Università degli Studi della Tuscia di Viterbo

Dipartimento di Scienze Agrarie e Forestali - DAFNE

Corso di Dottorato di Ricerca in

ENGINEERING FOR ENERGY AND ENVIRONMENT - **XXXVI ciclo**

The state of the art of mechanical harvesting of typical and emergent energy crops: assessment of the available harvesting systems and identification of the main bottlenecks

Settore scientifico-disciplinare

AGR/06

Tesi di dottorato di:

Dott. Francesco Latterini

Firma ....

Coordinatore del corso

Prof. Andrea Luigi Facci

Firma

Tutore

Prof. Rodolfo Picchio

Firma ....

A.A. 2022/23

Abstract: agriculture and forestry can strongly contribute to achieve the energetic independence for European Union. Among the possible solutions offered by the two sectors toward the supply of bioenergy, dedicated crops could play a major role. However, the mechanical harvesting of dedicated energy crops still represents a challenge for different species. In this PhD course I focused on the assessment of the mechanical harvesting issues related to different oilseeds, perennial grasses and Medium Rotation Coppice (MRC) plantations, this last with particular reference to the Mediterranean forestry context. The obtained findings showed that perennial grasses like giant reed, miscanthus, switchgrass and reed canary grass can be harvested without particular problems by using harvesting systems typical of haymaking. Similar conclusions can be drawn for the oilseed crop camelina, that can be harvested by a combine harvester equipped with a cereal header with limited adjustments to the combine cleaning shoe settings. The mechanical solution for castor bean is instead still far, considering that both sunflower and cereal headers did not show satisfactory performance in terms of seed loss and correct processing of the capsules by the cleaning shoe. The development of dedicated headers or a double passage harvesting can be listed among the possible solutions to be implemented. Finally, focusing on MRC poplar plants in the Mediterranean context, the evaluated small-scale prototype revealed very satisfactory working performance, although it can be applied only in the case the chipping operation can be performed on the field and there is no the need to ship the stems to a proper landing site.
Keywords: working performance; harvesting loss; energy independence; bioenergy; oilseeds; medium rotation coppice; perennial grasses

Summary

This thesis is firstly dedicated to my wife Dominika, the real reason and inspiration of all my scientific activities. It is dedicated also to my parents, my sister, my friends. A particular thank to my supervisor Prof. Rodolfo Picchio, who I have the pleasure to include as well in the list of friends…

1. Introduction

After the new Green Deal policy program was introduced in 2019, addressing climate change has risen to the top of the list of priorities in Europe. Due to the increased geopolitical difficulties the EU is currently experiencing, it is more crucial than ever for this continent to spearhead the energy transition and achieve early market independence.

In 2020, the EU consumed 37,086 PJ of energy overall, with 22.1% of that coming from renewable sources (Stefanoni et al. 2023). The primary objective of Europe, which now imports 97 and 83.6% of its petrol and natural gas, respectively, for domestic consumption, is energy independence. The market for renewable energy in Europe is also not entirely autonomous from those in other continents; for instance, the vast majority of solar panels used there are produced in Asia, and uranium used in nuclear energy is imported. As a result, during the past several years, Europe has seen an increase in worries about energy security, which has prompted the implementation of new initiatives targeted at lowering reliance on imported energy (Buonomano et al. 2022). The domestic production of raw materials is essential for the development of bioenergy.

By producing renewable energies from both specialized energy crops and residues, agriculture and forestry might significantly improve the security of the European energy supply (Latterini et al. 2020a; Latterini et al. 2020b; Pari et al. 2020; Latterini et al. 2022). On the other hand, there are still some significant obstacles to the sustainable implementation of bioenergy production from energy crops, most of which are associated with the high production costs, which are mostly caused by biomass harvesting and logistics (Wang et al. 2020a).

Energy crops can be classified in: herbaceous lignocellulosic, short and medium rotation forestry and oilseeds. For all these three categories, depending obviously on the specific species, harvesting operations are among the biggest challenge along the overall supply chain. In my PhD studies I focused on every of the three categories, in particular studying the mechanical harvesting issue for *Camelina sativa* L. Crantz and *Ricinus communis* L. concerning oilseeds; *Populus spp* regarding medium rotation forestry plantations; *Arundo donax* L., *Miscanthus* × *giganteus, Phalaris arundinacea* L. and *Panicum virgatum* L. concerning herbaceous lignocellulosic crops (perennial grasses).

1.1 Camelina

Camelina belongs to *Brassicaceae* family (Natelson et al. 2015). South-East Europe and South-West Asia are the origins of this species (Larsson 2013). The typical height range for plants is 65 to 110 cm (Berti et al. 2011). Silique, also known as seed capsules or pods, are pear-shaped, slightly flattened structures that range in length from 5 to 14 mm and contain eight to fifteen seeds (Berti et al. 2016). They are extremely tiny (0.7 mm 1.5 mm), weighing between 0.8 and 1.8 g per 1000 seeds, depending on the cultivar and growing environment (Zubr 2003). From 30% to 49% of seeds are said to contain oil (Zubr 2003; Vollmann et al. 2007; Blackshaw et al. 2011; Mupondwa et al. 2016). Camelina is particularly well suited for double cropping with small grain cereals, soybean, and sunflower since it is available in both winter and spring types, and because of its brief life cycle (Gesch and Archer 2013; Berti et al. 2017). When it comes to the establishment of the crop, sowing takes place at a depth of 6–13 mm (Berti et al. 2016), using 4–6 kg of seeds per hectare (Dobre et al. 2014).

Several causes are connected to the recent increase in interest in camelina cultivation. In addition to the double cropping, camelina exhibits high seed oil content (30–49%) (Florin and Duda 2011) and is used for a variety of purposes, including the production of biodiesel (Yang et al. 2016) and jet fuel (Wang et al. 2020b), animal feeding (Orczewska-Dudek and Pietras 2019), aquaculture (Hixson et al. 2014), raw material for agrochemical products (Pernak et al. 2018), and medical and veterinary applications (Pawlowska-Olszewska et al. 2018).

Furthermore, camelina requires fewer inputs than the majority of the commodity crops used for the manufacture of biofuels (Gesch and Archer 2013), which reduces its environmental effect (Li and Mupondwa 2014), especially when considering the suitability of camelina straw for the production of bioenergy (Mohammad et al. 2019; Krzyżaniak et al. 2020). According to the literature, even in the Mediterranean region, can be grown on poor soils and soils with challenging circumstances (Zanetti et al. 2020).

1.2 Castor

The world production of castor oil seeds (*Ricinus communis* L.) increased from 1.19 Mt in 1998 to 1.4 Mt in 2018, with a pick of 2.74 Mt in 2011 (FAO 2021), demonstrating a steadily increasing interest in this species. More than 80% of the world's castor oil is produced in India, which is followed in productivity by Mozambique, China, Brazil, Myanmar, Ethiopia, Paraguay, and Vietnam (Polito et al. 2019). Castor can thrive in poor soils and is pest- and drought-resistant. For high yield breed types, the oil content of the seeds ranges from 35% to 55% w/w (more than 1,000 L ha1 can be produced when grown), has one of the greatest viscosities among vegetable oils, and has a molecular weight of 298 (Khatiwora et al. 2010). It barely makes up 0.15 percent of the total vegetable oil produced globally (Scholz and Silva 2008), but it has a wide range of potential uses, from lubricants and oil-derived goods to the pharmaceutical and cosmetic industries (H Nautiyal 2018). The produced biooil can potentially be used as a source of chemical feedstock and sustainable fuel (Mohammed et al. 2014). However, the feasibility of widely cultivating castor plants is limited by the presence of harmful substances like ricin in castor beans. In reality, between 1981 and 2011 there were numerous incidents of intentional or unintentional ricin contaminations worldwide (Roxas Duncan 2011), yet scientists have never lost up on researching this species. When compared to other oil crops, such as soybean, castor is rather high-demanding in terms of nitrogen requirements, and soil nitrogen availability encourages leaf and stem elongation. Such impacts cause a significant amount of aerial biomass to develop, which lowers the crop's harvest index (Wnuk et al. 2013).

Figure 1. Castor field before harvesting.

1.3 Poplar medium rotation coppice (MRC)

The terms Short and Medium Rotation Coppice of Forestry (SRC/MRC – SRF/MRF) refers to dedicated plantations for the production of lignocellulosic biomass for bioenergy purposes (Spinelli 2011). The first instance of SRC was in Sweden in the early 1900s, and it thereafter expanded over all of Europe. Poplar is currently the most commonly used species, however eucalyptus and black locust also play a significant role (Spinelli and Visser 2009). In fact, SRC displays a harvesting cycle of 1-3 years with a planting density of 6000–7000 N/ha while MRC has a harvesting cycle up to 5–6 years with a planting density of 1000–1500 N/ha. This is the main difference between SRC and MRC. With an average diameter at the cut point of 5-8 cm for SRC and up to 15-20 cm for MRC, it is obvious that longer, higher cycles of MRC also imply larger dimension of plants to be harvested (Santangelo et al. 2015).

The sector's growing need for industrial roundwood and fiber wood has encouraged the growth of massive MRC poplar plantations (Hetemäki and Hurmekoski 2016). The majority of the new poplar MRC plants in Europe have been built in nations like Poland, Romania, and Slovakia, which have an excellent combination of fertile soil, affordable land prices, and a growing economy (Werner et al. 2012).

