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Assessing the Camelina (*Camelina sativa* (L.) Crantz) Seed Harvesting Using a Combine Harvester: A Case-Study on the Assessment of Work Performance and Seed Loss

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Abstract: The growing demand in food and non-food industries for camelina oil is driving the interest of farmers and contractors in investing in such feedstock. Nonetheless, the cost, performance and critical aspects related to the harvesting stage are still not properly investigated. In the present study, an ad-hoc test was performed in Spain in order to fulfill this gap. The results support the hypothesis to harvest camelina seeds with the same combine harvester used for cereal harvesting without further investment. Theoretical field capacity (TFC), effective field capacity (EFC), material capacity (MC), and field efficiency (FE) were 4.34 ha h^{-1}, 4.22 ha h^{-1}, 4.66 Mg h^{-1} FM, and 97.24%, respectively. The harvesting cost was estimated in 48.51 € ha^{-1}. Approximately, the seed loss of 0.057 ± 0.028 Mg ha^{-1} FM was due to the impact of the combine harvester header and dehiscence of pods, whilst 0.036 ± 0.006 Mg ha^{-1} FM of seeds were lost due to inefficiency of the threshing system of the combine harvester. Adjustment of the working speed of the combine and the rotation speed of the reel may help to reduce such loss.

Keywords: work productivity; harvesting costs; harvesting efficiency; wheat header; seed loss; header impact

1. Introduction

The European Union is currently fostering the replacement of fossil-based products with bio-based surrogates [1,2]. Oil crops play a key role concerning this issue, thanks to their suitability to synthesize molecular structures which could be used to displace substantial amount of petroleum oil derived compounds [3,4]. Worldwide production of vegetable oil is given for 75% by few crops, such as soybean, oil palm, cottonseed, rapeseed and sunflower; while the remaining 25% is obtained from other minor oilseeds [1]. On the other hand, some of these minor oilseeds show particular features, which make them particularly suitable in the concept of bio-economy. In particular, camelina (*Camelina sativa* (L.) Crantz) belonging to *Brassicaceae* family [5] and originating from South-East Europe and South-West Asia [6], is a very promising oil crop for multiple reasons [7]. Camelina oil can indeed be used as edible oil rich in omega-3 fatty acids [8], and its oil and meal are also suitable sources of protein for both fish and ruminant diets [9–12]. Camelina oil has also multiple industrial applications, such as biodiesel and jet-fuel production, even if with some drawbacks related to cetane number, iodine value, oxidation stability and linolenic acid methyl ester content [13,14]. Furthermore, camelina oil can be used in the production of

plasticizers, lubricants, polyols, resins, composites, coatings, elastomers, and adhesives [15]. Other interesting features of camelina are related to its cultivation. This species is indeed resistant to both drought and frost stress [16]. It has low nutritional requirements [17–19], with subsequent positive effects on the environment highlighted by life cycle assessment (LCA) studies [20,21], and can be grown on poor soils, also in a Mediterranean context [22], even if both seed yield and oil yield show substantial variability, i.e., 1.0–3.0 Mg ha^{-1} and 30–49% *w/w* respectively [23]. Finally, camelina, considering the presence of both winter and spring cultivar and the relatively brief life cycle, is suitable for double cropping with small grain cereals, soybean, and sunflower [24–29].

On the other hand, one of the main issues in camelina cultivation is the high costs of the supply chain [30]. Indeed, the higher percentage of costs for biodiesel production are related to the feedstock [31] and optimizing harvesting operation can lead to a substantial decrease of such costs [32].

