and n−6) fatty acid that can help to improve the quality of ruminant products (e.g., milk and meat) [25].

Harvesting of camelina seeds represents one of the biggest issues of the overall camelina cropping cycle due to the reduced seed size (1000-seed weight is attested around 0.8–1.8 g) that can require proper setting of the combine harvester in order to limit the seed loss as much as possible [26,27]. Camelina seeds can be harvested either via direct combining or threshed after natural drying in swaths. Results of previous studies stated that a combine harvester equipped with cereal header is suitable for camelina seed harvesting, if properly set and is convenient for farmers and contractor who use camelina in rotation systems with winter cereals since the same machine is applicable for both crops [28,29].

The swathing method is usually applied in the case of uneven maturity or as an aid to anticipate seed drying, thereby facilitating the timely planting of subsequent summer crops [30,31]. Double cropping of winter camelina, for example with sunflower, may be a strategy to diversify production systems and foster economic and environmental sustainability [32]. Furthermore, in specific studies on sunflower [33,34] an earlier sowing date resulted in higher yields, confirming the opportunity to reduce the camelina crop cycle.

However, authors [31,35] reported a seed loss as high as 11% after swathing. Conversely, swathing is a common practice, for example in Canola harvesting in Canada to reduce natural pod shattering and protect the crop from untimely frost or hail [36]. Another approach to facilitate mechanical harvesting is terminating the crop via chemical spraying, specifically by using chlorophyll depredating products whose effectiveness depends on concentration, temperature, plant coverage, and application technique [37]. The current literature is controversial; all methods were shown to be valid to act as an aid to facilitate mechanical harvesting in some studies, although other studies proved direct combining to be an effective method, at least in the Mediterranean region [27,29]. Therefore, the present study aimed to compare different camelina harvesting strategies in order to determine the following: (i) assess which strategy is more effective in reducing crop cycle, (ii) evaluate seed losses and impact on camelina yield, (iii) evaluate the costs associated.

2. Materials and Methods

2.1. Experimental Field

The experimental field was located in Montesquieu-Lauragais (43°24′30″ N, 1°37′24″ E), in the south of France about 30 km south of Toulouse (Figure 1).

The climate is generally mild, and can be defined as temperate, humid subtropical climate (i.e.,: Cfa in the Köppen climate classification) [38], with relatively mild winters and warm, sunny summers. The average temperature of the coldest month (January) is 6.3 °C (43.3 °F) and that of the warmest month (August) 22.8 °C (73 °F). Detailed weather data concerning the growing period of camelina, in the area of the study are depicted in Figure 2.

The soil type of the study area is a sandy silt clay (Table 1), classified according to the GEPPA soil texture triangle diagram, and was prepared with superficial tillage before seeding.

After the cultivation of Durum Wheat (*Tritivum durum Desf.*) in the season 2021–2022, camelina ('CCE 117') was sown, using a cereal drill seeder of 6 m (40 lines) at a rate of 8 kg ha^{-1} (corresponding to 725 seed m^{-2}) on 15 November 2022. Seeds were sown in the first centimetres of depth soil with 19 cm row spacing. At seeding, 60 kg of nitrogen was broadcast by using the granular fertilizer Smart N 41 + 12 SO_3 (https://www.invivo-group.com/fr accessed on 2 January 2024); no P or K fertilization were applied. Fertilization rate was selected following the experience of another study on the growth response of camelina [39]. No other operations were necessary before harvest.

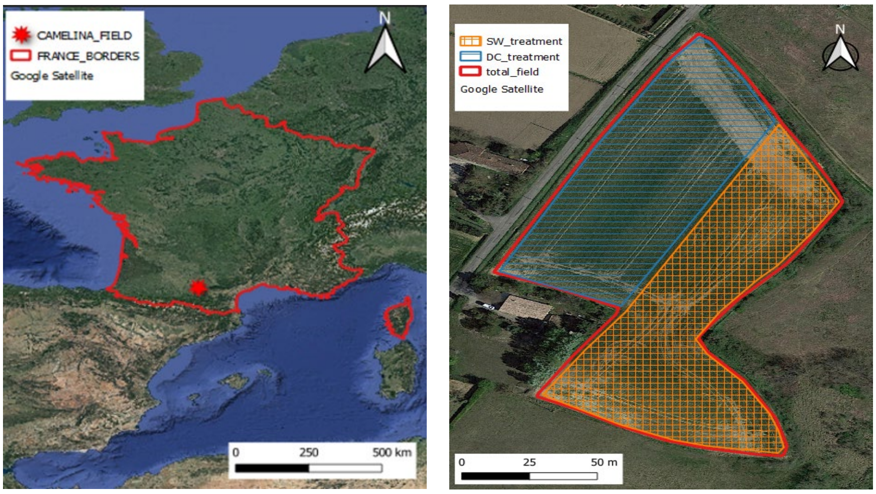


Figure 1. Map of the experimental field in Montesquieu-Lauragais region of France.

