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Mechanical Harvesting of Castor Bean (*Ricinus communis* L.) with a Combine Harvester Equipped with Two Different Headers: A Comparison of Working Performance

Walter Stefanoni [1,*], Francesco Latterini [1], Valantis Malkogiannidis [2], Vlasis Salpiggidis [2], Efthymia Alexopoulou [3] and Luigi Pari [1]

[1] Consiglio per la Ricerca in Agricoltura e l'analisi dell'Economia Agraria (CREA), Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari, Via della Pascolare 16, 00015 Monterotondo, Italy; francesco.latterini@crea.gov.it (F.L.); luigi.pari@crea.gov.it (L.P.)

[2] Bios Agrosystem SM SA, Koutso, 67064 Xanthi, Greece; malkogiannidis@bios-agrosystems.gr (V.M.); v.salpigidis@bios-agrosystems.gr (V.S.)

[3] Centre for Renewable Energy Sources and Saving, Marathonos Avenue, 19009 Pikermi, Greece; ealex@cres.gr

* Correspondence: walter.stefanoni@crea.gov.it

Abstract: Castor bean (*Ricinus communis* L.) is a promising industrial crop suitable for cultivation in marginal conditions in the Mediterranean area, but the mechanical harvesting of the seeds is still usually performed manually. In this manuscript, the authors present a preliminary test to assess the effectiveness of equipping a combine harvester with a sunflower header to mechanically harvest castor beans. Machinery performance, seed loss from impact (ISL) and cleaning systems (CSL), and seed cleaning were evaluated and compared with the results obtained from the same combine harvester equipped with a cereal header. According to the results, no statistically significant difference in CSL was found. Values ranged from 162. 41 kg dry matter (DM) ha^{-1} in the cereal header to 145.56 kg DM ha^{-1} in the sunflower header, corresponding, respectively, to 8% *w*/*w* and 7% *w*/*w* of the potential seed yield (PSY). Using the sunflower header significantly lowered ISL (158.16 kg DM ha^{-1}, i.e., 8% *w*/*w* of PSY) in comparison with the cereal header (282.02 kg DM ha^{-1}, i.e., 14% *w*/*w* of PSY). This suggests more gentle cutting and conveying capability of the sunflower header to harvest the plants without losing capsules. On the other hand, the use of different headers did not significantly affect the cleaning of the seeds which averaged at 20% of the total seeds collected in both cases. In conclusion, the study highlights that a conventional combine harvester equipped with a sunflower header could be the first step towards the development of a fully mechanized harvest phase in castor beans which triggers lower seed loss and does not negatively affect the cleaning capacity of the combine harvester. Further studies are also encouraged to confirm these findings in other hybrids.

Keywords: combine harvester; supply chain; seed loss; working performance; dehulling; castor bean

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1. Introduction

According to the most recent directives on bioeconomy issued by the European Union, the industrial sector should rely more on bio-based materials instead of conventional petrol-based sources [1–3] and the primary sector can help to achieve this goal via improving the exploitation of oilseed products and by-products [4,5]. However, the cultivation of industrial crops causes concerns regarding land use and the consequent competition between food and non-food cultivation [6], and the possibility to cultivate industrial crops on marginal lands can represent the best compromise to meet the future EU energy goals without reducing land availability for food production [7,8]. Consequently, the value chains of low-input-demanding crops should be further investigated to solve the current bottlenecks for large-scale applications. With this in mind, castor bean (*Ricinus communis* L.) is a very

promising non-food crop, which can be grown in low-input regimes in the Mediterranean area, reaching seed yields up to 4.44 Mg ha^{-1} [9,10]. Moreover, castor oil can be used for several purposes, i.e., biodiesel, cosmetic, pharmaceutic, paint, varnish, and lacquer production as well as lubricant in two-stroke engines or a component of semirigid foams in thermal insulation [11–15]. Its contribution to making the EU less dependent on the foreign vegetable oil market for industrial and energy purposes could be tangible if an effective domestic castor oil supply chain would be properly developed.