According to this, costs of harvesting and logistic have to be evaluated, in order to make camelina cultivation fully sustainable and give support in the decision-making process to farmers and other stakeholders. Currently, mechanical harvesting of camelina is mainly carried out by using a combine harvester equipped with wheat header [33], only few experiences on cutting and swathing are reported [34]. However, seed loss can be very high, as a consequence of the tiny dimension of the seeds which are very small and light in weight [35,36] moreover, presence of weeds can further increase seed loss amount. Indeed, the entrance within the combine harvester of the green material of weeds, which generally shows higher moisture content than camelina, can reduce the efficiency of the threshing and cleaning system of the combine harvester, leading to higher seed loss [37]. Considering this, appropriate setting of the combine harvester and adjustment of working speed are fundamental to reduce seed loss [38]. However, combine harvester settings are not the only important aspects to take into account. In fact, camelina suffers seed loss for shattering as the ripeness is completed. Pods can easily open as consequence of external mechanical input, as the cutting bar of the combine harvester can provide. Hence, it is also important to finely regulate the rotary speed of the reel as well as the working speed of the machine in order to reduce such a phenomenon as much as possible. Some authors also suggest to consider the swathing method for harvesting in case of uneven ripeness [38].

Notwithstanding the centrality of this topic in the optic of a sustainable cultivation of camelina, few studies have focused on the evaluation of work performance, harvesting costs, and seeds loss.

The only comprehensive study reported in literature is Stefanoni et al. (2020), who reported a work productivity of 3.17 ha h^{-1}, with harvesting costs of 65.97 € ha^{-1} and seed loss of 7.82% *w/w* for a John Deere combine harvester (John Deere, Moline, IL, USA) [39]. In a previous work related to harvesting loss evaluation using a plot combine Sintim et al. (2016) found seed loss of 11.60% *w/w* [40], while Stolarski et al. (2019) reported harvesting cost per surface unit of 46.70 € ha^{-1} with a New Holland (New Holland, PA, USA) combine harvester [41].

Considering what is written above, there is still a need to investigate such a topic with specific field tests, in order to fill the knowledge gap that still exists. The aim of the present work is properly to provide the literature with significant information for both farmers and contractors; about work performance, costs and seed loss when collecting camelina seeds by combine harvester.

2. Materials and Methods

2.1. Experimental Field

Harvesting test was performed in the town of Astudillo, Palencia (Castilla y Leon, Spain) during the 27th week of 2020 (Figure 1). The experimental field (WGS84-UTM30T coordinates 390,896 E; 4,661,826 N) was flat and it measured 24.00 ha in surface and 893 m a.s.l in altitude.
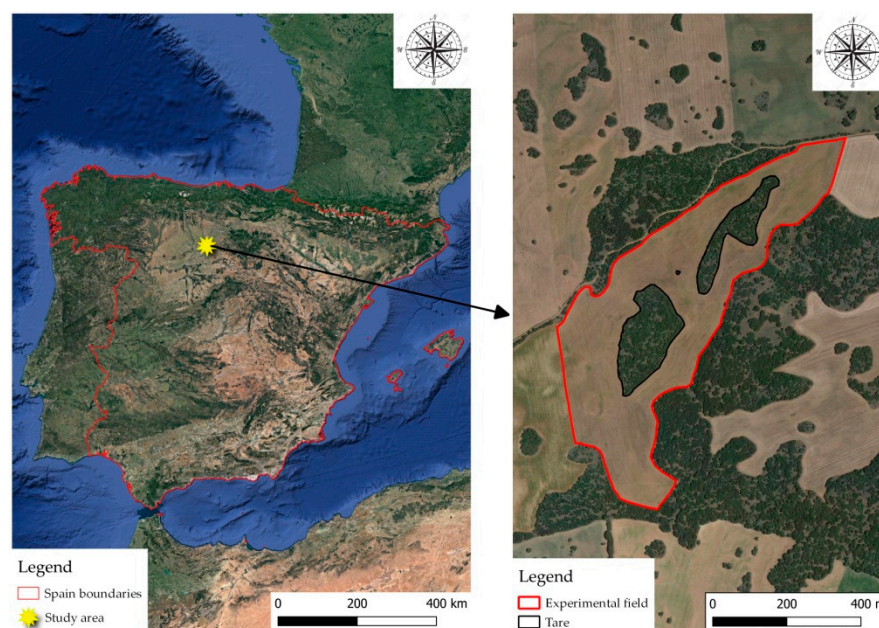
Figure 1. Experimental field location.