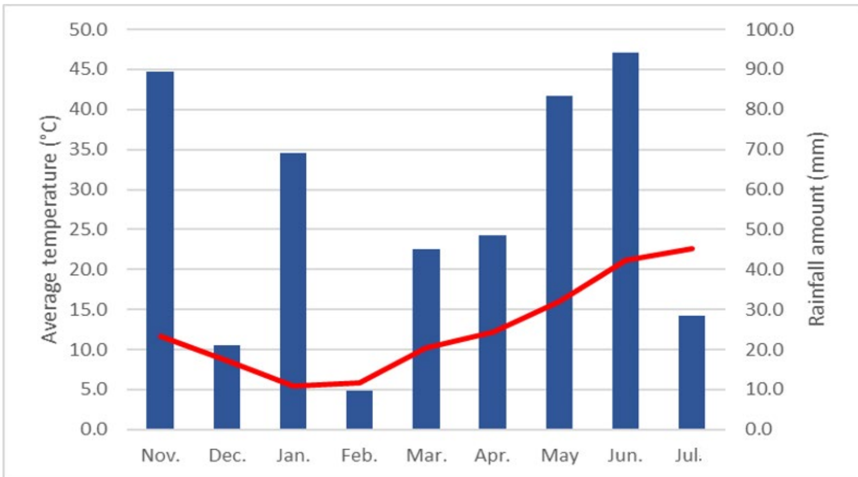


Figure 2. Graphic of the climatic trend during the growing season. The blue bar describes the rainfall amount and the red line represents the temperature.

Table 1. Soil chemical and physical characteristics of the field cultivated with camelina.

Parameters	Values
Clay (% DM)	29.40
Sand (% DM)	21.70
Silt (% DM)	34.10
Organic matter (% DM)	1.50
N (% DM)	0.18
pH (water)	8.40
P_2O_5 Olsen (mg kg^{-1} DM)	21.00
K_2O (mg kg^{-1} DM)	228.00

DM: Dry matter.

2.2. Harvesting Strategies

In order to meet the goals of the study, camelina was harvested by two different strategies: swathing when camelina has already reached maximum yield and oil content [40]:

+ combining at full seed maturity (SW) and direct combining at full seed maturity (DC). To do so, the experimental field was divided into two parts in order to apply the two treatments under the same conditions and eliminate external factors like climate and weather conditions that could affect the timing of the operations. The area of SW treatment had an extension of about 7000 m^2, while, the DC treatment had an area of about 6050 m^2. The field had an area with a slight slope on the south side and a flat slope on the north side. M.K Walia et al. [40] showed that seed yield and oil content have reached their maximal value at physiological maturity. Physiological maturity occurs when the cumulative growing degree-days (CGDD) are about 1200–1300 °C (base 4 °C) and at 41% of seed moisture. According to them, 150–250 CGDD more are then necessary for the plant to be mature enough for harvesting until reaching a final value of 35% [40].

They suggest that use of timely harvest strategies may save 1 or 2 weeks maintaining seed yield and quality. The target of the study was set to a seed moisture content of 35 ± 5%, considering the variability given by climate conditions [41,42]. The seed moisture content was continuously monitored during camelina maturation to detect the moment of swathing and combine harvesting. The procedure target was to collect a sample every week until values of 35% of seed moisture for swathing and 10% for combining operation were achieved. In practice, the frequency was adapted to previous results and meteorological conditions. Seed moisture was recorded after drying at 105 °C over 24 h [43].

2.2.1. Swathing and Combining Treatment (SW)

The swathing was carried out with a swathing machine of 85 kw with a 5.4 m header (Figure 3a). This machine is suitable for swathing large surfaces, in fact it has characteristics that make it particularly suitable for swathing crops that at maturity have high densities such as crops belonging to the Brassicaceae family. The characteristics that make it suitable are as follows:

- High height, which allows high swathing heights.
- Disjointed front wheels that facilitate turning operations.
- Swathing bar with tape that creates an oriented swath.