Ricinus communis L. is known as many wild and semiwild types which can differ in genetic and phenotypic traits, reaching heights similar to a moderate-sized tree [16]. In castor, the seeds grow inside capsules born on one or more racemes which develop progressively during the life of the plant. Consequently, seed ripening is heterogenous among racemes [17,18]. For this reason, the mechanization of castor seed harvesting is challenging, and the market still lacks dedicated machineries. Therefore, seeds must be harvested manually which increases costs for production of castor oil and related by-products. Thus, the supply chain has developed only in low labor cost countries such as Brazil, India, Ethiopia, or Mozambique [19] and this makes developed countries more dependent on the foreign market for castor oil. In order to also develop castor bean oil value chains in Europe and make the EU more independent, castor bean harvesting must be performed mechanically. The first challenge is represented by crop homogeneity which has been tackled by geneticists during recent decades by selecting highly performing hybrids of castor exhibiting higher harvest index and lower seed dehiscence [20,21]. Currently, some dwarf hybrids are available on the market and perform well in terms of productivity and suitability for developing a reliable mechanization of seeds. In fact, mechanical harvesting is still the main constraint for the development of a supply chain of castor bean due to the high heterogeneity of castor phenotypes [22]. Some prototypes have been made and tested, although never tested scientifically, for instance, by applying modifications to common maize headers for combine harvesters meant for harvesting castor seeds in a single passage. However, specific scientific studies dealing with the setup of the combine harvester, the related seed loss, and the overall performance of the machinery are still lacking. Only a few tests have been conducted, including those performed by Evogene Ltd. (Rehovot, Israel) and Fantini s.r.l (Mantova, Italy). Both companies also developed a prototype of a combine harvester header specifically meant for castor bean harvesting. In the literature, a different approach was suggested by Zhao et al. (2019) [23] who investigated a dual stage harvesting where only capsules were harvested from the field using an innovative vibrating system to shake the plants and collect the capsules only. However, scientific evidence of its suitability is still vague. The only scientific test on castor bean mechanical harvesting has been conducted recently in Greece. The authors specifically investigated the possibility to ease the mechanical harvesting by terminating the crop with different chemicals. However, in the same study, the authors also reported two important results: firstly, the cereal header triggered the loss of 29% to 62% of the potential seed yield due the impact and, secondly, the percentage of seeds correctly selected by the combine harvester ranged from 26.79% *w*/*w* to 38.34% *w*/*w* of the overall collected seeds [24]. Combine harvesters offer the possibility to harvest seeds from several herbaceous species, which may be quite different in shape and size, by adjusting the setup and using a proper header. Since dwarf castor plants exhibit thick and hard stems, similar to a sunflower's stem, we hypothesized that using a sunflower header would stress castor plants less than a cereal header. In fact, contrary to the cereal header, the sunflower header relies on a different feeding system consisting of a header table arranged in rows and transport chains conveying the cut plants to a crop elevator without a reel. These main differences could help to reduce seed loss, particularly due to the impact.

Therefore, this preliminary study investigates the possibility of using a sunflower header for: (i) reducing the seed loss at the impact (ISL), (ii) reducing seed loss deriving from the cleaning shoe of the combine (CSL), (iii) increasing the percentage of correctly selected seeds stored in the seed tank of the machinery.

2. Materials and Methods

2.1. Study Area and Experimental Field

Tests of mechanical harvesting of castor bean seeds were performed on a sandy soil located in Koutso (Xanthi, Greece) (WGS84-UTM35T coordinate 334961 E, 4546505 N) on 8 September 2021.

The overall surface of the field was 0.46 ha. Pre-seeding operations consisted of ploughing (20 April 2021) and harrowing (29 April 2021).

Sowing was carried out on 29 April 2021 by applying 21 kg ha^{-1} of seed of hybrid C1012 (provided by Kaiima company, Moshav Sharona, Israel) with sowing distance 95 cm × 22 cm through a cotton seed sowing machine.

The same day, a first fertilization with 270 kg ha^{-1} of fertilizer NPK 21-17-3 was carried out. To remove weeds, a chemical control with 4000 g ha^{-1} of Stomp (BASF, Ludwigshafen, Germany) was carried out, as well as a mechanical control via ripper on 8 June 2021, further refined with manual weed removal on 14 June 2021. Irrigation was performed on 30 April, 9 May, 14 July, 22 July, 28 July, 6 August, and 20 August; it was not needed in June because of sufficient natural rainfall.

