agronomy

Communication

Effectiveness of Three Terminating Products on Reducing the Residual Moisture in Dwarf Castor Plants: A Preliminary Study of Direct Mechanical Harvesting in Central Greece

Francesco Latterini [1], Walter Stefanoni [1,*], Chris Cavalaris [2], Christos Karamoutis [2], Luigi Pari [1] and Efthymia Alexopoulou [3]

[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] Department of Agricultural Crop Production and Rural Environment, School of Agricultural Sciences, University of Thessaly, Fytokou Str., 38446 Volos, Greece; chkaval@uth.gr (C.C.); chkaram@uth.gr (C.K.)
[3] Centre for Renewable Energy Sources and Saving, 19th km Marathonos Avenue, 19009 Pikermi, Greece; ealex@cres.gr
* Correspondence: walter.stefanoni@crea.gov.it; Tel.: +39-0690675205

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Citation: Latterini, F.; Stefanoni, W.; Cavalaris, C.; Karamoutis, C.; Pari, L.; Alexopoulou, E. Effectiveness of Three Terminating Products on Reducing the Residual Moisture in Dwarf Castor Plants: A Preliminary Study of Direct Mechanical Harvesting in Central Greece. *Agronomy* **2022**, *12*, 146. https://doi.org/10.3390/agronomy12010146

Academic Editor: Hussein Abdel-Haleem

Received: 22 December 2021
Accepted: 6 January 2022
Published: 8 January 2022

Abstract: The contribution of castor oil for reaching the targets set by RED1 and RED2 in Europe can be tangible if the problem related to the mechanical harvesting is overcome. Dwarf hybrids suitable for mechanical harvesting are already available on the market but the residual moisture of plants and capsules has to be lowered in order to allow mechanization. In the present case of study, three common terminating products (Glyphosate GLY, Diquat DIQ and Spotlight DEF) were tested on Kaiima C1012 hybrid in a complete randomized block design to assess the effectiveness of using chemical products to decrease residual moisture in castor plants. Plants were harvested via combine harvester equipped with cereal header to evaluate seed loss (due to dehiscence, impact and cleaning shoe) and the dehulling capacity of the combine harvester's cleaning shoe. DIQ decreased significantly moisture content of capsules (7.32%) in comparison to the other treatments, while the lowest plant moisture was recorded in DIQ (62.38%) and GLY (59.12%). The use of DIQ triggered the highest impact seed loss (61.75%) in comparison with GLY (46.50%) and DEF (29.02%). Control plants could not be harvested mechanically due to the high residual moisture content and high density of weeds. The present case of study provides highlights regarding the need to further investigate the best practice to terminate castor plants and to develop a specific combine header to reduce seed loss from impact.

Keywords: vegetable oil; feedstock; biofuel; advanced biofuel; seed loss; combine harvester

1. Introduction

Herbaceous oil crops are gaining interest all over the world for vegetable oil production suitable for industrial applications [1]. Furthermore, the European Directives on Renewable Energy (RED I and RED II) aim to increase the contribution of renewable energy to the overall domestic energy production in Europe [2]. Castor (*Ricinus communis* L.) is among the most promising crops to achieve these goals, and the production of vegetable oil generates a large quantity of press cakes, husks and crop residues that, in a framework of bioeconomy, could be used as by-products for different purposes [3].