Figure 2. MRC poplar plantation.

1.4 Giant reed

The *Poaceae* family's herbaceous perennial crop known as giant reed can survive a variety of ecological and abiotic environments, is resistant to a wide range of pests and diseases, and may produce comparatively large biomass yields with minimal agronomic inputs. These characteristics have made huge reed appealing for the generation of bioenergy in many parts of the world. The growth of giant reed is done using either hydroponic or in vitro methods because it is thought to be a sterile plant (Popp et al. 2016). However, in flooded places, giant reed can become an invasive species. Currently, this crop is planted for the management of grasslands, phytoremediation, and primarily for the generation of bioenergy (Prochnow et al. 2009). In comparison to other energy crops, giant reed has a number of benefits, including great adaptability to environmental, soil, and growth conditions; a high biomass output; and the capacity to be produced as a low-input crop (Piccitto et al. 2022). Additionally, it has been shown that giant reed can produce a significant amount of biomass under high salinity circumstances (Angelini et al. 2009). Additionally, it can be grown on submarginal or marginal fields, including contaminated areas and low soils (Cosentino et al. 2006). This species' biomass output ranges from 30 to 40 Mg DM/ha annually (Angelini et al. 2009). Regarding its bioenergy properties, giant reed has a greater heating value between 18 and 20 MJ/kg (Bonanno et al. 2013). The ash content is between 5.0 and 8.0% (Lewandowski et al. 2003).

1.5 Miscanthus

Miscanthus (*Miscanthus × giganteus*) is a sterile, rhizomatous perennial C4 grass (Lewandowski et al. 2000). Up to 44 Mg/ha*yr of potential biomass output are shown (Lewandowski et al. 2003). It exhibits cold resilience and the capacity to grow under low-input management, particularly in terms of fertilizers and herbicides, in European temperature conditions (Robson et al. 2012). Miscanthus biomass has a wide range of applications, including combustion, the generation of bioethanol or bio-based products like paper, construction materials, or essential chemicals. Because this plant has been evaluated in so many various environmental situations, the miscanthus yields reported in the literature likewise exhibit significant diversity. In a Southern European irrigation regime, the yield might reach up to 30 Mg/ha DM, whereas in Central European settings, it was between 10 and 25 Mg/ha DM (Lewandowski et al. 2000). Miscanthus biomass typically has a heating value of 17 MJ/kg (Lewandowski et al. 2000). With an ash fusion temperature of 1020 °C, the ash concentration reported in the literature is lower than for other herbaceous energy crops, ranging between 1.6 and 4.0% (Lewandowski et al. 2000).

Figure 3. Miscanthus harvesting by self-propelled forage harvester.

1.6 Reed Canary Grass

Reed canary grass belongs to the *Gramineae* family. It is a naturally occurring perennial grass found in temperate parts of North America, Europe, and Asia. In Europe, the Nordic nations are particularly prone to it. This grass is typically found in wet locations, such as lakeshores.

Despite the fact that today the primary function of interest for this species is energy generation, reed canary grass (*Phalaris arundinacea*) is still primarily used as a grazing crop in North America (Lewandowski et al. 2003). It exhibits strong drought resistance, but is best suited for cultivation in poorly drained soils since it can withstand flooding (Lewandowski et al. 2003). The biomass output varies between 7.5 and 9 Mg/ha DM under favourable conditions (Becker et al. 1992). The biomass of reed canary grass has been observed to have heating values between 16.6 and 19.3 MJ/kg (Nilsson et al. 2015).

1.7 Switchgrass

Switchgrass is a member of the same family as reed canary grass, the *Graminae*. Its native range is in North America, from Central Mexico to a latitude of 55° North. It has primarily been grown as fodder grass in the central United States (Lewandowski et al. 2003). Switchgrass exhibits high soil adaptation and considerable drought tolerance (Larnaudie et al. 2022). The maximum yields, with values ranging from 16 to 22 Mg/ha DM, can be obtained with one or two harvests each year (Larnaudie et al. 2022). The biomass of this species has a reported heating value of 17 MJ/kg (Sladden et al. 1991). Ash melting temperature is estimated to be around 1016 °C, and the proportion of ash remaining after combustion ranges between 4.5 and 10.5% (Sladden et al. 1991).

2. The main issues in mechanical harvesting for the investigated species

2.1 Camelina

Similar to canola, camelina is either swathed and then combined with conventional wheat or combined straight with it. Similar seed yields are obtained using both techniques. The main issue in mechanical harvesting of camelina is related to the very tiny dimension of the seeds, therefore to avoid seed loss, the combine harvester's settings should be adjusted to the characteristics of the species, such as speed, wind flow (fan speed), small aperture screens, leak sealing, and the distance between the threshing cylinder and the concave.

Figure 4. Camelina field just before harvesting.

2.2 Castor

Due to castor's indeterminate growth and evergreen habit, which both lead to considerable fresh aerial biomass generation and heterogeneous capsule ripening, there are problems with mechanically harvesting castor beans (Pari et al. 2020). The huge volume of fresh biomass readily clogs the combine harvester's cleaning shoe, and it is difficult to choose the ideal time for combine harvesting, which results in considerable seed loss. These two characteristics make direct combine harvesting all but impossible. Castor plants' indeterminate growth tendency is now virtually well understood. In fact, dwarf genotypes are presently on the market, and numerous studies have shown that they perform well even in challenging environments (Carrino et al. 2020). On the other hand the mechanical harvesting by direct combining is still a key issue.

2.3 Poplar MRC plantations

In contrast with SRC plantations, the single passage harvesting option for MRC is fairly challenging since the size of the stems makes the cutting components of the adapted self-propelled forage harvester work harder. Therefore, a twofold passage biomass collection is the foundation for the potential harvesting systems. Naturally, some adjustments are required to address the bigger stem diameter issue, and a reduced field capacity (ha/h) is expected, even though a higher biomass output may still result in a suitable material capacity (Mg/h). These types of plantations are typically harvested using equipment used in forest operations, such as feller-bunchers, skidders, and forwarders (Sperandio et al. 2021). Fully mechanized systems should be employed in order to get higher working performances, even though these systems depend on expensive machinery (Spinelli et al. 2021). However, only a few sizable forest firms in the Mediterranean region have access to these machines. As a result, it is critical to look for alternative solutions that may guarantee high levels of productivity by using simple and inexpensive machinery, which is appealing to small-scale operators with limited capital availability (Spinelli et al. 2020).

2.4 Perennial energy grasses

Perennial grasses can be used to produce bioenergy sustainably, but there are still some significant challenges to overcome, most notably the high production costs that are primarily caused by biomass harvesting and logistics (Wang et al. 2020a).

The bulk density and moisture content of lignocellulosic feedstocks are typically low, which raises the costs of the supply chain and the risk of storage losses (Pari et al. 2017). When attempting to solve these problems, the harvesting approach used may be crucial.

Table 1. Summary of the main harvesting issues for the investigated energy crops.

Species	**Main issues for mechanical harvesting**
Camelina	Tiny dimension of the seeds that requires fine tuning of the setting of the combine harvester
Castor	Scalar ripening, high leaves and stem biomass with high moisture
Poplar MRC	In the Mediterranean area it is needed to develop small-scale harvesting systems
Perennial grasses	Overall optimisation of the harvesting operations

3. Research questions and goals

3.1 Research hypotheses

The activities carried out during the PhD course were established to test three main research hypotheses which can be listed as:

1. It is possible to harvest camelina seeds with a combine harvester equipped with a cereal header
2. It is possible to harvest castor seeds with a combine harvester equipped with a sunflower header
3. The developed prototype for harvesting medium rotation poplar plants is a valuable option for small-scale harvesting operations in the case of suitable topographical and logistic conditions

3.2 Specific goals

By investigating the validity of the mentioned above hypotheses the research was aimed to deepen the scientific knowledge on the complex topic of mechanical harvesting of various energy crops. We focused the research activities on the main bottlenecks for each investigated crop, with particular reference to the needs of cultivation in the Mediterranean area. In particular on the possibility of a single passage harvesting by combine harvester for camelina and castor, and on the development of sustainable small-scale harvesting systems for poplar medium rotation coppice. Furthermore, we focused the attention also on perennial grasses, trying to understand by a detailed literature review if the current technology readiness level of the available harvesting option is suitable for large scale cultivation of these species.

We aimed to assess to what extent the current harvesting systems are suitable and efficient, and what can be possible possibilities for improving their performance. All can be summarised in the aims of the study listed below.

3.3 Aims of the study

1. Assessing the mechanical harvesting of camelina and castor by combine harvester and identifying the main bottlenecks

2. Evaluating the working performance of a prototype to harvest poplar MRC plantation biomass in the framework of small-scale forestry

3. Reviewing the current literature in the topic of mechanical harvesting of perennial grass Species

4. General methods and approaches

The characteristics of each experimental field will be presented in the dedicated section. In this section, the general methods applied for studying the performance of the machineries, pre-harvest conditions, post-harvest conditions, seed loss and cost will be presented

4.1 Performance of the machineries: study of the working times and fuel consumption

4.1.1 Working times

Concerning oilseeds, in each experimental unit, the performance of the machines was evaluated through the study of the working times according to the standards ASAE S496.2, according to the most recent scientific publications in the topic. In addition to working times, the machinery test was used to obtain other data such as the field speed and the fuel consumption. All the gathered data was used to define the performance of the machine and the operative costs. Below are explained in detail how these data were collected in each experimental unit.