On 29 July 2021, the foliar fertilizer Nutri-Gemma B-Zn (Biolchim, Bologna, Italy) was applied at a rate of 10 L ha^{-1}. The same day, 500 cm^3 ha^{-1} of Score 25C fungicide (Syngenta, Basel, Switzerland) was also applied. The crop was terminated via the application of 6000 cm^3 ha^{-1} of Reglone 20 SL (Syngenta, Basel, Switzerland) performed on 28 August 2021.

A picture of the experimental field before harvesting is given in Figure 1.



Figure 1. Experimental field just before harvesting operation.

2.2. Pre-Harvest Test: Aerial Biomass, Expected Seed Yield, and Dehiscence

To estimate the main crop features, 10 sample plots of 1.90 m^2 each (2 rows wide and 2 m long) were randomly established within the experimental field. In each plot, both the number of plants and the number of racemes per plant were recorded. Then, plants were measured in height, and truss distance from the collect level was recorded as well. Subsequently, capsules were carefully manually collected from the plants, put into sealed bags, and carried to the laboratory for fresh and dry weight estimation. Likewise, all plants from each plot were cut with a shear at the collect level and fresh aerial biomass was weighed. Capsules on the ground were collected manually and brought to the lab to assess the natural dehiscence (DSL), i.e., the loss of seeds that was not imputable to the mechanical harvesting per se. At the lab, five randomly chosen plants from each plot were used for dry weight estimation. To estimate potential seed yield (PSY), aborted and unripened capsules were excluded by visual assessment. Then, all capsules from each plot were weighed with a precision scale. Subsequently, a representative subsample of capsules

from each plot was manually processed to separate hulls from seeds, then weighed and put in an oven at 105 °C until constant weight to estimate seed and capsule moisture. Then, the dry weights of seeds, hulls, and whole capsules were recorded and used for both PSY and h-index assessment.

2.3. Combine Harvester and Headers

A New Holland CX8060 (New Holland, PA, USA) combine harvester was used throughout the test. The cleaning shoe was set as follows: threshing drum 600 r.p.m., concave clearance 10 mm, fan speed 700 r.p.m., upper sieve clearance 9 mm, and lower sieve clearance 9 mm. The setting was kept constant throughout the trial for both treatments (cereal header and sunflower header).

Approximately half of the field was harvested after equipping the combine harvester with a 5.5 m wide New Holland cereal header. Then, the machinery was stopped and a 4 m wide Fantini (Mantova, Italy) sunflower header was installed instead. Consequently, the second half of the field was harvested.

A view of the combine harvester equipped with the two different headers is given in Figure 2. The average working speed of the combine harvester was 2.3 km h^{-1}, corresponding to an effective field capacity (EFC) of 1.03 ha h^{-1}, with a fuel consumption of 21.27 L h^{-1}. This low value of EFC is related to the small dimensions of the experimental field which negatively influenced the turning time of the machinery.



Figure 2. (**a**) New Holland CX8060 combine harvester with cereal header. (**b**) New Holland CX8060 combine harvester with sunflower header.

2.4. Seed Loss Evaluation

Seed loss was evaluated by applying the methodology proposed by Stefanoni et al. [25], involving collecting the capsules and seeds lying on the ground after the passage of the combine harvester. In detail, two different areas behind the machinery were selected as shown in Figure 3a: (A) on the swath; (B) beside the swath but within the cutting bar width. Five sample plots (Figure 3b) were randomly identified for both treatments (cereal header vs. sunflower header). The sample plot surface was 8 m^2 (4 × 2 m) of which 4 m^2 corresponded to the A zone (considering 2 m of swath width) and 4 m^2 corresponded to the B zone.