Castor oil accounts for 0.15% of the global vegetable oil production [4] and more than 80% of it is produced by India, Mozambique, China, Brazil, Myanmar, Ethiopia, Paraguay and Vietnam [5]. Although castor is a low-input crop also suitable for cultivation in European climate conditions [6,7], the low degree of mechanization associated with castor beans harvesting [8] limits the production to either undeveloped or developing countries where harvesting is performed manually since the low labor cost [9]. The issues associated with castor beans mechanical harvesting lie in the fact that castor naturally exhibits indeterminate growth and evergreen habit, which both trigger high fresh aerial biomass production and heterogenous ripening of the capsules [8,10,11]. These two features, make the direct combine harvesting practically impossible: firstly, high volume of fresh biomass easily clogs the combine harvester's cleaning shoe; secondly, selecting the best period for combine harvesting is challenging and high seed loss is unavoidable. Nowadays, the indeterminate growth tendency in castor plants has been almost solved. In fact, dwarf genotypes are currently available on the market and several studies have proved them performing well also in marginal conditions [1]. Generally, dwarf hybrids exhibit higher harvest index, lower seed dehiscence [10,12] and even early flowering, which helps to shorten the productive cycle [13]. They can also perform well in the Mediterranean climate, but though the maximum height ranges between 0.83 and 1.12 m which is acceptable for combine mechanical harvesting, the residual moisture in stems and leaves was reported extremely high (76–78.5%) [6,14]. For this reason, the effectiveness of using terminating products to lower the residual moisture in castor plants to permit the mechanical harvesting was investigated.

In this case of study, a systematic herbicide (Glyphosate), a non-selective herbicide (Diquat) and a defoliant (Spotlight© BASF) were selected for field trial and tested on hybrid Kaiima C1012.

2. Materials and Methods

2.1. Experimental Field and Plant Coltivation

The experimental field (0.94 ha) was situated at the farm of University of Thessaly in central Greece (651591 E, 4362784 N, 68 m asl.). The soil is characterized as clayey (47.1 clay 32.7 silt 20.1 sand), with 1.48% OM and PH 7.9. The previous year the field was at fallow. The mean annual rainfall in the region is 434 mm with about $\frac{1}{4}$ of it allocated from April to September.

Hybrid Kaima C1012 was established on 24 April 2021 by direct drilling at rows 0.75 m apart using 62,300 seeds per ha. Glyphosate was applied ten days prior sowing at a rate of 5 L per ha to control natural vegetation. Weed control was accomplished with one mechanical operation with a row crop cultivator in June. Basal fertilization was performed before sowing by applying 13 kg N ha^{-1} and 46 kg P ha^{-1}. Further 58.5 kg N ha^{-1} were provided gradually with fertigation during the growing period. Sprinkler irrigation was applied for the first two irrigation events and afterwards, a drip irrigation system, with pipes every second row, was established. Irrigation provided plants with 5100 m^3 ha^{-1} of water, whilst rainfall provided further 2840 m^3 ha^{-1} of water.

2.2. Terminating Products and Experimental Design

Glyphosate, Diquat and Spotlight© BASF were selected for testing the efficacy in reducing residual moisture in castor plants before mechanical harvesting. Glyphosate is a broad spectrum systematic herbicide that acts via inhibition of aromatic amino-acids synthesis involved in plant growth [15]. Glyphosate is widely used worldwide although recently some concerns arose regarding possible correlation with some human disorders [16] and environmental pollution [17]. On the other hand, Diquat is a non-selective herbicide that, in presence of light, causes the destruction of chlorophyll a and inhibits photosystem I [18]. Eventually, Spotlight© BASF (a.i. carfentrazone-ethyl) causes photobleaching and necrosis on leaves. It is commonly used as defoliant in cotton [19].

The experimental design was a randomized plot with four replications per treatment (as shown in Figure 1). All products were diluted in 400 L ha^{-1} of water and applied as follows:

- Glyphosate (GLY): sprayed at a dose of 6 L ha^{-1} 20 days before harvesting
- Spotlight© BASF (DEF): Sprayed at a dose of 6 L ha^{-1} 20 days before harvesting
- Diquat sprayed (DIQ): At a dose of 5 L ha^{-1} 10 days before harvesting

- Control (CON): No chemicals were applied.