The swathing height was set as high as possible (i.e., 20 cm from the ground) to foster the air circulation inside the swath and speed up the drying process. The combine harvesting of the previously swathed biomass was carried out with the combine harvester of 260 kw equipped with a cereal header of 6.60 m (Figure 3b). The yield was quantified by discharging the seed collected by the combine on the scale at farm level.

Figure 3. Machineries involved in camelina mechanical harvesting: swathing machine (**a**); combine harvester (**b**).

2.2.2. Direct Combining Treatment (DC)

The experimental design stated as a target performing direct combining at full seed maturity (as for treatment SW) in order to calculate the difference in crop cycle length to reach the same seed moisture content. No mechanical operations were performed before DC. As for treatment SW, the harvesting was carried out with the same combine machine, and seed yield quantified with the same scale at farm level.

2.3. Pre-Harvesting Sampling

Before each harvesting operation, 6 squared sample plots of 1 m^2 each were randomly established to assess the amount of the whole epigeous biomass (stem, siliques, and seeds). All plants from each plot were closed in sealed bags and transferred to the laboratory of the Research Centre for Engineering and Agro-Food Processing (CREA-IT, Monterotondo, Rome, Italy) to perform further analysis. In particular, the number of plants for each sample, potential seed yield (PSY), dry weight (DW), and moisture content were evaluated. Dry weight and moisture content were estimated according to the EN ISO 18134-2:2017 standard [43].

2.4. Work Performances and Cost Analysis

Work performances during mechanical operations were calculated according to the methodology developed by Reith et al. [44]. The investigated parameters were the following: working speed (km h^{-1}), theoretical field capacity (TFC, ha h^{-1}, calculated knowing the working speed and the width of the header), effective field capacity (EFC, ha h^{-1}, calculated taking into account accessory times), and material capacity (MC, Mg h^{-1}, calculated knowing the EFC and the effective seed yield). The percentage ratio between EFC and TFC is named field efficiency (FE).

The whole cost for each harvesting system investigated was also calculated. Briefly, CRPA (Research Centre on Animal productions) methodology was followed to retrieve the standard values for the calculation [45], whilst standard ASAE D497.4 was used to calculate lubricant consumption [46]. Price of machineries was discounted to 2022 according to the Banca D'Italia Institute landing rate of 3.9% [47]. Work performances and cost analysis for camelina harvesting were assessed by the methodology described by Stefanoni et al. [27].

2.5. Seeds Loss Assessment

Seed loss was evaluated after the passage of machineries to assess seed loss triggered by each mechanical operation. Seed loss caused by the combine harvester was assessed according to the methodology proposed for camelina by Stefanoni et al. [27,29].

Camelina seed loss was evaluated by using two different methods:

(1) by counting the number of the seeds lying on the ground after the passage of the combine harvester. Ten squared sampling plots 10 cm $\times$ 10 cm (Figure 4) were randomly selected for each treatment. By knowing the 1000-seed weight, the amount of seed loss in the sampling plot was calculated in weight and referred to hectare.
(2) by considering the mere difference between the potential seed yield, resulting from pre-harvesting, and the harvested seed yield from the combine machine.

A different approach was applied for estimating seed loss after swathing. Before the combine harvesting of the swaths, 6 plots were randomly chosen on the swaths. Each plot measured 1.5 m in length (along the swath) and 2.45 m in width (as much as the swath). Plants within the plots were carefully removed and put in sealed bags, and thus brought to the laboratory for residual seed yield (RSY, i.e., seed yield after the application of the swathing content using a stationary thresher (PLOT 2375 Thresher, Cicoria Company, San Gervasio, Italy). In the SW system, the difference between PSY (measured during pre-harvesting) and RSY was assumed to be as the seed loss triggered by the swathing operation.

Figure 4. Example of a sample plot (i.e.: yellow box) to detect seeds on the ground.

2.6. Statistical Analysis

The analysis of variance (ANOVA) was performed using the R 3.6.1 software to separate statistically different means among the groups; when a significant effect was found; the means of the treatments were compared by the Tukey test ($p \leq 0.05$). Previously, all data were tested for normality and homoscedasticity [48].