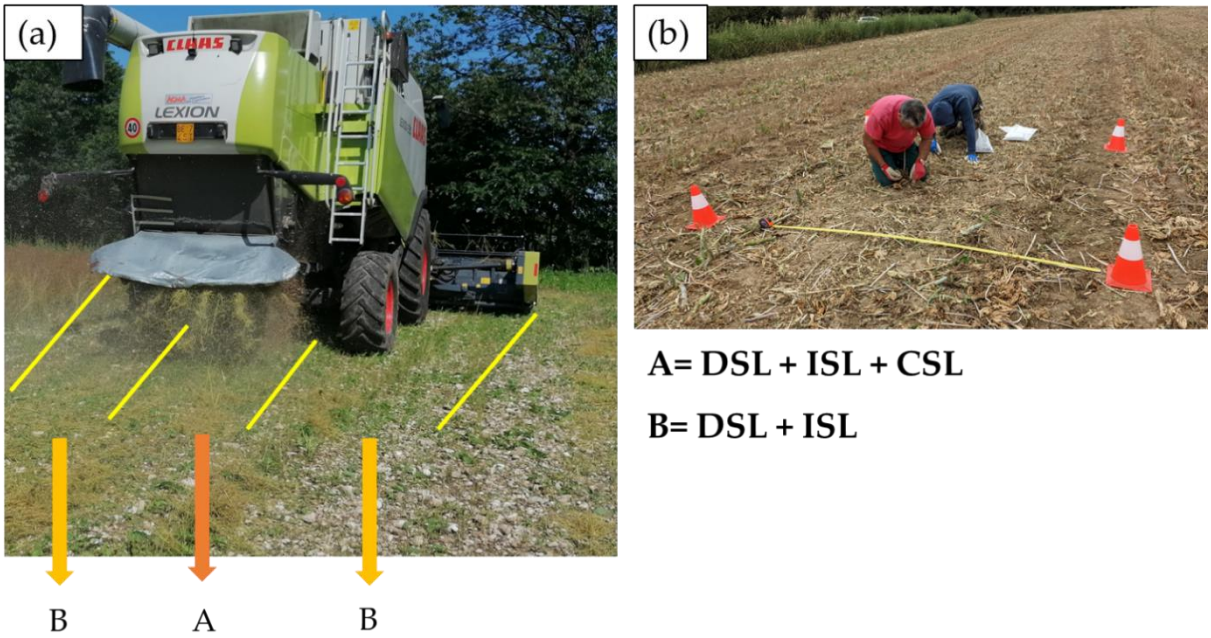


Figure 3. (**a**) Identification of the different zones behind the machinery, image from Stefanoni et al. [25]. (**b**) Sample plot to determine ISL and CSL.

Therefore, in the A zone, the seed loss was due to natural dehiscence (DSL), impact of the header (ISL), and inefficiency of the cleaning shoe (CLS). Instead, in B, the seed loss was due to only DSL and ISL. Thus, CLS was calculated as the difference between the total seed loss found in A and B areas, while ISL was calculated as the difference between total seed loss found in the B zone and DSL value.

Capsules lying on the ground in the different zones were collected and put into sealed bags, then taken to the laboratory, manually processed to separate seeds from hulls, and then weighed for the estimation of ISL and CSL.

2.5. Seed Quality Assessment

To evaluate the ratio between correctly processed seeds, unprocessed seeds (not hulled), and damaged seeds, three randomly selected samples per treatment were taken from the seed tank of the combine harvester. The fresh weight of the samples ranged between 1.247 kg FM and 1.553 kg FM. Firstly, material other than grain was removed from the samples. Subsequently, each sample was separated into the three abovementioned categories. A representative subsample for each category was oven dried at 105 °C until constant weight to estimate moisture content and calculate the results in dry weight. The ratio between the weight of each category and the total weight of the sample indicates the percentage of correctly processed seeds, unprocessed seeds, and damaged seeds.

2.6. Statistical Analysis

Data were tested for homoscedasticity and normality by applying Levene and Shapiro–Wilk tests, respectively. Statistically significant differences between treatments were evaluated via unpaired *t*-test. The statistical analysis was carried out with Statistica Statsoft (Tulsa, OK, USA) software version 7.0 [26].

3. Results and Discussions

3.1. Castor Bean Crop Features

Results of the pre-harvest test are reported in Table 1.

Table 1. Morphologic traits of dwarf Kaiima hybrid C1012, potential seed yield, and natural dehiscence of seeds.