The field speed (FS) is the average rate of machine travel in the field during an uninterrupted period of functional activity (m/s or km/h). Average field speed can be measured by marking off a fixed distance (at least 100 m) in the field, placing a mark at each end, and counting the seconds it takes to drive between the marks. Average field speed can then be calculated from equation deriving from the formula of the velocity:

Velocity (v) = Space/Time

In this case the space is intended as the linear meters covered by the machine between a mark and the other. In case the combine is equipped with digital tachymeter, it is possible to obtain the field speed recording the value directly from the display.

Working times: the study of the working times and the evaluation of the field speed allowed determining parameters such as Theoretical field capacity (ha/h), Effective field capacity (ha/h), and the Field efficiency (%). By knowing the yield of the field (Mg/ha), it was possible to obtain the Material capacity (Mg/h).

Theoretical field capacity (TFC): depends only on the full operating width of the machine and the average travel speed in the field. It represents the maximum possible field capacity that can be

obtained at the given field speed when the full operating width of the machine is being used. It is calculated multiplying the field speed for the working width of the machine.
Effective field capacity (EFC): The Effective Field Capacity of a farm machine is the rate at which it performs its primary function, i.e., the number of hectares that can be harvested per hour.
Measurements or estimates of machine capacities are used to schedule field operations, power units, labor and to estimate machine operating costs. The effective field capacity (EFC) of a machine in the field can be easily calculated by dividing the hectares completed by the hours of Operative Time (OT).

EFC = worked area (ha) / OT (h)

The operative time is the real time necessary to complete the harvest of the surface object of the test, including also turnings, stops, regulations, etc.

The formula used for the estimation of the operative time is the following:

Operative Time (OT) = ET + AT

ET = is the effective time, i.e. the time in which the machine is actually harvesting the product.

AT = are the accessory times which includes accessory time for maintenance (ATM), that includes the pauses required for filling or unloading the hoppers (seeds, fertilizers, grains, etc.); accessory time for turning (ATT), corresponding to the time needed to reverse the direction; accessory time for regulations (ATR), corresponding to the times for adjustments in relation to the conditions of the field or the work.

Field efficiency (FE): expressed as percentage, the field efficiency is the ratio of actual or effective field capacity (EFC) to theoretical field capacity (TFC)

FE (%) = EFC (ha/h) / TFC (ha/h)

Material Capacity (MC): The working capacity of harvesting machines can be measured also by the quantity of material harvested per hour. This capacity is called the machine's material capacity (MC), expressed as tons per hour (Mg/h). It is the product of the machine's EFC and the average yield of crop per hectare and can be calculated from equation (5).

MC (Mg/h) = EFC (ha/h) x crop yield (Mg/ha)

Regarding the test on poplar medium rotation coppice plants, the time to carry out each working cycle was measured and recorded with a handheld chronometer with an accuracy of 1/100 min, separating work time from delay time. By knowing the working times and the volume of the trees in each working cycle, it was possible to derive the net work productivity measured in m3 PMH^{-1} (productive machine hour, calculated not accounting for delay) and gross productivity measured in m3 SMH^{-1} (scheduled machine hour, calculated accounting for delay).

4.1.2 Fuel consumption

Fuel consumption can be determined through machine tank refilling until full level at the end of each experimental unit (plot) using a graduated large cylinder to define the volume of fuel consumed (l/ha or l/t of biomass harvested). Another way could be to weight the amount of fuel consumed (kg of diesel/ha or kg/t of biomass harvested) considering that 1 liter of diesel is 0.835 kg.
It is important to start each experimental unit with the tank completely full. The fuel consumed must be proportioned to the exact surface of the experimental unit tested in order to define the fuel consumed per hectare in that experimental unit. In case of onboard computer availability, the fuel consumption can be derived directly from the dashboard of the tractor or the combine harvester.

4.2 Pre-harvest test: aerial biomass, expected seed yield and dehiscence

To estimate the main crop features 10 sample plots (2-3 m^2 of area) were randomly selected within the experimental field. In each plot the plants were counted, and measured in height. In case of castor, the respective capitula and racemes were counted and sampled for potential yield (PSY) estimation and moisture content assessment. Stems and leaves were also sampled for moisture, fresh and dry weight estimation. At the laboratory, samples from each plot were weighted through a precision scale. Subsequently, a representative subsample was weighted and put into the oven at 105 °C until constant weight in order to estimate residual moisture. Eventually, h-index was also calculated.

During the pre-harvest, seed loss due to dehiscence (DSL) was also assessed. In castor, the capsules found on the ground were collected and processed at the laboratory for the fresh and dry weight of DSL. Samples were processed in laboratory as already described. In camelina, dehiscence was not evaluated.

4.3 Post-harvest test, seed loss and seed quality

Regarding camelina, the total seed loss (TSL) was calculated as the mere difference between the theoretical biomass assessed during the pre-harvest and the effective quantity of seeds collected and weighted at the farm scale. This includes the seed loss due to the impact of the combine header (ISL) and the ineffectiveness of the cleaning shoe of the machine (CSL).

Subsequently, a tarpaulin was installed at the end of two sample plots to collect the seeds lost by the combine harvester from the sieves and straw walkers. The entire amount of biomass expelled by the machine was thus collected by the tarpaulin laying on the ground. The biomass was shipped to the laboratory, weighted and sieved to estimate CSL. The weight of the seeds found was referred to a surface of 13.4 m^2 given by the width of the combine header (6.4 m) multiplied by the length of the tarpaulin (2 m). Furthermore, the 1000-seed weight was recorded in order to compare it with the 1000 seed-weight of the harvested camelina seeds. The loss of seeds due to the impact (ISL) of the combine harvester with the siliques is calculated as TSL-CSL. In camelina, an evaluation of Material Other than Grain (MOG) was carried out sampling the material collected from the combine harvester and discharged into the trailer.

In castor, 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 meters after the start) a sample of about 20 kg of seeds were collected from the tank and brought to the laboratory for qualitative analysis. During the last 15 m of the plot, the threshed biomass was harvested behind the combine harvester (Figure 5a) and carried to laboratory, then sieved to permit the quantitative assessment of loss seeds due to the cleaning shoe (CSL). In correspondence to the sampled area for CSL assessment, all capsules laying on the ground were manually collected and weighted (Figure 5b). The weight was reduced by dehiscence value for the impact seeds loss assessment (ISL).

Figure 5. Collection of threshed biomasses (a) and lost capsule (B) for CSL and ISL assessment respectively.

Seeds collected from the combine harvester's hopper were further processed for the determination of the ratio between damaged seeds, undamaged seeds and unopened seeds (Figure 6). In particular, from the 20kg bags collected from each plot, three subsamples approximately 500g each were randomly taken and dispersed on a flat disk. The foreign material was removed manually and the remaining part was classified either as damaged seeds, undamaged seeds or unopened seeds (stuck in a valve of the capsule) then dried and weighted. Unopened seeds were manually opened to allow the weighting.

Figure 6. Sample of seeds collected within the tank of the combine harvester showing: a) damaged seeds; b) undamaged seeds; c) unopened seeds.

4.4 Estimation of harvesting costs

An interview with the contractors allowed to identify purchase and operating costs of the applied machineries, whilst the performance of the harvesting system was gained from the results of the field tests and used as input data. Finally, standard values for calculation were taken from CRPA (Research Centre on Animal productions) methodology (Pari et al.). Hourly costs of combine harvester were estimated taking into account the market value of the agricultural machinery. The price of the machine was discounted through the application of a lending rate of 3%.

Regarding poplar plants, machine costs were estimated by applying the Harmonized European Costing Model developed within EU COST Action FP0902.

4.5 Statistical approach

Each developed trial represented a separated case-study, as it very often happens in complex field trials in which it is needed to organize a multitasking team of researchers, farmers and contractors, Being the obtained data spatially independent within the same trial, we could exclude any nested structure of the data and thus we decided to apply a statistical approach based only on fixed effects, thus excluding random factors. We basically used paired samples T-test and One-Way Analysis of Variance (ANOVA). Prior of the application of these tests their further requirements (data normality and homoschedasticity) were checked by Shapiro-Wilk and Levene test respectively. HSD Tukey test was applied as post-hoc.

5. Organization of the results

The following scheme represents the applied approach for achieving the goals behind the rationale of the PhD.

Aim	Solution	Output
Aim 1 Assessing the mechanical harvesting of camelina and castor by combine harvester and identifying the main bottlenecks	**Solution** Field trials in different parts of Europe in established realities (Camelina Company in Spain) and emerging ones (experimental field of castor in Greece)	**Output** Three publications: Latterini et al. 2021 10.3390/agronomy12010146 Stefanoni et al. 2021a 10.3390/en15092999 Stefanoni et al. 2021b 10.3390/su13010195
Aim 2 Evaluating the working performance of a prototype to harvest poplar MRC plantation biomass in the framework of small-scale forestry	**Solution** Field trial in controlled conditions (experimental field in a research center in Italy) comparing the developed prototype with the state-of-the-art machinery	**Output** One publication: Latterini et al. 2022 10.3390/f13040569
Aim 3 Reviewing the current literature in the topic of mechanical harvesting of perennial grass species	**Solution** Systematic Literature Review	**Output** One publication: Stefanoni et al. 2023 10.3390/en16052303

6. Summary of the activities implemented during the PhD studies

6.1 Harvesting test of camelina in Spain

Publication: Stefanoni,W.; **Latterini, F**.; Ruiz, J.P.; Bergonzoli, S.; Palmieri, N.; Pari, L. 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. Sustainability 2021, 13, 195. https://doi.org/10.3390/su13010195

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, 4.22 ha/h, 4.66 Mg/h FM, and 97.24%, respectively. The harvesting cost was estimated in 48.51 €/ha. Approximately, the seed loss of 0.057 - 0.028 Mg/ha FM was due to the impact of the combine harvester header and dehiscence of pods, whilst 0.036 - 0.006 Mg/ha 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.