3. Results and Discussions

3.1. Pre Harvesting

The main results obtained during the pre-harvesting operation are reported in Table 2.

Table 2. Plant characteristics as a result of pre-harvesting (mean ± SD). Values between columns followed by a different letter are statistically different at the level of $p \leq 0.05$ according to Tuckey's HSD test.

Parameter	SW	DC
	Before Swathing	**Before Harvesting**
Potential seed yield DM (Mg ha^{-1})	1.39 ± 0.23 b	1.86 ± 0.16 a
Total biomass DM (Mg ha^{-1})	8.46 ± 0.18 b	9.99 ± 0.18 a
Seed/straw ratio DM (%)	0.55 ± 0.06 a	0.51 ± 0.03 a
Plant density (n m^{-2})	188.00 ± 46.10 b	197.00 ± 67.10 a

DM: Dry matter.

The pre-harvest tests were performed in order to study the development of the camelina before application of mechanical operations. The aim of the activity was to evaluate differences among treatments, referring to the standing crop, due to uncontrolled biotic and abiotic factors that might have affected the crop performance before trial. Regarding the treatment SW, the pre-harvesting test before combining was aimed to evaluate the seed losses caused by the swathing operation.

According to the results reported in Table 2, potential seed yield (PSY) was higher for treatment DC (1.86 Mg ha^{-1}) with respect to SW (1.39 Mg ha^{-1}) as well as the total biomass (9.99 and 8.46 Mg ha^{-1}, respectively) and plant density (197 and 188 plants m^{-2}, respectively) with statistically significant differences.

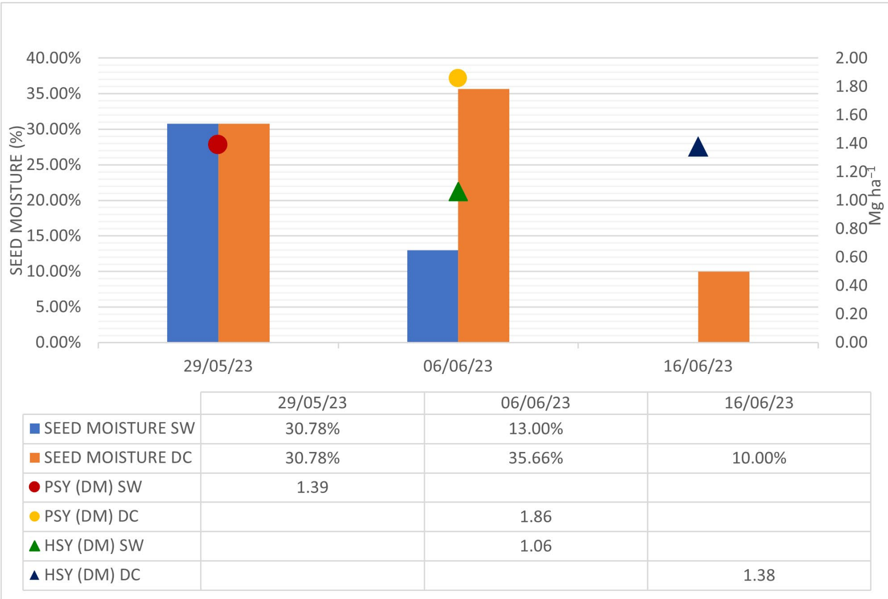
The PSY is consistent with other studies performed in Italy, Eastern Spain, and Romania, reporting seed yield ranging from 1.8 to 2.3 Mg ha^{-1} FM [49–52]. Lower values

(0.35–1.18 Mg ha^{-1} FM) were experienced in Spain and North-West USA by others [27,29]. PSY of treatment DC was 25% higher than SW, with statistically significant differences. This data stated that treatments were different in terms of PSY before any mechanical operations were applied due to factors not depending on the variables of the object of the trials.

Seed/straw ratio did not highlight statistically significant differences among treatments even if higher values were detected in treatment SW.

3.2. Crop Harvesting and Moisture Content

Results of crop harvesting are depicted in Figure 5.



	29/05/23	06/06/23	16/06/23
SEED MOISTURE SW	30.78%	13.00%	
SEED MOISTURE DC	30.78%	35.66%	10.00%
PSY (DM) SW	1.39		
PSY (DM) DC		1.86	
HSY (DM) SW		1.06	
HSY (DM) DC			1.38

Figure 5. Seed moisture trend, potential (PSY) and harvested seed yield (HSY) of the SW and DC treatments.