Camelina cultivation in the experimental field was carried out in conventional farming regime. Cultivar *Alba* (commercial variety provided by Camelina Company España) was sown in the first half of December 2019 with a seeding rate of 8 kg ha^{-1}. The previous crop was Barley. Fertilization was provided two times, with a rate of 250 kg ha^{-1} of NPK 8-15-15 in winter using a trailed fertilizer spreader and 250 kg ha^{-1} of liquid Nitrogen fertilizer (32%) in April by means of a mounted liquid fertilizer spreader. Chemical control of weeds was carried out before the nitrosulphate ammonium distribution by using a graminicide (Pilot, Quizalofop-p-ethyl 10%) to control the narrow-leaf weeds.

2.2. Pre-Harvest Test

Prior to the harvesting operation, 10 squared sample plots of 1 m^2 each were randomly established in order to assess the amount of the whole epigeous biomass (straw, siliques, and seeds). Camelina plants were cut at ground level with a shear, counted and then measured in both weight and height. Siliques and seeds were pulled and weighed separately. Consequently, siliques, seeds and a sample of straw from each plot were closed in sealed bags and transferred to the laboratory of Research Centre for Engineering and Agro-Food Processing (CREA-IT, Monterotondo, Rome, Italy) in order to perform further analysis. In particular, potential seed yield (PSY), dry weight (DW), 1000 seed-weight, bulk density and moisture content were evaluated. Dry weight and moisture content were estimated according to EN ISO 18134-2:2017 standard [42]. Seeds bulk density (kg m^{-3}) was calculated according to ISO 17828:201 [43] in 15 randomly selected samples.

2.3. Combine Harvester Model and Setting

The harvesting machinery was provided by the contractor. In particular the operation was carried out with a Claas Lexion 570 (Westfalia, Harsewinkel, Germany) combine harvester equipped with a conventional cleaning shoe and a 6.6 m wide cereal header. The machine had 273 kW diesel engine and the applied setting was as follow: rotor speed 800 rpm, cleaning fan speed 700 rpm, opening of the upper sieve 5/22 mm while lower sieve was closed. The combine harvester was moreover equipped with a straw chopper system, to thresh the straw and spread it on the ground.

2.4. Work Productivity

Harvesting productivity was tested in 6 sample plots randomly established in the study area. The area of each plot ranged between 420 to 950 m^2, and the evaluation of the working times was performed according to the methodology developed by Reith et al. (2017) [44]. The investigated parameters were: 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, %).

After harvesting operation, the collected material was unloaded onto a trailer and transported to the farm scale in order to be weighted.

2.5. Cost Analysis

Purchase and operating costs of the machinery were obtained interviewing the contractor, whilst the work productivity of the combine harvester was derived from the results of field tests and standard values for calculation were obtained from CRPA (Research Centre on Animal productions) methodology [45] as reported in Suardi et al. (2020) [46–48].

Hourly costs of harvesting machinery were calculated taking into account the market value of the combine harvester. The price of the combine harvester was discounted to 2019, using the lending rate of 3% provided by Banca d'Italia [49]. The parameter used for cost analysis are given in Table 1.