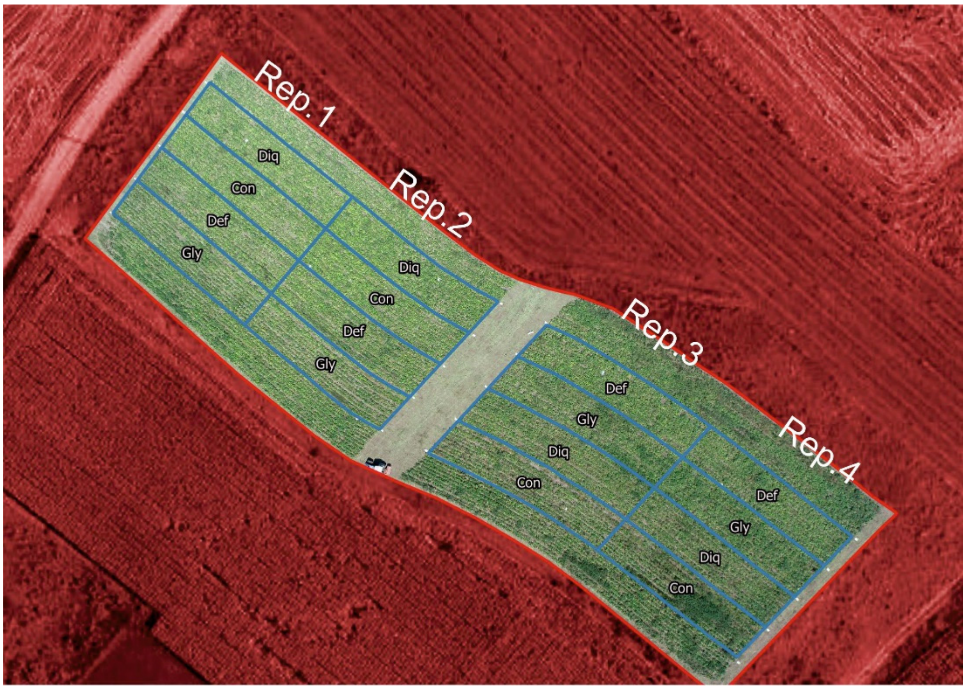

Figure 1. Aerial picture of the field trial with indication of the experimental design Gly = Glyphosate, Def = Defoliant, Diq = Diquat, Con = Control.

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

In each replication, two sample plots of 3 m^2 each were randomly selected to assess growth parameters, expected seed yield, natural dehiscence (DSL) and h-index. Specifically, all plants within the plot were counted and measured in height. The number of racemes per plant were also recorded. Then, all capsules borne on racemes were harvested by hand and put in a sealed bag. Successively, plants were cut at the collect level and put in sealed bag. Afterwards, loss capsules (lost due to natural dehiscence) were collected from the ground and put in sealed bags. Eventually, all bags were collected and brought to laboratory for assessing fresh and dry weight of seeds, hulls, stems and leaves. At the laboratory, capsules were manually opened to retrieve the seeds. Capsules for DSL were processed likewise. At the laboratory, fresh and dry weight of samples were measured using a precision scale Kernel mod. FXN10K-3N. Samples were dried in the oven at 105 ± 1 °C until constant weight.

2.4. Settings of the Combine Harvester

The combine harvester used was a New Holland mod. CX 780 equipped with a New Holland cereal header Type 17 V 5.10 m wide. Before beginning with the mechanical harvesting of castor beans, a preliminary test was performed in order to figure out the best setting of the combine harvester for that experimental field. Briefly, the cleaning shoe of a combine harvester relies on sieves and fans to select seeds by size and weigh without chaff or damages to kernels. Therefore, the goal of the preliminary test was to find out the best compromise between beater speed and clearance. Sieves opening was set at 17 mm and 10 mm for upper and lower sieve, respectively, whilst fan speed was set at 800 r.p.m. Three different rotation speeds of the threshing drum (i.e., 300, 400 and 500 r.p.m.) were tested three times at 10 mm and 12 mm clearance values. Seeds were sampled three times per run and processed immediately outside the field calculating the percentage of undamaged, not opened and damaged seeds per each combination of drum speed and clearance opening. According to results (Figure 2), the best setting for the cleaning shoe of the combine harvester was: 400 r.p.m. for the threshing drum, 10 mm of clearance for the concave, while fan speed and sieves were set as reported above. This setting was kept constant throughout the harvesting in all treatments.