The swathing was carried out on 29 May 2023 and the seed moisture content was 30.8% for both treatments SW and DC, that was not interested by the mechanical operation. The combine harvesting of the SW biomass was performed after a week, i.e., on 6 June, with a seed moisture content of 13%. The same day the seed moisture content of treatment DC was 35.7%. The combining of treatment DC was applied 11 days after the combining of the SW treatment, i.e., on 17 June with a seed moisture content of 10%.

Results highlighted that the SW treatment reduced the crop cycle of camelina by 11 days with respect to treatment DC. This result was achieved because the drying of the seed was faster in the swath (SW) than in the standing biomass of the treatment (DC) as shown in Figure 6.

This result offers new opportunities for growing the following crops. In fact previous study demonstrated that sunflower could be successfully double-cropped after winter camelina [32,53], since the time saved corresponded to 8–10% of the total crop cycle of sunflower (i.e., 90–130 days). On the contrary, in other studies, double-cropped sunflower yield was reduced by 28% and seed oil content by 13% as compared with a monocrop treatment [54]. The primary reason for the differences was likely due to delayed sunflower sowing in the double-crop system, and hence, a shorter growing season than for the monocrop. The possibility of anticipating the sowing, offered by the results of the experimentation, could allow the cultivation of sunflower in double cropping without reducing the crop cycle and then maintaining the seed quantity and quality of the monocrop system [53,54].

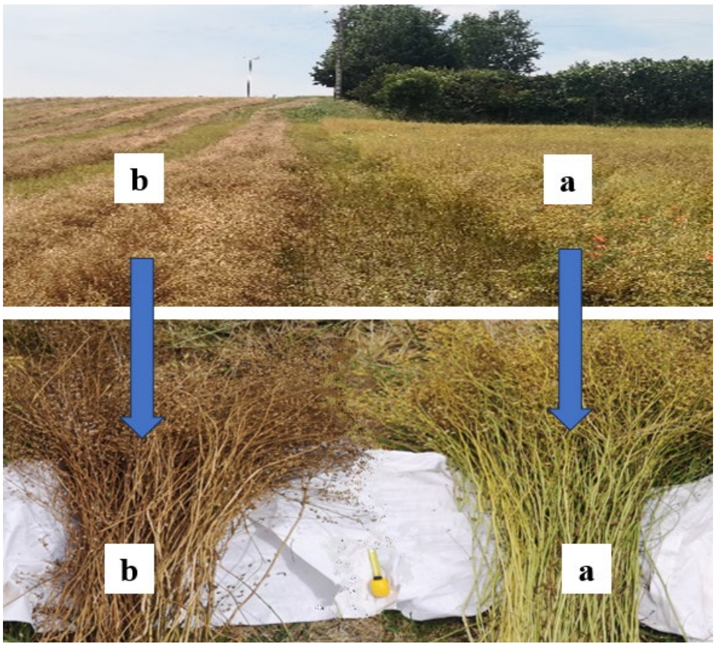


Figure 6. Comparison photo between (**a**) standing biomass of treatment DC, (**b**) swathed biomass of treatment SW on 6 June.

Results of seed yield highlighted a higher value for treatment DC with respect to SW (1.38 t ha^{-1} and 1.06 t ha^{-1}, respectively). The yield of treatment DC was 23% higher than the yield of treatment SW; a similar ratio was found also during the pre-harvesting operation when the potential seed yield of DC was 25% higher than SW (Table 1). This data show how the seed yield was higher for treatment DC before starting the test (PSY) and at harvesting time (HSY), therefore it could be stated that the effect of the harvesting operation did not specifically influence the treatments and did not alter the differences already present among them.

3.3. Harvesting Cost

Results of the working performance of the machines used for the harvesting operation and cost analysis are depicted in Table 3 with reporting of the main parameters.

Table 3. Evaluation of the working performance and associate costs of the machineries involved in camelina seed harvesting. Calculations were performed relying on average working times per treatment, therefore statistical analysis was not applied.