Harvesting test was performed in the town of Astudillo, Palencia (Castilla y Leon, Spain) during the 27th week of 2020 (Figure 7). 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.

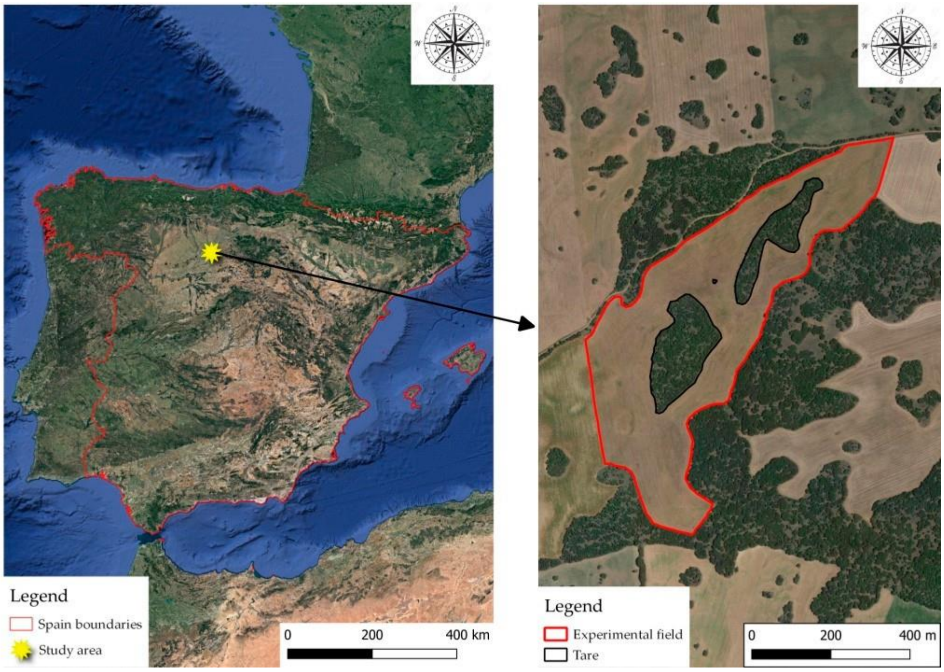

Figure 7. Experimental field location.

In the experimental field, camelina was grown using conventional farming regime. Using a seeding rate of 8 kg/ha, cultivar Alba (a commercial variety given by Camelina Company Espana) was planted in the first half of December 2019. Barley was the preceding harvest. Fertilization was applied twice, once in the winter using a trailed fertilizer spreader and once in April using a mounted liquid fertilizer spreader, at a rate of 250 kg per hectare of NPK 8-15-15. Before the distribution of nitrosulphate ammonium, weeds were chemically controlled by using the graminicide Pilot, Quizalofop-p-ethyl 10%, to eradicate the narrow-leaf weeds.

Biomass and seed yield; working performance, harvesting costs and seed loss were evaluated.

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

Figure 8. biomass and seed yield.

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

Figure 9. work productivity analysis.

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.

Figure 10. Seed loss evaluation. CSL (seed loss from the cleaning system of the combine harvester), SS (seed shattering), ISL (seed loss from the impact of the harvester header), TSL (total seed loss), ESL (seed loss evaluated after weighting the tractor trailer in which the seeds were unloaded).

Our results corroborate the hypothesis that a combine harvester equipped with a wheat header is acceptable for harvesting camelina seeds. Since the same machine can be used for both crops, this is especially useful for farmers and contractors who use camelina as a rotation crop in winter cereals. In addition, the price and performance are comparable. There is little cause for alarm when it comes to seed loss, which is mostly caused by the impact of the combine harvester's header and the cleaning shoe's inability to effectively separate the seeds from the rest of the biomass. Simply lowering the machine's speed can somewhat solve the latter issue. Instead, natural pod breakage only slightly increases seed loss.

6.2 Castor mechanical harvesting to test various terminating products

Publication: **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

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.

The experimental field (0.94 ha) was located in the center of Greece (651591 E, 4362784 N, 68 m asl) at the University of Thessaly farm. Clayey (47.1 clay, 32.7 silt, 20.1 sand), with 1.48% OM and PH 7.9, is how the soil is classified. The field was fallow the year before. The average annual rainfall in the area is 434 mm, with 1/4 of that amount falling between April and September. On April 24, 2021, 62,300 seeds per ha were used in direct drilling to establish the hybrid Kaima C1012. To control natural vegetation, glyphosate was administered ten days before seeding at a rate of 5 L per ha. In June, a row crop cultivator was used to eradicate weeds with a single mechanical operation. Prior to planting, basal fertilization was done by applying 13 kg N and 46 kg P per hectare. Throughout the growing season, fertigation was gradually increased to provide an additional 58.5 kg N/ha. For the first two irrigation events, sprinkler irrigation was used; following that, a drip irrigation system was created with pipes every other row. Water for plants came from irrigation (5100 m^3 per hectare), and rainfall added another 2840 m^3 to that total. The objective was to compare seed loss triggered by the four experimental treatments.

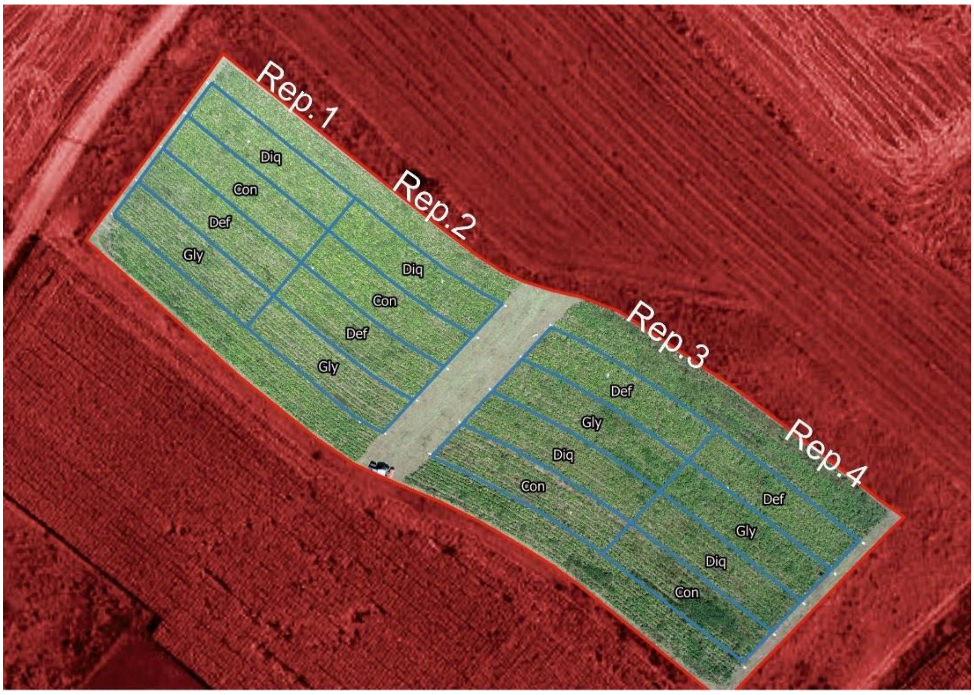

Figure 11. Experimental design.

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.

Figure 12. 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.

The present case study was undertaken in Central Greece, and the preliminary findings shed more light on the mechanical harvesting of castor beans. It has been demonstrated that dwarf hybrid castor plants are suitable, however a terminating procedure needs to be used to prevent clogs and damage to equipment. The residual moisture in plants was sufficiently decreased by glyphosate, spotlight, and defoliant to enable mechanized harvesting. None of them, however, turned out to be particularly effective for this crop. Furthermore, during mechanical harvesting, cereal header was the cause of the most seed loss. The right dosage of termination products and various heads for direct mixing castor beans should therefore be the subject of future research.

6.3 Mechanical harvesting of castor to test cereal and sunflower headers for the combine harvester

Publication: Stefanoni, W.; **Latterini, F.**; Malkogiannidis, V.; Salpiggidis, V.; Alexopoulou, E.; Pari, L. Mechanical Harvesting of Castor Bean (Ricinus communis L.) with a Combine Harvester Equipped with Two Different Headers: A Comparison of Working Performance. Energies 2022, 15, 2999. https://doi.org/10.3390/ en15092999

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.

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

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

Sowing was carried out on 29th April 2021 applying 21 kg/ha of seed of hybrid C1012 with sowing distance 95 cm X 22 cm through a cotton seed sowing machine.