Parameter	Measurement Unit	Avg.	St. Dev
Plant height	cm	78.29	18.29
Truss height	cm	38.81	10.37
Racemes per plant	n	1.33	0.67
Plant density	n m^{-2}	4.11	0.30
Plant biomass *	kg DM ha^{-1}	3067.63	1959.39
Plant moisture	%	80.71%	3.62%
Capsules biomass	kg DM ha^{-1}	1117.77	285.59
Capsules moisture	%	7.45%	0.21%
Potential seed yield (PSY)	kg DM ha^{-1}	2003.01	511.77
Seed moisture	%	4.15%	0.22%
DSL	kg ha^{-1}	13.86	7.83
DSL	%	0.69%	0.39%
H-index		0.36	0.12

*: Plant biomass is the total fresh weight of the aerial biomass excluding capsules and seeds.

Data on agronomic features of the crop are consistent with previous studies conducted on castor bean in the Mediterranean area. Zanetti et al. (2017) reported a range of PSY from 1.6 to 2.2 Mg DM ha^{-1} which is very similar to the recorded value of 2.03 Mg DM ha^{-1} [27]. Plant height averaged at 80 cm as reported by Alexopoulou et al. (2015) in a similar study [10]. Interestingly, the plant aerial biomass was higher than reported by Latterini et al. (2022) in a similar study conducted in Greece on castor bean cv. C1012, and this also affected the harvest index, which was lower (0.36 vs. 0.49–0.51) [24].

Interestingly, the average number of racemes per plant was 1.33 (0.94 lower than reported in the study cited above). A lower number of racemes per plant eases the cutting and conveying of plants into the header of a combine harvester. In addition, lower aerial biomass shall enter the cleaning systems which, in turn, can better discriminate seeds.

Seed moisture at harvesting was 4.15% *w*/*w*, considerably lower than the threshold of 7% proposed for proper storage of seeds [28]. By contrast, stems and leaves still averaged at 80.71% *w*/*w* residual moisture. This high value could represent a problem during baling or storing due to possible fermentation of the vegetable tissues. However, mechanical harvesting can also benefit from lower residual moisture in castor aerial biomass. In fact, the coefficient of friction between biomass and metal increases with moisture content in solid biomass [29,30]. Furthermore, some moisture can be released during the cleaning and be absorbed by seeds with possible negative effects during storage.

In the present preliminary study, it is noteworthy to highlight the negligible loss of seeds from dehiscence, namely DSL. In a similar study, Latterini et al. (2022) reported DSL ranging from 3.28 to 11.50% *w*/*w* [24].

3.2. Comparison between the Two Different Headers

ISL averaged at 282.02 ± 60.22 kg DM ha^{-1} (14% *w*/*w* of PSY) in the cereal header and 158.16 ± 18.8 kg DM ha^{-1} (8% *w*/*w* of PSY) in the sunflower header (Figure 4a). On the other hand, CSL averaged at 162.41 kg DM ha^{-1} in the cereal header and 145.56 kg DM ha^{-1} in the sunflower one, corresponding to 8% and 7% *w*/*w* of PSY, respectively, as shown in Figure 4b. In the latter case, the difference is not statistically significant.

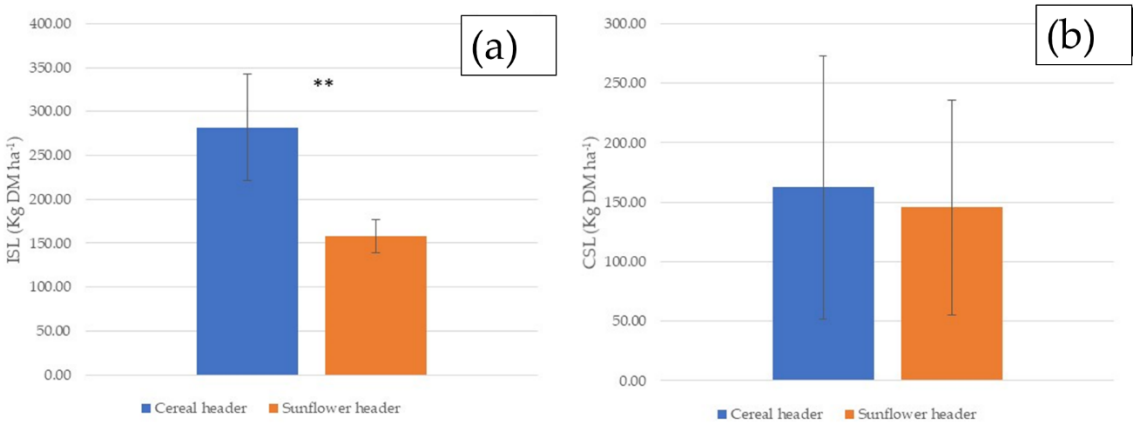


Figure 4. (**a**) Comparison of ISL between the two headers. (**b**) Comparison of CSL between the two headers. "**" indicates statistically significant differences at 0.01% according to *t*-test.