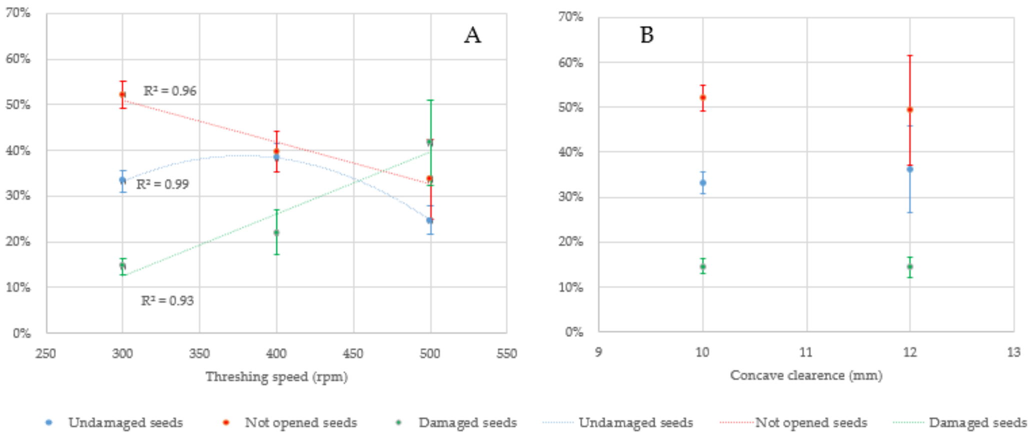

Figure 2. Percentage of undamaged, not opened and damaged seeds in relation to the rotational speed of the thrashing drum (**A**) and the clearance (**B**).

2.5. Harvest and Seed Loss Evaluation

After setting the cleaning shoe of the combine harvester, the harvesting phase started. The machinery was positioned at the beginning of each plot assuring that the cutting bar could work at full capacity; then the harvesting started. Once the cleaning system started working at full capacity (approximately 50–80 m after the start) a sample of about 20 kg of seeds were collected from the tank, put in a sealed bag and brought to the laboratory for qualitative analysis (see Paragraph 2.5). During the last 15 m of the plot, the threshed biomass was harvested behind the combine harvester (Figure 3a) and carried to laboratory, then sieved to permit the quantitative assessment of seed loss due to the cleaning shoe (CSL). In correspondence to the sampled area for CSL assessment, all capsules on the ground were manually collected and weighted (Figure 3b). The weight was reduced by dehiscence value for the impact seeds loss assessment (ISL).

Figure 3. Collection of threshed biomass (**a**) and lost capsule (**b**) for CSL and ISL assessment, respectively.

As shown in Figure 4A1,2, unterminated plants exhibited vigorous aerial biomass and high density of weeds within the plots. After some attempts of harvesting these plots, authors along with the contractor declared the mechanical harvesting of castor plants grown in this condition unsuitable and dangerous for the machinery. The prohibitive conditions are particularly evident from the comparison between terminated and non-terminated plants shown on Figure 4B1,2.