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

On 29th July 2021 a foliar fertilizer Nutri-Gemma B-Zn (Biolchim, Bologna, Italy) was applied at a rate of 10 l/ha. The same day also 500 cm3/ha of Score 25C fungicide (Syn-genta, Basel, Switzerland) were applied. On 28th August 2021 crop was terminated via the application of 6000 cm3/ha of Reglone 20 SL (Syngenta, Basel, Switzerland).

A combine harvester New Holland CX8060 (New Holland, Pennsylvania, USA) was provided by a local contractor and utilized for the harvesting trial. Half of the experimental field was harvested with a New Holland cereal header with 5.5 m working width, while the remaining half with a Fantini (Mantova, Italy) sunflower header with 4 m working width. A vision of the combine harvester equipped with the two different headers is given in Figure 18. The applied settings of the combine harvester were: Threshing speed 400 rpm, Fan speed 800 rpm, Concave clearance 10 mm, Upper sieve clearance 17 mm, Lower sieve clearance 10 mm.

The goal was to investigate the difference in seed loss between the two headers.

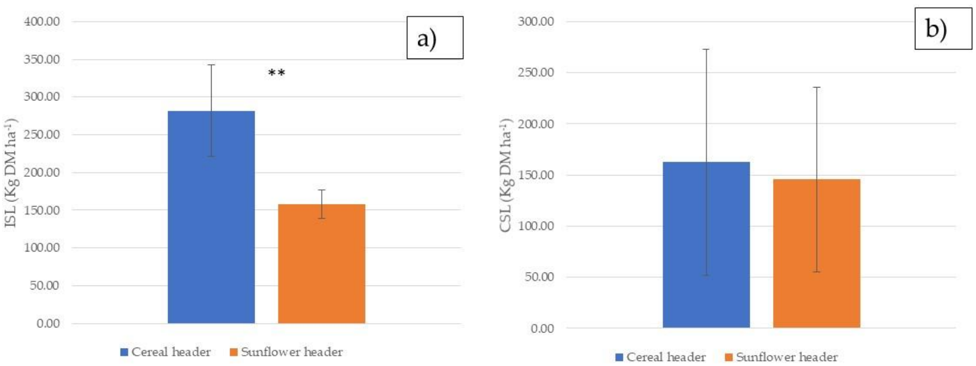

Figure 13. a) Comparison of ISL between the two headers. b) Comparison of CSL between the two headers. "**" indicates statistically significant differences at 0.01% according T-test.

Its greater potential for mechanical castor bean harvesting was highlighted by sunflower header's much lower ISL than cereal header. CSL, on the other hand, showed no differences, as would be predicted given that this variable is mostly impacted by the cleaning shoe's setting, which in this trial was the same for both treatments.

The key conclusion of this trial is that there is still much work to be done before developing a castor bean seed harvesting method that would be effective. A sunflower heading does indeed serve as a solid starting point, but its ISL performance is still behind that of other oilseeds. The creation of specifically tailored heads for castor bean appears to be the way forward, along with additional developments in this crop's genetics and agronomy.

The quality of the seeds that were harvested is another crucial factor that was examined in this research. The results were not at all good; in fact, for both treatments, the percentage of seeds that were correctly opened (not harmed and without capsules) was around 20%. The majority of the seeds were either incompletely opened (still inside the capsule) or damaged (broken or without an envelope). This is likely due to the significant amount of fresh biomass that was introduced into the threshing system along with the seeds, which reduced the cleaning shoe's efficiency. This problem might be solved by creating a special header that can only let seeds and a small amount of biomass into the combine, as well as by enhancing crop drying before harvesting. Another option is to adjust the combine's concave clearance and threshing speed to harvest castor bean seeds without cracking them open but without damaging them, and then perform the dehulling as a second passage operation with stationary equipment.

6.4 Small-scale prototype for harvesting poplar MRC plantations

Publication: **Latterini, F.**; Stefanoni, W.; Alfano, V.; Palmieri, N.; Mattei, P.; Pari, L. Assessment of Working Performance and Costs of Two Small-Scale Harvesting Systems for Medium Rotation Poplar Plantations. Forests 2022, 13, 569. https://doi.org/10.3390/f13040569

Abstract: Considering the increasing need to produce energy from renewable sources, the interest towards Medium Rotation Coppices (MRC) plantations has increased. One of the main issues that require tackling for the comprehensive sustainability of these plantations is related to the development of sustainable harvesting systems. Indeed, as a consequence of the average tree diameters at a breast height (dbh) of about 15 cm, single-pass harvesting typical of short rotation coppice is not applicable. Therefore, these plantations are generally harvested with machinery specifically developed for forest operations, as for instance harvesters, feller-bunchers and forwarders. In the Mediterranean area, the availability of such machines is still limited to a few big forest enterprises. In- deed, the majority of forest contractors carry out their activities in the framework of small-scale forestry, without the financial possibility of purchasing expensive machineries. Thus, the present study had the objective to evaluate the performance of two small-scale harvesting systems in a 7- year-old poplar plantation in Central Italy. The difference between the two systems was the different machinery applied for wood extraction, i.e., a forestry-fitted farm tractor equipped with winch (WINCH) and a fork lift prototype, attached to a crawler tractor (CFL). Extraction via CFL system reached very high working performance with about 21.5 m^3 SMH^{-1} (Scheduled Machine Hours, including delays), comparable to the productivities reported in the literature for forwarders work- ing in similar plantations. Harvesting costs with CFL were 24.74 EUR m^{-3}, of which 4.48 EUR m^{-3} was for felling with chainsaw, 4.61 EUR m^{-3} for extraction with CFL prototype and 15.64 EUR m^{-3} for wood chipping. WINCH showed unsatisfactory results instead, possessing a wood chip production cost of 41.95 EUR m^{-3}, which is practically equivalent to the market price of wood chips.

The study area was located in Monterotondo Municipality (Latium, Italy), and it con- sisted of an experimental poplar (clone AF-8) plant with an overall area of 0.42 ha (Coor- dinates in WGS84UTM33T 303994 E; 4663859 N). Terrain has a plain morphology and no roughness. Since the plantation had been established for seven years and the intervention constituted the first harvest, the plants had a single stem. Planting was done at a density of 1666 N ha^{-1} (2 m between rows). According to the national allometric equations created for poplar, the average diameter at breast height (dbh) was 13 cm, and the average height was 13.2 m, resulting in an average plant volume of 0.08 m^3. The developed prototype is a crawler fork lift (CFL). A Fiat 80C crawler tractor outfitted with the fork lift prototype was used for extraction operation. This was a fork lift that was fastened to the tractor's front loader. To make it easier to unload cut trees, the fork lift was fitted with a metal frame connected to a hydraulic piston. The trees were cut down perpendicular to the orientation of the row for extraction by CFL. The crawler tractor then proceeded to push or load the trees as it approached them so they were outside the field. Therefore, the extraction distance was 50 m, or one-half of a row.

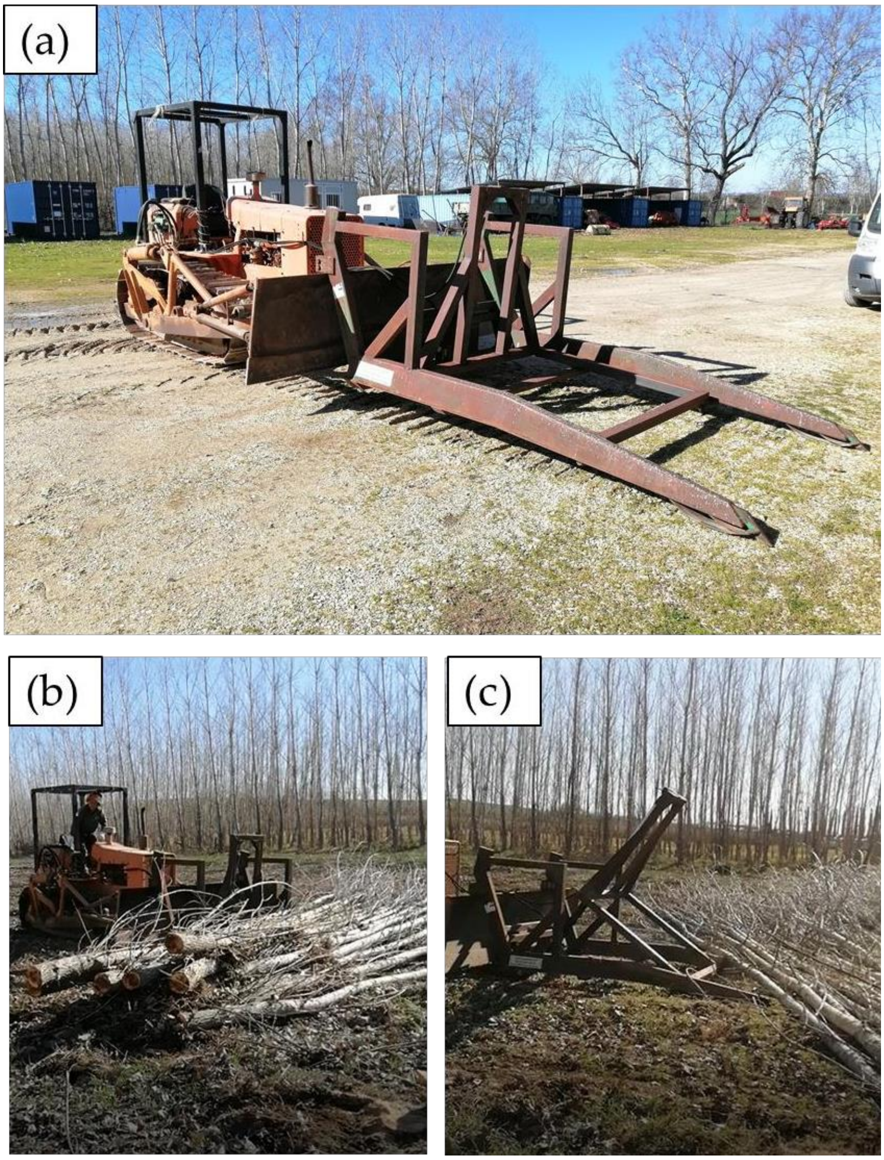

Figure 14. (a) Vision of CFL. (b) CFL while loading trees. (c) CFL while unloading trees.