**Table 1.** Applied parameters for cost analysis.

	Parameter	Measure Unit	Value
Machine	Power	kW	240
	Investment	€	362,615
	Service life	year	10
	Service life	H	3000
Financial costs	Resale	%	19.00
	Resale	€	68,896.85
	Depreciation	€	293,718.15
	Annual usage	h year^{-1}	312
	Interest rate	%	3
	Ownership costs	€ year^{-1}	29,371.82
	Interests	€ year^{-1}	6472.67775
Fixed costs	Machine shelter	m^2	35.64
	Value of the shelter	€ m^{-2}	100
	Value of the shelter	€ year^{-1}	71.28
	Insurance	€ year^{-1}	906.5375
	Repair factor	%	40
	Repairs and maintenance	€ h^{-1}	50.28
Variable costs	Fuel cost	€ l^{-1}	0.57
	Fuel consumption	l h^{-1}	42.50
	Fuel cost	€ h^{-1}	24.23
	Lubricant cost	€ l^{-1}	3.03
	Lubricant consumption	l h^{-1}	0.38
	Lubricant cost	€ h^{-1}	1.14
	Worker salary	€ h^{-1}	11.5

2.6. Seed Loss Evaluation

Camelina seed loss was evaluated by counting the number of the seeds lying on the ground after the passage of the combine harvester. Specifically, two different areas behind the machine were selected as shown in Figure 2a: (A) in correspondence of the swath; (B) beside the swath but within the maximum cutting bar width. Ten squared sampling plots

10 cm $\times$ 10 cm (Figure 2b) were randomly selected within each region. Thus, in A, the seed loss was due to natural shattering (SS), impact of the header (ISL) and inefficiency of the cleaning shoe (CLS). On the other hand, in B, the seed loss was due to SS and ISL. Consequently, CLS was calculated as difference between the total seeds found in A and B regions. Since the loss due to CLS was concentrated in 1.6 m (the width of the swath), the difference in seed number between A and B was divided by 4.125 (the ratio between the cutting bar width and the swath width). By knowing the 1000-seed weight, the amount of seed loss was calculated in weight and referred to hectares.

A= SS + ISL + CSL

B= SS + ISL
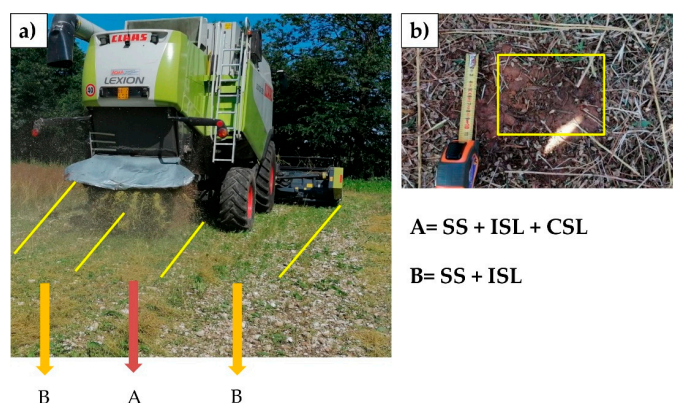
Figure 2. On the left (**a**), identification of the areas A and B behind the combine harvester. On the right (**b**), example of a sample plot to detect seeds on the ground.

Furthermore, the effective seed loss (ESL) was also estimated by calculating the difference between the potential seed yield (PSY), measured in the pre-harvesting plot, and effective seed yield (ESY), measured by the farm scale after weighing the trailer.

The difference of the two methodologies was used to estimate the SS.

2.7. Statistical Analysis

The analysis of variance (ANOVA) was performed using the R 3.6.1 software to separate statistically different means among the groups ($p \leq 0.05$) [50].

3. Results

3.1. Pre-Harvest Test

Results of the pre-harvest tests are shown in Table 2. Before harvesting, 424 plants per m^2 were standing on the field and the mean plant height was 60 cm. Straw, siliques and seed moisture were 44.40%, 9.91%, and 6.45% respectively.