The sum of ISL and CSL led to a harvested seed yield of 1558.57 kg DM ha^{-1} and 1699.28 kg DM ha^{-1}, respectively, for the cereal header and sunflower one.

The results confirmed the hypothesis that using a sunflower header to mechanically harvest castor beans triggers lower seed loss. In fact, the sunflower header showed significantly lower ISL than the cereal header, which means less mechanical stress to plants when cut and conveyed to the crop elevator. During the cut, plants neatly enter the cutting bar because of the presence of long divider points before the cutting bar. Afterwards, two gathering chains hold the plants gently but firmly and transport them to the central auger, maintaining a consistent flow. On the other hand, the cereal header needs the reel to accompany the plants to the cutting bar of the header and the rotary movement of the reel triggers the loss of capsules.

However, no differences were found regarding CSL, confirming that this variable is mainly affected by the setting of the cleaning shoe, which in this trial was the same in both treatments. Since the cleaning system of combine harvesters is also sensitive to the quantity and quality (moisture and size of the particles) of the biomass entering it, from this result it is possible to speculate that cereal and sunflower headers do not damage stems, leaves, and capsules differently. Then, the critical passage that negatively affects ISL in castor bean mechanical harvesting has to be sought in the cut and conveying stages which in sunflower headers is performed more smoothly.

The comparison with previous literature suggests further food for thought. Firstly, the values of CSL were higher than those found by Latterini et al. (2022), i.e., 7–8% vs. 0.4–4.3% [24]. This is probably related to the higher plant moisture and lower harvest index shown in the present study. This aspect further highlights the importance of both genetic and agronomic studies in castor bean cultivation. The selection of cultivars exhibiting high harvest index is indeed fundamental to improving the mechanical harvesting in castor bean crops. Simultaneously, a lower moisture content of the aerial biomass should be reached.

Focusing on ISL, values obtained with the cereal header are definitely lower than ISL reported by Latterini et al. (2022) when applying the same equipment [24]. In fact, the authors reported ISL ranging from 29% and 72% w/w of PSY in the case of cereal header use. The lower values obtained in the present study could be related to the very low working speed of the combine harvester (lower than 2 km h^{-1}). However, the working speed of the machinery was not reported in the cited study, therefore a straightforward conclusion cannot be drawn yet.

Regarding the capability of the cleaning shoe to select and clean castor beans correctly, the results highlight that the two combine headers tested did not affect it differently (Figure 5). In fact, only 20% w/w of the seeds were correctly removed for capsules with no damage in either case with no statistically significant difference between the two headers. Indeed, it is even lower than literature values [24]. Clearly, approximately 80% of the harvested seeds require further processing before being suitable for either storing or direct

oil extraction. Storing damaged seeds can trigger high loss in quality of castor oil [31,32]. This, eventually, leads to high production costs that negatively affect the economic sustainability of the whole supply chain [33]. Interestingly, the ratio of unprocessed seeds and damaged seeds is affected by the header. The cereal header triggered a higher percentage of unprocessed seeds (52.15% w/w vs. 19.00% w/w), while the sunflower header did the opposite (57.63% w/w vs. 29.22% w/w). This could be related to the higher cutting height of the sunflower header (data not shown). In fact, when cutting height is higher from the ground, a lower quantity of fresh biomass (stems and leaves) is expected to enter the cleaning shoe of a combine harvester. Fresh biomass indirectly acts like a buffer between seeds and the iron parts of the cleaning system. Since the drum speed and beater and counter-beater clearance were not adjusted after shifting from the cereal to sunflower header, it can be speculated that capsules crashed more violently against the rods of the drum beater, causing damage to kernels. However, this is a hypothesis proposed from a preliminary study which should be confirmed in ad hoc trials.