Parameter	**SW**		**DC**
	Swathing Machine	**Combine Harvester**	**Combine Harvester**
Theoretical Field Capacity (TFC ha h^{-1})	3.60	3.79	3.83
Effective Field Capacity (EFC ha h^{-1})	2.26	3.32	3.50
Field Efficiency (FE %)	0.63	0.87	0.91
Cost (€ ha^{-1})	35.20	54.52	51.72
Total cost (€ ha^{-1})	89.72		51.72

The total cost of SW treatment was 89.72 (EUR ha^{-1}) of which 39.2% was due to the swathing phase and 60.8% to the combine harvesting. The total cost of DC treatment was 51.72 (EUR ha^{-1}), corresponding to the 57.6% of the total cost of treatment SW. Considering the combine harvesting operation that was performed in both treatments, results showed a lower value of working performance (i.e., TFC, EFC, FE) and a higher value of unitary cost for SW with respect to DC. These differences could be ascribed to the different material collected. In fact, the material in the swath had a much higher density than the standing biomass and this determined a lower forward speed of the combine harvester resulting in lower TFC, EFC, FE, and higher cost.

However, the cost of direct combining was in line with the results of other studies; In fact, in similar studies the harvesting of camelina seeds via direct combining costed 48.51 and 65.97 EUR ha^{-1} [27,29] (costs were not discounted to the present day). The cost of SW was similar to the value reported in a comparative study on canola where a cost of 74.9 EUR ha^{-1} was reported [55]. In the authors' experience this is the first comparative study to analyse the harvesting cost of camelina.

3.4. Seed Losses

Current literature actually lacks specific harvesting tests, including the seed loss in direct combining against swathing. Only a few authors have dealt [56–58] with this matter who found that swathing can trigger seed loss, especially if the time is not appropriate.

As shown in Figure 7, camelina was intentionally mowed around 20 cm from the ground for two main reasons: first, keeping the cut plants suspended from the ground would help the air to dry the seeds; second, a common cereal header would have enough clearance from the ground to gather in the plants without using a dedicated pick-up header for the combine harvester. During the period from swathing until combine harvesting, 10 mm of rain was registered on the experimental field including 5 mm the day before harvest. These rain events did not influence the seed losses, the drying of the biomass, or causing rotting.

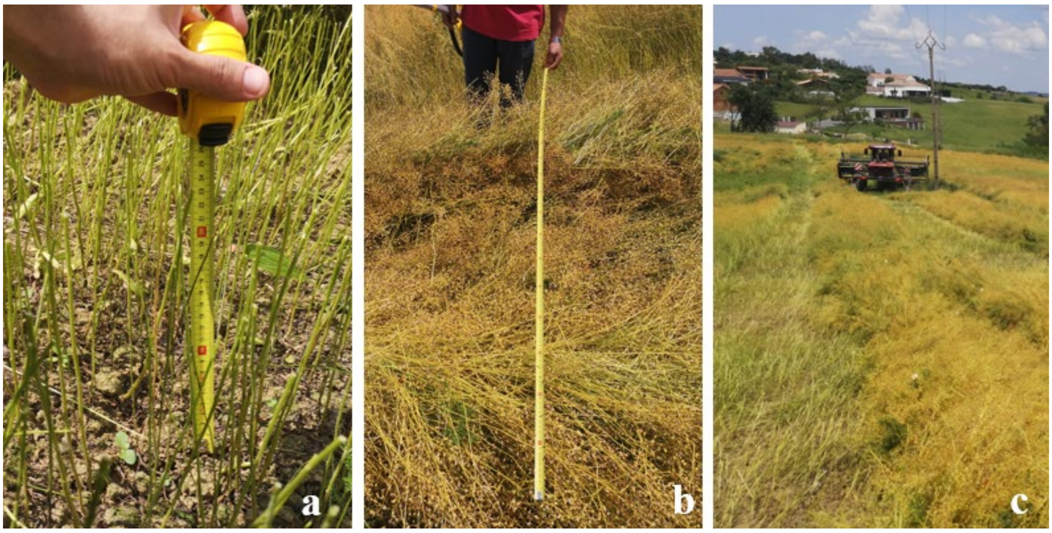


Figure 7. View of close-up of the cut-height (**a**); swathed camelina (**b**); camelina field during swathing (**c**).

From the analysis of seed losses, depicted in Table 4, it is highlighted that the swathing operation caused negligibly seed losses. In fact, from the analysis of the biomass present in the swath during pre-harvesting, seeds losses amounted to 1%. This result illustrated that seed losses caused by dehiscence or caused mechanically for the swathing operation were very low.