As reported in Figure 3, the largest aboveground portion was straw (69.62% *w/w*), then siliques and seeds (14.44% *w/w* and 15.94% *w/w* respectively). The harvest index (HI) was 0.223 and the potential seed yield was 1.17 Mg ha^{-1} FM.
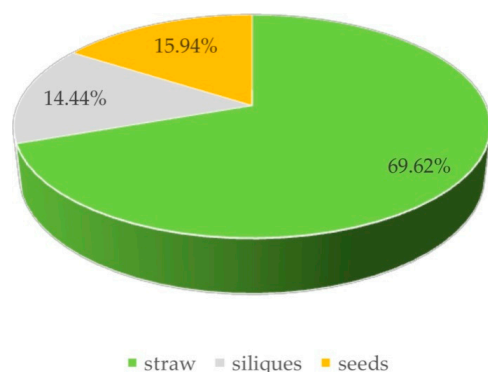
Figure 3. Percentage of straw, siliques and seeds of the aboveground biomass.

Table 2. Results of pre-harvest test reporting the mean quantity of available aboveground biomass, moisture content, and allocation among siliques, seeds and stalks. Weigh and bulk density of seeds is also reported.

Parameter	Measure Unit	Average	St.Dev.
Harvested surface	ha	24	-
Number of plants	N m^{-2}	424	176
Plant height	cm	60	8
Straw weight	Mg ha^{-1} FM	5.10	1.15
Straw moisture content	%	44.40	6.21
Siliques weight	Mg ha^{-1} FM	1.06	0.25
Siliques moisture content	%	9.91	0.49
Potential seed yield (PSY)	Mg ha^{-1} FM	1.17	0.18
Seed moisture content	%	6.45	0.40
1000-seed weight	g	1.04	0.07
Seed bulk density	kg m^{-3}	687.82	13.60

3.2. Work Productivity and Costs

Working performance of the combine harvester is reported in Table 3. The working speed was estimated being 6.57 km h^{-1}, while TFC and EFC were 4.34 ha h^{-1} and 4.22 ha h^{-1}, respectively. Considering the effective seed yield (1.10 Mg ha^{-1} FM), the MC and FE resulted in 4.66 Mg h^{-1} FM and 97.24%, respectively.

Table 3. Evaluation of the work performance of the combine harvester: theoretical and effective field capacity, field efficiency and material capacity.

Parameter	Measure Unit	Average	St.Dev.
Working speed	km h^{-1}	6.57	1.00
Theoretical Field Capacity (TFC)	ha h^{-1}	4.34	0.66
Effective Field Capacity (EFC)	ha h^{-1}	4.22	0.63
Field Efficiency (FE)	%	97.24	0.41
Material capacity (MC)	Mg h^{-1}	4.66	0.69

The analysis of working performance allowed to estimate the harvesting costs which were: 205.17 € h^{-1}, 48.51 € ha^{-1} and 43.92 € Mg^{-1} FM.

3.3. Seed Loss Evaluation

The seed loss calculated for each source of is reported in Table 4. TSL was 0.093 ± 0.033 Mg ha^{-1}, or 7.95 ± 0.28% of PSY. The majority of seed loss (4.87 ± 2.35% *w/w*) is linked to the impact of the header and the natural shattering. The latter further estimated in 1.97% *w/w* of the PSY as difference between TSL and ESL. On the other hand, CLS accounted for 3.08 ± 0.54% *w/w* of the TSL. The effective seed loss measured as the mere difference between the PSY and ESY, was 0.07 Mg ha^{-1}.

Table 4. Seed loss assessment according to the two methodologies. Common letters within columns denote the absence of significant difference ($p < 0.05$).

Parameter	Average	
	Mg ha^{-1} FM	%
Area A (CSL)	0.036 ± 0.006 b	3.08 ± 0.54
Area B (SS+ISL)	0.057 ± 0.028 a	4.87 ± 2.35
Total seed loss (TSL)	0.093 ± 0.033	7.95 ± 0.28
Potential Seed Yield (PSY)	1.17 ± 0.18	
Effective Seed Yield (ESY)	1.10 *	
Effective seed loss (ESL)	0.07 *	5.98 *