	CFL		WINCH		Significance
	Avg.	St.Dev	Avg.	St.Dev	
m^3 SMH^{-1}	21.524	3.839	2.836	0.728	***
Mg FM SMH^{-1}	18.706	3.337	2.465	0.633	***
Mg DM SMH^{-1}	8.595	1.533	1.132	0.291	***

Figure 15. Work productivity SMH (including delays) for the two investigated extraction systems. “***” indicates statistically significant differences at $p > 0.001$ between the mean values of the treatments.

In a seven-year poplar plantation, the current study sought to assess the effectiveness of two small-scale harvesting technologies. The technologies for harvesting that were under investigation relied on stationary chippers and motor-manual chainsaw felling. A forestry-equipped farm tractor with a winch (WINCH) and a fork lift prototype mounted on a crawler tractor (CFL) were the two machines utilized for extraction operations that were distinct between the two systems. The obtained results revealed the unsuitability of the WINCH system in the study context. On the other hand, CFL reached very satisfactory working performance, comparable to those reported in the literature for harvesting systems based on much more ex- pensive machines. Therefore, CFL represents a very interesting harvesting system for these plantations; in the case that there is no need to shift the trees to a landing site, but it is possible to accumulate the trees in the headland before chipping.

6.5 A review of harvesting systems for perennial grasses

Publication: Stefanoni, W.; **Latterini, F**.; Pari, L. Perennial Grass Species for Bioenergy Production: The State of the Art in Mechanical Harvesting. Energies 2023, 16, 2303. https://doi.org/10.3390/en16052303

Abstract: Future European strategies to reduce dependence on foreign markets for energy supply and energy production will rely on the further exploitation of the primary sector. Lignocellulosic feedstock for bioenergy production is a valuable candidate, and dedicated crops such as giant reed (*Arundo donax* L.), miscanthus (*Miscanthus* × *giganteus*), reed canary grass (*Phalaris arundinacea* L.), and switchgrass (*Panicum virgatum* L.) have been proven to be suitable for extensive cultivation on marginal lands. The present review aimed at providing a comprehensive picture of the mechanical strategies available for harvesting giant reed, miscanthus, reed canary grass, and switchgrass that are suitable for the possible upscaling of their supply chain. Since harvesting is the most impactful phase of a lignocellulosic supply chain in dedicated crops, the associated performance and costs were taken into account in order to provide concrete observations and suggestions for future implementation. The findings of the present review highlighted that the investigated species have a sufficient technology readiness level concerning mechanical harvesting for the upscaling of their cultivation. All the species could indeed be harvested with existing machinery, mostly derived from the context of haymaking, without compromising the work productivity.

6. Conclusion

This thesis represents an attempt to put higher light on one of the most complex topic in the framework of bioenergy production, i.e. the mechanical harvesting. This part of the supply chain is indeed still the most challenging and the one with generally higher costs. We focused on different crops, ranging from poplar, to oilseeds to perennial grasses. Thus having the possibilities of testing both established species investigated since many years, and emerging crops which are gaining more and more attention, as suggested by the several Horizon projects funded and dealing with them. We focused our attention on the Mediterranean area, which is a very sensitive zone in the framework of bioenergy, considering the long road ahead for Mediterranean Countries to achieve the energy independence.

The main results for each of the investigated crop are listed below:

- **Camelina**: A traditional combine harvester fitted with a cereal header is capable of gathering camelina seeds. Due to the microscopic size of camelina seeds, extra care must be taken throughout the growing phase to prevent an excessive weed presence, which can be particularly harmful during harvesting. Limiting the machine speed is as well recommended to limit the losses from the cleaning shoe, which resulted the most sensitive part of the combine harvester during camelina harvesting. The research hypothesis "*It is possible to harvest camelina seeds with a combine harvester equipped with a cereal header*" is therefore confirmed.

7. **Castor**: Before developing a castor bean seed harvesting method that is effective, there is still considerable work to be done. Even while a sunflower header is a solid place to start, the performance in terms of seed loss still falls short of the average for other oilseeds. The creation of specifically tailored heads for castor bean appears to be the way forward, along with additional developments in this crop's genetics and agronomy. When it comes to the quality of the collected seeds, the findings were far from adequate; in fact, only 20% of the seeds were correctly opened (i.e., not damaged and without capsules). The majority of the seeds were either incompletely opened (still inside the capsule) or damaged (broken or without an envelope). This is likely due to the significant amount of fresh biomass that was introduced into the threshing mechanism along with the seeds. This problem might be solved by creating a special header that can only let seeds and a small amount of biomass into the combine, as well as by enhancing crop drying before harvesting. Another option is to arrange the combine to have a higher concave clearance and a slower threshing speed in order to harvest castor bean seeds without damaging them and

without opening them, and then to carry out the dehulling as a second passage operation using stationary machinery. The research hypothesis "*It is possible to harvest castor seeds with a combine harvester equipped with a sunflower header*" is therefore rejected.

- **Poplar MRC plant**: Coppices with a medium rotation are an intriguing source of clean energy and high-quality lignocellulosic biomass for other industrial uses. However, in a plantation of this nature, harvesting procedures call for special consideration. In fact, due to the dimension of the trees, the single-pass harvesting method typical of short rotation coppice is not an appropriate choice. These stands are currently harvested using machinery created expressly for forestry operations, such as harvesters, feller-bunchers, and forwarders. Such equipment is still not widely available in the setting of Mediterranean forestry, particularly in Central and Southern Italy. In fact, the majority of forest contractors work within the parameters of small-scale forestry and lack the resources to buy expensive machinery. The tested small-scale harvesting systems revealed different performance. On the one hand the typical forestry-fitted farm tractor equipped with a winch did not achieve satisfactory results. On the other hand, the crawler fork lift prototype achieved very high working productivity and low costs, even if it is a solution appliable only in the case there is no need to move the biomass to a landing site. The research hypothesis "*The developed prototype for harvesting medium rotation poplar plants is a valuable option for small-scale harvesting operations in the case of suitable topographical and logistic conditions*" is therefore confirmed.

- **Perennial grasses**: The examined species are technologically prepared enough for the expansion of their cultivation in terms of mechanical harvesting. With currently available equipment, which is mostly from the haymaking context, all species might be gathered without sacrificing work productivity.

8. Reference list

Angelini LG, Ceccarini L, Nassi o Di Nasso N, Bonari E (2009) Comparison of Arundo donax L. and Miscanthus x giganteus in a long-term field experiment in Central Italy: Analysis of productive characteristics and energy balance. Biomass Bioenergy 33:635–643 . https://doi.org/10.1016/j.biombioe.2008.10.005

Becker R, Meyer D, Wagoner P, Saunders RM (1992) Alternative crops for sustainable agricultural systems. Agric Ecosyst Environ 40:265–274 . https://doi.org/10.1016/0167-8809(92)90097-U

Berti M, Gesch R, Eynck C, Anderson J, Cermak S (2016) Camelina uses, genetics, genomics, production, and management. Ind Crops Prod 94:690–710 . https://doi.org/10.1016/j.indcrop.2016.09.034

Berti M, Samarappuli D, Johnson BL, Gesch RW (2017) Integrating winter camelina into maize and soybean cropping systems. Ind Crops Prod 107:595–601 . https://doi.org/10.1016/j.indcrop.2017.06.014

Berti M, Wilckens R, Fischer S, Solis A, Johnson B (2011) Seeding date influence on camelina seed yield, yield components, and oil content in Chile. Ind Crops Prod 34:1358–1365

Blackshaw R, Johnson E, Gan Y, May W, McAndrew D, Barthet V, McDonald T, Wispinski D (2011) Alternative oilseed crops for biodiesel feedstock on the Canadian prairies. Can J Plant Sci 91:889–896

Bonanno G, Cirelli GL, Toscano A, Giudice R Lo, Pavone P (2013) Heavy metal content in ash of energy crops growing in sewage-contaminated natural wetlands: Potential applications in agriculture and forestry? Sci Total Environ 452–453:349–354 . https://doi.org/10.1016/j.scitotenv.2013.02.048

Buonomano A, Barone G, Forzano C (2022) Advanced energy technologies, methods, and policies to support the sustainable development of energy, water and environment systems. Energy Reports 8:4844–4853 . https://doi.org/10.1016/j.egyr.2022.03.171

Carrino L, Visconti D, Fiorentino N, Fagnano M (2020) Biofuel Production with Castor Bean: A Win–Win Strategy for Marginal Land. Agronomy 10:1690 . https://doi.org/10.3390/agronomy10111690