On the contrary, from the analysis of the mini plot after the combining operation, the seed losses amounted to 18% for treatment DC and 15% for SW, without statistically significant differences. Values of seed losses calculated comparing the potential seed yield obtained in pre-harvesting and the seed yield harvested by the combining machine, amounted to 25% for DC and 23% for SW. Seed losses assessed by the miniplot method were 28% and 26% lower, for DC and SW treatment, respectively, then the seed losses were estimated as the mere difference between the PSY and HSY.

Table 4. Assessment of seed loss during swathing and combine harvesting. Values within rows followed by a different letter are statistically different at the level of $p \leq 0.05$ according to Tuckey's HSD test.

Parameter	SW		DC
	Swathing	Combine Harvester	Combine Harvester
Potential Seed Yield (FM Mg ha^{-1})	1.38 b	1.39 b	1.86 a
Harvested Seed Yield (FM Mg ha^{-1})	1.06 *		1.38 *
Seed Losses (%)	1.00	23.00 * a	25.00 * a
Seed Losses MINIPLOT (%)		17.00 a	18.00 a

Note: (*) this value was not replicated since all grains were collected within one trailer and weighed only once at the end of the harvesting.

Results of previous studies [29] confirmed that different methods of seed loss assessment in camelina could provide results with around 25% of difference even if applied on the same conditions (e.g., machine, field, etc.). Recorded values of seed losses of treatment DC were higher respect to other values found in similar works [27,29]. Concerning treatment SW, seed losses were similar to other values found after swathing and combining of other crops. For instance, Brown et al. [56] recorded 17% w/w seeds loss in canola, Price et al. [57] reported seed loss of commercial oilseed rape ranging from 11 to 25%, and reaching 32% in flax as highlighted in Gubbels et al. [58].

The evaluation of the seed loss during the harvesting stage is a fundamental aspect to take into consideration since it contributes to reducing the revenue of farmers and contractors. Therefore, the loss of seeds should be as low as possible. No statistically significant differences were found between seed losses of the two treatments, despite the method used to assess them, and thus highlighting how combining was not affected by the type of biomass (standing or swathed).

4. Conclusions

Camelina is a promising annual crop for food, feed, and industrial uses. It has been gaining interest in Europe because of its low agronomic input requirements and high adaptability to a wide range of climatic conditions. Regarding mechanical harvesting, the literature lacks information on the most appropriate systems to minimize seed loss, costs, and reduce the crop cycle to better adapt to crop rotations. In the present work we addressed the advantages and disadvantages of direct combining in comparison with the swathing and combining system which is claimed to ease crop drying and anticipate crop harvesting.

Seed losses were higher with respect to other similar studies on camelina, but results were not statistically significant between treatments, thus highlighting how the harvesting strategy (SW or DC) did not influence the value obtained. We can speculate that such high seed losses were caused by improper setting of the combine while harvesting.

The harvesting cost of SW treatment was higher with respect to DC, because two machines were used, but the cost could be compensated for from the cultivation of a following crop after camelina. In fact, the swathing operation was very efficient for drying the crop due to the machine used and to the cutting height, resulting in a reduction of the camelina crop cycle of 11 days, without affecting the seed moisture content at harvest and therefore the seed quality. Future studies [32,52,53] will be performed on sunflower cultivation, in the double cropping system, after camelina is harvested by the two different strategies.

Author Contributions: Conceptualization, L.P.; methodology, L.P., S.B. and L.C.; validation, L.P., S.B. and L.C.; formal analysis, L.P., S.M., S.B. and L.C.; investigation, L.P., S.B., L.C., S.M. and L.H.; resources, L.P. and S.M.; data curation, L.P., S.B., L.C., L.H. and S.M.; writing—original draft preparation, S.B., L.C. and L.H.; writing—review and editing, L.P., S.B., L.C., S.M. and L.H; supervision, L.P.,

S.B. and S.M.; project administration, L.P. and S.M; funding acquisition, L.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was carried out within the 4CEMED Project funded by the European Union's PRIMA, under grant agreement No. 1911. The APC was funded by 4CEMED Project.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: All authors owe a special thanks to all technicians who passionately contributed to carry out the practical activities. Authors acknowledge Sandu Lazar from CREA-IT of Monterotondo (RM), and ARVALIS technicians.

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

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