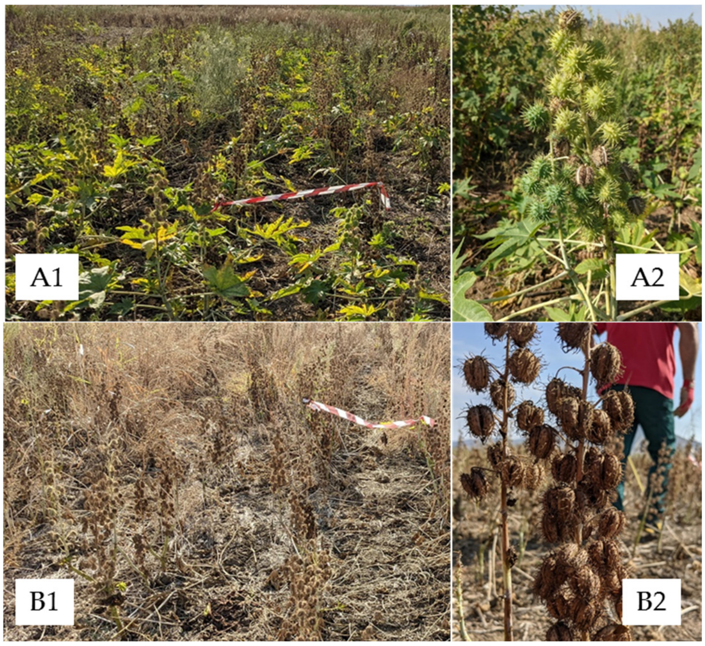

Figure 4. Difference between control (**A1**,**A2**) and terminated castor plants (**B1**,**B2**).

2.6. Evaluation of the Combine Harvester's Cleaning Shoe: Percentage of Damaged Seeds, Undamaged Seeds, Broken Seeds

During the mechanical harvesting of terminated plants, approximately 20 kg FM of seeds were sampled from the combine harvester's hopper and brought to the laboratory for assessing if GLY, DIQ and DEF had different effects on the resulted harvested seeds. At the laboratory, three subsamples of about 500 g FM each were used to estimate the percentage of damaged seeds, undamaged seeds and unopened seeds. A representation of the before mentioned categories is given in Figure 5. Unopened seeds (either completely or partially contained in the hull) were opened manually. Then dried and weighted.

Figure 5. Sample of seeds collected within the tank of the combine harvester and classified as: (**a**) damaged seeds; (**b**) undamaged seeds; (**c**) unopened seeds.

2.7. Statistics

ANOVA and Tukey HSD tests were performed through STATISTICA StatSoft version 7.0. to separate different means among treatments ($p \leq 0.05$) [20].

3. Results and Discussions

3.1. Pre-Harvest

In the pre-harvest, several parameters were estimated, and results are given in Table 1. Crop terminations did not affect significantly plant height, aerial biomass, 1000-seed weight and potential seed yield whom values are consistent with [21]. On the contrary, the Potential Seed Yield (PSY) was lower than expected. In fact, Zanetti et al. reported seed yield ranging from 1.6 to 2.2 Mg ha^{-1} of PSY for castor beans cultivated in Italy and Greece [14] with possible values as high as 4.44 Mg ha^{-1} [6]. Moreover, the reported average plants' height was higher (83–153 cm) than what found in the present study (55–64 cm on average). These differences are probably related to the adopted crop system. In fact, in the present study plants were seeded directly in the soil without tillage and with reduced nitrogen use. These practices could have slightly reduced the performance of the plants. Indeed, castor plants are considered sensitive to high soil bulk density [22] and to limited access to available nitrogen [23].

Table 1. Effects of Glyphosate, Spotlight and Diquat on hybrid Kaiima C1012: plant growth, aerial biomass production, seed yield, residual moisture in seeds, capsules and stems.

Variable	Significance	GLY	DEF	DIQ	CON
Plant height (cm)	ns	55.63	59.88	64.53	61.43
Truss height (cm)	ns	20.05	22.38	21.75	21.25
Raceme height (cm)	ns	35.15	37.50	37.95	40.18
Plant density (n m^{-2})	ns	4.42	4.58	4.50	4.58
Raceme density (n m^{-2})	ns	9.96	10.21	9.88	9.54
Racemes per plant (n plant^{-1})	ns	2.27	2.23	2.17	2.10
PSY (kg DW ha^{-1})	ns	1181.7	1245.86	1259.49	1165.35
Seed moisture (%)	ns	4.46	4.51	4.75	5.26
Capsules biomass (kg DW ha^{-1})	ns	538.19	538.86	576.55	543.26
Capsules moisture (%)	*	8.39 ab	7.63 ab	7.32 b	9.53 a
Plant biomass (kg DW ha^{-1})	ns	592.83	760.21	681.29	968.46
Plant moisture [1] (%)	***	59.12 b	69.63 a	62.38 b	74.06 a
H-index	*	0.51 a	0.49 a	0.51 a	0.43 b
1000-seed weight (g)	ns	260.28	253.52	253.28	255.69

ns, *, *** non-significant or significant at $p < 0.05$, 0.001, respectively. [1] refers to stems, leaves and racemes without capsules. Different letters indicate different homogeneous groups according HSD Tukey test.