Cosentino SL, Copani V, D'Agosta GM, Sanzone E, Mantineo M (2006) First results on evaluation of Arundo donax L. clones collected in Southern Italy. Ind Crops Prod 23:212–222 . https://doi.org/10.1016/j.indcrop.2005.06.004

Dobre P, Jurcoane S, Matei F, Stelica C, Farcas N, Moraru AC (2014) Camelina sativa as a double crop using the minimal tillage system. Rom Biotech Lett 19:9190–9195

FAO (2021) FAOSTAT Agriculture data. http://www.fao.org/faostat/en/#data

Florin I, Duda MM (2011) Camelina sativa : A new source of vegetal oils Camelina sativa : A new source of vegetal oils Introduction Camelina , though cultivated for over 2 , 000 years in the area for its seeds containing. Rom Biotechnol Lett 16:6263–6270

Gesch RW, Archer DW (2013) Double-cropping with winter camelina in the northern Corn Belt to produce fuel and food. Ind Crops Prod 44:718–725 . https://doi.org/10.1016/j.indcrop.2012.05.023

H Nautiyal O (2018) Castor Oil and Its Derivatives' With Market Growth, Commercial Perspective: Review. Org Med Chem Int J 6:1–13 . https://doi.org/10.19080/omcij.2018.06.555692

Hetemäki L, Hurmekoski E (2016) Forest products markets under change: review and research implications. Curr For Reports 2:177–188

Hixson SM, Parrish CC, Anderson DM (2014) Use of camelina oil to replace fish oil in diets for farmed salmonids and atlantic cod. Aquaculture 431:44–52 . https://doi.org/10.1016/j.aquaculture.2014.04.042

Khatiwora E, Adsul VB, Kulkarni MM, Deshpande NR, Kashalkar R V. (2010) Spectroscopic determination of total phenol and flavonoid contents of ipomoea carnea. Int J ChemTech Res 2:1698–1701

Krzyżaniak M, Stolarski MJ, Graban Ł, Lajszner W, Kuriata T (2020) Camelina and Crambe Oil Crops for Bioeconomy—Straw Utilisation for Energy. Energies 13:1503 . https://doi.org/10.3390/en13061503

Larnaudie V, Ferrari MD, Lareo C (2022) Switchgrass as an alternative biomass for ethanol production in a biorefinery: Perspectives on technology, economics and environmental sustainability. Renew Sustain Energy Rev 158:112115 . https://doi.org/10.1016/j.rser.2022.112115

Larsson M (2013) Cultivation and processing of Linum usitatissimum and Camelina sativa in southern Scandinavia during the Roman Iron Age. Veg Hist Archaeobot 22:509–520

Latterini F, Stefanoni W, Cavalaris C, Karamoutis C, Pari L, Alexopoulou E (2022) 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 12:146 . https://doi.org/10.3390/agronomy12010146

Latterini F, Stefanoni W, Sebastiano S, Baldi GM, Pari L (2020a) Evaluating the Suitability of a Combine Harvester Equipped with the Sunflower Header to Harvest Cardoon Seeds : A Case Study in Central Italy. Agronomy 10:1981 . https://doi.org/doi:10.3390/agronomy10121981

Latterini F, Stefanoni W, Suardi A, Alfano V, Bergonzoli S, Palmieri N, Pari L (2020b) A GIS Approach to Locate a Small Size Biomass Plant Powered by Olive Pruning and to Estimate Supply Chain Costs. Energies 13:3385 . https://doi.org/10.3390/en13133385

Lewandowski I, Clifton-Brown JC, Scurlock JMO, Huisman W (2000) Miscanthus: European experience with a novel energy crop. Biomass Bioenergy 19:209–227

Lewandowski I, Scurlock JMO, Lindvall E, Christou M (2003) The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass Bioenergy 25:335–361 . https://doi.org/10.1016/S0961-9534(03)00030-8

Li X, Mupondwa E (2014) Life cycle assessment of camelina oil derived biodiesel and jet fuel in the Canadian Prairies. Sci Total Environ 481:17–26 . https://doi.org/10.1016/j.scitotenv.2014.02.003

Mohammad BT, Al-Shannag M, Alnaief M, Singh L, Singsaas E, Alkasrawi M (2019) Production of multiple biofuels from Whole Camelina Material: A renewable energy crop. BioResources 13:4870–4883 . https://doi.org/10.15376/biores.13.3.4870-4883

Mohammed TH, Lakhmiri R, Azmani A, Hassan II (2014) Bio-oil from Pyrolysis of Castor Shell. Int J Basic Appl Sci 1–5

Mupondwa E, Li X, Tabil L, Falk K, Gugel R (2016) Technoeconomic analysis of camelina oil extraction as feedstock for biojet fuel in the Canadian Prairies. Biomass Bioenergy 95:221–234

Natelson RH, Wang WC, Roberts WL, Zering KD (2015) Technoeconomic analysis of jet fuel production from hydrolysis, decarboxylation, and reforming of camelina oil. Biomass Bioenergy 75:23–34 . https://doi.org/10.1016/j.biombioe.2015.02.001

Nilsson D, Rosenqvist H, Bernesson S (2015) Profitability of the production of energy grasses on marginal agricultural land in Sweden. Biomass Bioenergy 83:159–168 . https://doi.org/10.1016/j.biombioe.2015.09.007

Orczewska-Dudek S, Pietras M (2019) The effect of dietary Camelina sativa oil or cake in the diets of broiler chickens on growth performance, fatty acid profile, and sensory quality of meat. Animals 9:1–15 . https://doi.org/10.3390/ani9100734

Pari L, Alfano V, Mattei P, Santangelo E (2017) Pappi of cardoon (Cynara cardunculus L.): The use of wetting during the harvesting aimed at recovering for the biorefinery. Ind Crops Prod 108:722–728 . https://doi.org/10.1016/j.indcrop.2017.07.037

Pari L, Latterini F, Stefanoni W (2020) Herbaceous Oil Crops, a Review on Mechanical Harvesting State of the Art. Agriculture 10:309 . https://doi.org/10.3390/agriculture10080309

Pari L, Sissot F, Giannini E European Union Research Project Biocard : Mechanization Activities Results. In: Technology and Management to Increase the Efficiency in Sustainable Agricultural Systems, Rosario, Argentina, 1-4 September 2009

Pawlowska-Olszewska M, Puzio I, Harrison AP, Borkowski L, Tymicki G, Grabos D (2018) Supplementation with camelina oil prevents negative changes in the artery in orchidectomized rats. J Physiol Pharmacol 69:109–116 . https://doi.org/10.26402/jpp.2018.1.12

Pernak J, Łęgosz B, Klejdysz T, Marcinkowska K, Rogowski J, Kurasiak-Popowska D, Stuper-Szablewska K (2018) Ammonium bio-ionic liquids based on camelina oil as potential novel agrochemicals. RSC Adv 8:28676–28683 . https://doi.org/10.1039/c8ra03519a

Piccitto A, Scordia D, Corinzia SA, Cosentino SL, Testa G (2022) Advanced Biomethane Production from Biologically Pretreated Giant Reed under Different Harvest Times. Agronomy 12:712 . https://doi.org/10.3390/agronomy12030712

Polito L, Bortolotti M, Battelli M, Calafato G, Bolognesi A (2019) Ricin: An Ancient Story for a Timeless Plant Toxin. Toxins 11:324 . https://doi.org/10.3390/toxins11060324

Popp J, Harangi-Rákos M, Gabnai Z, Balogh P, Antal G, Bai A (2016) Biofuels and Their Co-Products as Livestock Feed: Global Economic and Environmental Implications. Molecules 21:285 . https://doi.org/10.3390/molecules21030285

Prochnow A, Heiermann M, Plöchl M, Amon T, Hobbs PJ (2009) Bioenergy from permanent grassland – A review: 2. Combustion. Bioresour Technol 100:4945–4954 . https://doi.org/10.1016/j.biortech.2009.05.069

Robson P, Mos M, Clifton-Brown J, Donnison I (2012) Phenotypic Variation in Senescence in Miscanthus:

Towards Optimising Biomass Quality and Quantity. BioEnergy Res 5:95–105 . https://doi.org/10.1007/s12155-011-9118-6

Roxas Duncan VI (2011) Of Beans and Beads: Ricin and Abrin in Bioterrorism and Biocrime. J Bioterror Biodef s2: . https://doi.org/10.4172/2157-2526.S2-002

Santangelo E, Scarfone A, Giudice A Del, Acampora A, Alfano V, Suardi A, Pari L (2015) Harvesting systems for poplar short rotation coppice. Ind Crops Prod 75:85–92 . https://doi.org/10.1016/j.indcrop.2015.07.013

Scholz V, Silva J (2008) Prospects and risks of the use of castor oil as a fuel. Biomass Bioenergy 32:95–100 . https://doi.org/10.1016/j.biombioe.2007.08.004

Sladden SE, Bransby DI, Aiken GE (1991) Biomass yield, composition and production costs for eight switchgrass varieties in Alabama. Biomass Bioenergy 1:119–122 . https://doi.org/10.1016/0961-9534(91)90034-A

Sperandio G, Acampora A, Del Giudice A, Civitarese V (2021) Models for the Evaluation of Productivity and Costs of Mechanized Felling on Poplar Short Rotation Coppice in Italy. Forests 12:954 . https://doi.org/10.3390/f12070954

Spinelli R (2011) Supply of wood biomass for energy purpose: global trends and perspectives. In: Proceedings of the 22nd Annual Meeting of the Club of Bologna, November. pp 13–14