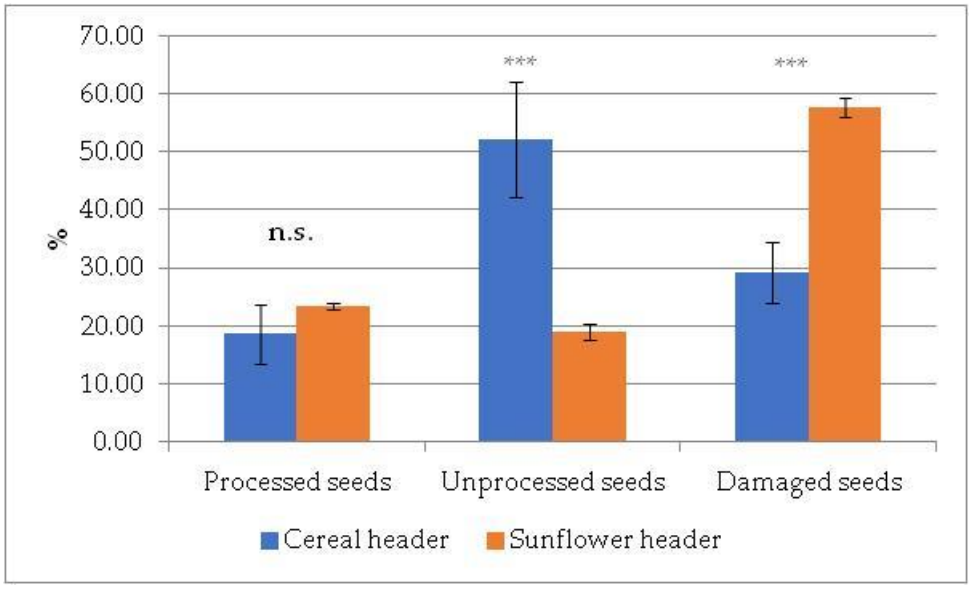


Figure 5. Percentage share of correctly processed seeds, unprocessed seeds, and damaged seeds for both treatments. "***" indicates statistically significant difference at $p < 0.001$ according to t-test. "n.s." indicates no significant difference between the treatments according to t-test.

The comparison between the two headers highlighted important aspects in the mechanical harvesting of castor beans that have been lacking in the literature for a long time. In fact, the results obtained in the present study point out that two fundamental aspects have to be addressed: seed loss (mainly due to the impact of the header on the racemes) and inadequate capacity of the cleaning shoe of the combine harvester to produce clean intact seeds. Concerning the first problem, the sunflower header has been proved to be a good candidate for developing an ad hoc header for castor bean mechanical harvesting. Fine adjustments can help to reduce ISL as much as possible to values recorded in other oil seed crops [22,25,34]. On the other hand, improving the cleaning shoe of a combine harvester requires much more effort. Firstly, specific studies should focus on the relationship between fresh aerial biomass entering the combine harvester and seed quality (quality is the ratio between processed seeds vs. unprocessed seeds vs. damaged seeds). Consequently, the material of the parts composing the beater and counter-beater can be investigated with the aim to make the system operate more gently on capsules and seeds.

4. Conclusions

Castor bean mechanical harvesting has to date been considered either impracticable of exclusive of specific hybrids cultivated only in arid regions of the world to due to the

high loss of seeds and remarkable damage to kernels that jeopardize seed storage and oil extraction. In the present preliminary study, the possibility of using a conventional combine harvester equipped with cereal header or sunflower header was investigated on the dwarf Kaiima hybrid C1012 of castor beans. Hybrid C1012 exhibited short height and high potential seed yield. The reduced height permitted the mechanical harvesting of its seeds with both headers without clogging in the machinery. The cutting and conveying systems constituting the sunflower header performed better on castor bean harvesting in comparison with a common cereal header. The latter probably causes more mechanical stress to plants which triggers the detachment of the capsules from the raceme. This is demonstrated by the higher impact seed loss found in cereal header usage. On the contrary, the use of a sunflower header demands further investigations concerning the reduction of damage to kernels via: (a) fine tuning of the cleaning shoe and (b) the possibility to modify both beater and threshing cylinder so that they separate seeds more gently from capsules.

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