However, the use of terminating products affected positively the residual moisture in organs of the plants. For instance, the lowest value of capsule moisture was recorded in DIQ treatment which reduced the humidity by 22% in comparison with control. Plant moisture was reduced significantly by 19% in both DIQ and GLY treatments; whilst DEF did not perform better than control. Nonetheless, the significant reduction in plan moisture experienced after application of DIQ and GLY are still not satisfying as 59–62% of residual moisture is still present in plant. Interestingly, the 19% of residual moisture reduction permitted the mechanical harvesting of castor plants without clogging and damages to the cleaning shoe of the combine harvester. Seed moisture averaged at 4.5–5% *w*/*w* that was lower than 7% found in literature [24] which is an accepted values for good processing and storage of seeds in general [25]. Nevertheless, GLY, DEF and DIQ significantly improved h-index by 15.7, 12.2 and 15.7%, respectively.

3.2. Seed Loss and Dehulling Capacity of the Combine Harvester's Cleaning Shoe

During the mechanical harvesting of castor beans treated with terminating products, interesting results were found. Although the present study refers only to one year experiment and to a single hybrid of castor, it is undoubtful that the use of terminating practice is mandatory for the mechanical harvesting of castor beans grown in these environmental conditions. In fact, in CON treatment the vigorous plants and the presence of weeds within rows did not permit the harvesting operation. However, the weed management can also be performed mechanically without use of pesticides but this practice, probably, it is of low interest since it may trigger capsules' shattering [26]. Furthermore, spacing row in castor plant cultivation systems is generally set at 0.75 m which is neither enough for manual weed removal nor for rototiller use. A special tractor with narrow and high wheels should be use in order to fit with both row distance and plant height.

The highest and lowest values of DSL were recorded in DEF and DIQ, respectively. On the contrary, the use of DIQ was responsible of the highest impact loss of seeds (61.5% *w*/*w*). Among the three products, DEF performed better (29% *w*/*w* of ISL), whilst GLY averaged at 46.5% *w*/*w*. The results for ISL found in DEF are encouraging in comparison with DIQ, but still one third of seed loss only from the combine header is not acceptable. The loss of seeds from the impact is a critical aspect that must be solved. Scientific literature still lacks specific studies carried out on this matter. Some research has been conducted by private companies like Evogene Ltd. and Fantini s.r.l which announced in 2018 the development of a specific header for castor beans harvesting able to reduce ISL from 50% to an astonishing 5% in 2017 and 2018 on proprietary castor varieties [27]. Concerning the loss of seeds found at the exit of the combine harvester's cleaning shoe, namely CSL, a tidy difference among treatments was highlighted: 0.41, 1.6 and 4.36% in DIQ, GLY and DEF, respectively. As found in the pre-harvest test (Table 1), the absolute value of residual moisture in plants treated with Diquat was the lowest and, probably, this helped the sieves and the fan within the cleaning system of the combine harvester to discriminate better the seeds from the other fraction of harvested biomass. On the other hand, the highest value of residual moisture in plants treated with DEF corresponded to highest value of CSL reported in Table 2. This relationship was not investigated via statistical analysis but, it can be speculated that the residual moisture content affects the loss of seeds from straw walkers and sieves.

Table 2. Effects of Glyphosate, Spotlight and Diquat on mechanical harvesting of hybrid Kaiima C1012 castor beans. Seed loss due to dehiscence (DSL), impact of the header (ISL) and cleaning shoe (CLS); and dehulling capacity of the cleaning shoe.