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

4. Discussions

4.1. Aboveground Biomass Yield

The potential seed yield assessed in the pre-harvest test of 1.17 ± 0.18 Mg ha^{-1} FM (seed moisture content of 6.45 ± 0.40%) is in line with the findings reported in Mauri et al. (2019) and Stefanoni et al. (2020) for similar experiments conducted in Spain [39,51] as well as in USA as reported by Schillinger et al. 2019 [52]. Higher values of seed yield are reported by Royo-Esnal et al. (2018) in Eastern Spain with seed yield ranging from 0.92 to 2.31 Mg ha^{-1} FM after a comparison of different sowing rates: 8 kg ha^{-1} and 11 kg ha^{-1} [27]. However, the authors did not find a significant effect of the sowing rate upon potential seed yield, nor with the weed coverage. Similarly, Zanetti et al. (2020) reported a negligible effect of the plant density on seed yield, whilst later sowing could improve oil content [22]. In the present study, instead, fertilizer and chemicals were used to both providing nutrients and controlling the weeds. In similar studies, where camelina was grown under conventional farming, the potential seed yield doubled in comparison with not fertilized fields (namely, 0.93 Mg ha^{-1} FM and 1.81 Mg ha^{-1} FM) [53]. Comparing with other herbaceous oilseeds, for instance, camelina performs slightly lower than castor (*Ricinus communis* L. up to 4.4 Mg ha^{-1}), canola (*Brassica napus* L. 2.19 Mg ha^{-1} FM), sunflower (*Heliantus annuus* L. 1.97 Mg ha^{-1} FM) [33], although it is suitable for cropping in marginal land [54]. After harvesting, seeds usually face some storing which could be also long in time before being processed. This condition can lead to low quality product, or even loss of the entire product if moisture is too high. In the present study, seed moisture was found as low as 6.45 ± 0.4% which is far below the threshold of 8% as reported by [55]. 1000 seed-weight was also recorded and it averaged to 1.04 ± 0.07 g in fresh weight which is consistent with the value found by other authors [39]. If compared with other Brassicaceae family and seed weight, it is rather low. In fact, Kuai et al. (2015) reported 3.3 and 3.5 g in rapeseed (*Brassica napus* L.) [56], Zhu et al. (2016) reported values ranging from 6.0 to 9.5 g per thousand seeds in crambe (*Crambe abyssinica*) [57].

Despite the seeds that find application on both food and non-food sectors, straw and siliques from camelina (5.10 ± 1.15 Mg ha^{-1} FM and 1.06 ± 0.25 Mg ha^{-1} FM respectively) can also be attractive for energy industry. In fact, they both are valid feedstocks for bioenergy production via pyrolysis due to the low nitrogen content (0.4–0.5%) and the low char production (approximately 25.5%) [58]. However, the chemical-physical properties of camelina residual biomass can vary according to the growth conditions. For instance, camelina grown in the Central Italy exhibits high cellulose and hemicellulose content in comparison with camelina grown in the Northern Italy while the ash content is not affected by such factor [59]. This implies that different scenarios are opened for the exploitation of camelina residual biomass in a sustainable green chemistry approach. Moreover, the development of a proper value chain of the residual biomass may contribute to the reduction of greenhouse gas emissions that occur during the degradation of the organic matter in the soil as reported in other oil crops [60].

4.2. Work Productivity and Costs

In the present study, a conventional combine harvester equipped with a cereal header was used. The literature still lacks the knowledge on such kind of strategy for harvesting camelina seeds, therefore a comparison is possible relying on the findings reported in Stefanoni et al. (2020) [39]. Here, the working speed of the machine was 30.1% higher. This caused the increase of TFC, EFC, FE, and MC by 29.29%, 33.12%, 3.54%, and 54.82% respectively. Interestingly, the cutting bars of the combine harvesters measured 6.6 and 6.7 m wide. Such a negligible deviation leads to the conclusion that the difference in the performance are exclusively related to the different working speeds.