Variable	Significance	GLY	DEF	DIQ	CON
DSL (kg ha^{-1})	*	66.10 ab	135.84 a	38.75 b	60.17 ab
ISL (kg ha^{-1})	**	549.55 ab	342.97 b	729.71 a	
CSL (kg ha^{-1})	***	18.87 b	51.54 a	4.83 c	
DSL (%)	*	5.59 ab	11.50 a	3.28 b	3.28 ab
ISL (%)	**	46.50 ab	29.02 b	61.75 a	
CSL (%)	***	1.60 b	4.36 a	0.41 c	
Undamaged seeds DW (%)	**	26.79 b	38.34 a	26.91 b	
Not opened seeds DW (%)	ns	50.72	39.65	48.95	
Damaged seeds DW (%)	ns	22.49	22.01	24.14	

ns, *, **, *** non-significant or significant at $p < 0.05$, 0.01, 0.001, respectively. Different letters indicate different homogeneous groups according HSD Tukey test.

Harvested seeds were also divided into three main categories to assess the dehulling capacity of the combine harvester's cleaning shoe, namely: undamaged, not opened and damaged seeds as shown in Figure 5. The percentage of not opened (40–50% *w*/*w*) and damaged seeds (22–24% *w*/*w*) was similar in all treatments, whilst the percentage of undamaged seeds was highest in DEF (38.34% *w*/*w*). Undamaged seeds in GLY and DIQ averaged at 26.79 and 26.91%, respectively. Unfortunately, if considering not opened and damaged seeds altogether, between 62 and 73% *w*/*w* of seeds have to be further processed to either removed damaged seeds or eliminate the hull in unopened seeds. During the storage, broken seeds and foreign material can trigger fermentative process that increase the temperature and reduce the quality of the seeds in few months [28]. Therefore, it is important to investigate the most suitable terminating product to reduce residual moisture in castor plant and allow effective mechanical harvesting, to reduce cost and passes within the value chain.

Considering the three sources of seed loss (DSL, ISL and CSL) the effective seed yield in GLY, DEF and DIQ averaged at 51.90, 68.33 and 41.68% of the PSY, respectively. The most responsible factor of seed loss was the combine header as reported in Table 2. Usually, when the mechanization is properly developed, the loss of seeds due to impact is 1% w/w canola (*Brassica napus* L.) [29], or 2.58% w/w in cardoon (*Cynara carduncul*us L.) [30] up to 7.95% w/w in camelina (*Camelina sativa* (L.) Crantz) [31,32]. CSL also contributed to increase the total seed loss. Its values usually ranges between 0.58% w/w as reported in cardoon [30] and 5.80% w/w as reported in camelina whose seeds are small and light in weight, thus easy to lose via sieves and fans [31,32].

4. Conclusions

The preliminary results obtained by the present case of study conducted in Central Greece provide deeper understanding in the castor beans mechanical harvesting. The suitability of dwarf hybrids of castor plants has been proved although a terminating practice must be adopted to avoid clogs and damages to machinery. Glyphosate, Spotlight and Defoliant reduced the residual moisture in plants sufficiently to perform the mechanical harvesting. However, none of them proved to be specifically suitable for this crop. Moreover, cereal header was the responsible of the highest seed loss experienced during the mechanical harvesting. Therefore, further investigations should focus on the proper dosage of terminating products and different headers for direct combining castor beans.

Author Contributions: Conceptualization, F.L., W.S., C.C., C.K., L.P. and E.A.; methodology, F.L., W.S., C.C. and C.K.; data curation, F.L., W.S., C.C. and C.K.; writing—original draft preparation, F.L., W.S. and C.C.; writing—review and editing, F.L., W.S., C.C., C.K., L.P. and E.A.; supervision, L.P. and E.A.; funding acquisition, L.P. and E.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Horizon 2020 project Magic (grant number 727698).

Informed Consent Statement: Not applicable.

Acknowledgments: Authors would like to thank Sandu Lazar for the help in performing the field and laboratory tests.

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

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