Interestingly, comparing the performance of the combine harvester found in the present study with those reported in similar studies but conducted on wheat grains harvesting, here again the findings are higher. Normally, TFC ranges from 2.61 ha h^{-1} to 3.72 ha h^{-1}, while the EFC is 1.92–2.28 ha h^{-1} and the FE is as high as 83% [46–48]. However, it is important to underline that such high working performance is related to the dimensions and to the particular shape of the experimental field, which allowed to minimize the turnings, thus decreasing the accessory time and increasing the EFC and FE.

The harvesting cost was assessed in 48.51 € ha^{-1} and 43.92 € Mg^{-1} FM which are consistent with the cost shown by Stolarski et al. (2019) [41], but much lower than that calculated in a similar harvesting trial performed in Spain on camelina crop (65.97 € ha^{-1} and 69.42 € Mg^{-1} FM) [39]. Other trials performed on wheat and corn grain harvesting with combine harvester showed harvesting costs being 77.98 and 129.51 € ha^{-1}, respectively [46,61].

4.3. Seed Loss Evaluation

The evaluation of the seeds loss during harvesting stage is an important parameter to take into account since it contributes to reduce the revenue of farmers and contractors therefore, the loss of seeds should be as low as possible. Generally, the amount of seed lost is calculated as the difference between the potential seed yield (1.17 ± 0.18 Mg ha^{-1} FM) and the effective seed yield (1.10 Mg ha^{-1} FM) which, in this specific trial, was 0.07 Mg ha^{-1} FM (5.98% *w/w*). Higher values were found by Stefanoni et al. (2020) and Sintim et al. (2016) which found 7.82 and 11.70% *w/w*, respectively [39,40]. In other herbaceous oil crops, seed loss ranges from 1% as in sunflower [62,63] or in canola [64,65], and 3% as in safflower [33], or even higher as in castor bean harvesting [33]. However, such information only provides evidence regarding the total amount of seed loss, but it fails in pointing out what is responsible for that loss. A combine harvester is a complicated machine which can generate different sources of loss particularly if seeds are small and light in weight (only 1.04 ± 0.07 g FM per 1000 seeds). The main sources of loss are the impact of the header and the inefficiency of the cleaning shoe. If some actions have to be taken against the seed loss in camelina harvesting, their respective contribution to the TSL must be investigated. According to Table 4, the inefficiency of the cleaning shoe of the combine harvester (CSL) triggered the loss of 0.036 ± 0.006 Mg ha^{-1} FM (3.08 ± 0.54% *w/w*) of the seeds, while 0.057 ± 0.028 Mg ha^{-1} FM (4.87 ± 2.35% *w/w*) of seeds were lost due SS and ISL. Interestingly, TSL and ESL differed for 0.023 Mg ha^{-1} FM (1.97% *w/w* of the PSY) which can be partially explained as the loss due to SS (natural pod shattering) which occurs spontaneously in camelina as it ripens. In fact, late harvesting can lead to a loss of seeds due to SS as high as 25% *w/w* in some cultivars [66]. Moreover, pod shattering can be triggered by a minimum external input in completely ripened pods. Therefore, the mechanical disturbance provided by the combine harvester can contribute significantly to increase such phenomenon, particularly as working and rotation speed of the reel (the latter value was not measured in the present study).

5. Conclusions

Camelina is gathering more and more attention throughout the Europe since its multipurpose oil as well as the aboveground suitability for bioenergy purposes. However, the related value chain is still not well developed, partially because the crucial phase of the

harvest has not been comprehensively investigated so far. Our findings support the hypothesis that a combine harvester equipped with wheat header is suitable for camelina seed harvesting, which is particular convenient for farmers and contractor who use camelina as rotation crop in winter cereals since the same machine is valid for both crops. Furthermore, the cost and the performance are similar. Little concern may arise regarding the seed loss which are mainly linked to impact of the header of the combine harvester, and the inability of the cleaning shoe to efficiently discriminate the seeds from the other portions of the biomass. This latter problem can be partially addressed by simply reducing the speed of the machine. Instead, natural pod shattering contributes marginally to the loss of seeds.

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