Spinelli R, Magagnotti N, Lombardini C (2020) Low-Investment Fully Mechanized Harvesting of Short-Rotation Poplar (populus spp.) Plantations. Forests 11:502 . https://doi.org/10.3390/f11050502

Spinelli R, Magagnotti N, Lombardini C, Mihelič M (2021) A Low-Investment Option for the Integrated Semi-mechanized Harvesting of Small-Scale, Short-Rotation Poplar Plantations. Small-scale For 20:59–72 . https://doi.org/10.1007/s11842-020-09456-3

Spinelli R, Visser RJM (2009) Analyzing and estimating delays in wood chipping operations. Biomass Bioenergy 33:429–433

Stefanoni W, Latterini F, Pari L (2023) Perennial Grass Species for Bioenergy Production: The State of the Art in Mechanical Harvesting. Energies 16:2303 . https://doi.org/10.3390/en16052303

Vollmann J, Moritz T, Kargl C, Baumgartner S, Wagentristl H (2007) Agronomic evaluation of camelina genotypes selected for seed quality characteristics. Ind Crops Prod 26:270–277

Wang Y, Wang J, Schuler J, Hartley D, Volk T, Eisenbies M (2020a) Optimization of harvest and logistics for multiple lignocellulosic biomass feedstocks in the northeastern United States. Energy 197:117260 . https://doi.org/10.1016/j.energy.2020.117260

Wang Z, Feser JS, Lei T, Gupta AK (2020b) Performance and emissions of camelina oil derived jet fuel blends under distributed combustion condition. Fuel 271:117685 . https://doi.org/10.1016/j.fuel.2020.117685

Werner C, Haas E, Grote R, Gauder M, Graeff-Hönninger S, Claupein W, Butterbach-Bahl K (2012) Biomass production potential from P opulus short rotation systems in R omania. Gcb Bioenergy 4:642–653

Wnuk A, Górny AG, Bocianowski J, Kozak M (2013) Visualizing harvest index in crops. Commun Biometry

Crop Sci 8:48–59

Yang J, Caldwell C, Corscadden K, He QS, Li J (2016) An evaluation of biodiesel production from Camelina sativa grown in Nova Scotia. Ind Crops Prod 81:162–168 . https://doi.org/10.1016/j.indcrop.2015.11.073

Zanetti F, Gesch RW, Walia MK, Johnson JMF, Monti A (2020) Winter camelina root characteristics and yield performance under contrasting environmental conditions. F Crop Res 252:107794 . https://doi.org/10.1016/j.fcr.2020.107794

Zubr J (2003) Qualitative variation of Camelina sativa seed from different locations. Ind Crops Prod 17:161–169

Annex I – WoS indexed publications developed within the PhD studies

sustainability

Article

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

Walter Stefanoni [1], Francesco Latterini [1], Javier Prieto Ruiz [2], Simone Bergonzoli [3,*], Nadia Palmieri [1] 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; walter.stefanoni@crea.gov.it (W.S.); francesco.latterini@crea.gov.it (F.L.); nadia.palmieri@crea.gov.it (N.P.); luigi.pari@crea.gov.it (L.P.)
2 Camelina Company Espana, Camino de la Carrera, 11, Fuente el Saz de Jarama, 28140 Madrid, Spain; jprieto@camelinacompany.es
3 Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA), Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari, Via Milano 43, 24047 Treviglio, Italy
* Correspondence: simone.bergonzoli@crea.gov.it

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

check for updates

Citation: Stefanoni, W.; Latterini, F.; Ruiz, J.P.; Bergonzoli, S.; Palmieri, N.; Pari, L. 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. *Sustainability* **2021**, *13*, 195. https://doi.org/10.3390/su13010195

Received: 30 October 2020
Accepted: 23 December 2020
Published: 28 December 2020

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.

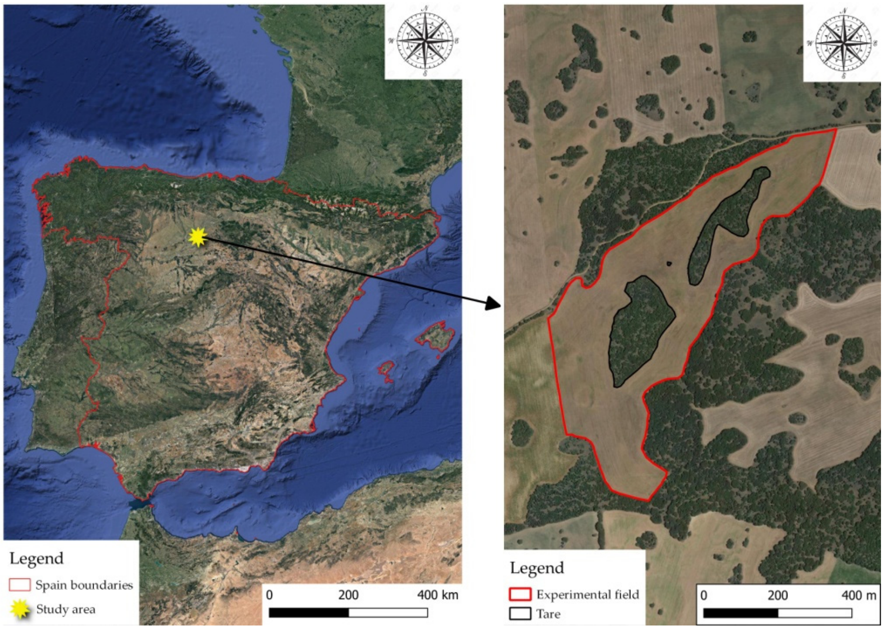

Figure 1. Experimental field location.

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
Financial costs	Investment	€	362,615
	Service life	year	10
	Service life	H	3000
	Resale	%	19.00
	Resale	€	68,896.85
	Depreciation	€	293,718.15
	Annual usage	h $year^{-1}$	312
	Interest rate	%	3
Fixed costs	Ownership costs	€ $year^{-1}$	29,371.82
	Interests	€ $year^{-1}$	6472.67775
	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
Variable costs	Repair factor	%	40
	Repairs and maintenance	€ h^{-1}	50.28
	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 × 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.

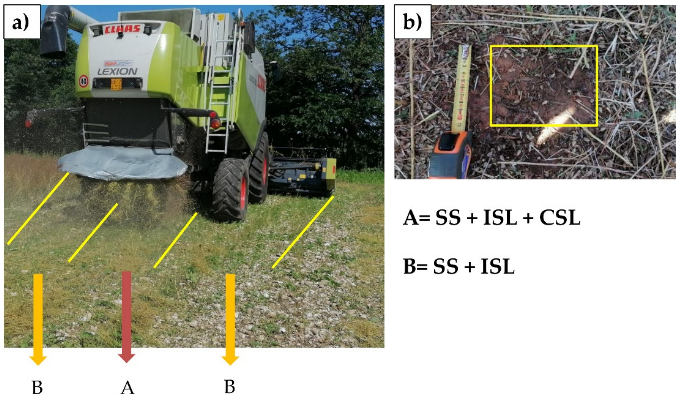

Figure 2. On the left (**a**), identification of the areas A and B behind the combine harvester. On the right (**b**), example of a sample plot to detect seeds on the ground.

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.

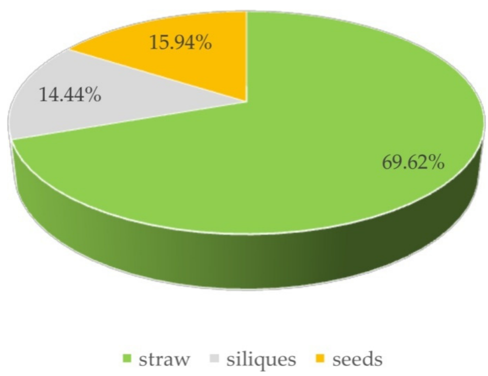

Figure 3. Percentage of straw, siliques and seeds of the aboveground biomass.

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 $\pm$ 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 $\pm$ 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 $\pm$ 0.006 Mg ha^{-1} FM (3.08 $\pm$ 0.54% *w/w*) of the seeds, while 0.057 $\pm$ 0.028 Mg ha^{-1} FM (4.87 $\pm$ 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.

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

Funding: This research was funded by PRIMA foundation, project 4CE-MED, grant Number 1911 and by Horizon 2020 project Panacea, grant Number 773501.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

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

Acknowledgments: The authors wish to thank Camelina Company (Camino de la Carrera, 11-11, 28140 Fuente el Saz, Madrid, Spain) for the organization of the tests and the support during the trials and Sandu Lazar for the help in performing the field and laboratory tests.

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

References

1. Righini, D.; Zanetti, F.; Monti, A. The bio-based economy can serve as the springboard for camelina and crambe to quit the limbo. *OCL* **2016**, *23*, D504. [CrossRef]
2. Krzyżaniak, M.; Stolarski, M.J.; Graban, Ł.; Lajszner, W.; Kuriata, T. Camelina and Crambe Oil Crops for Bioeconomy—Straw Utilisation for Energy. *Energies* **2020**, *13*, 1503. [CrossRef]
3. de Espinosa, L.M.; Meier, M.A.R. Plant oils: The perfect renewable resource for polymer science? *Eur. Polym. J.* **2011**, *47*, 837–852. [CrossRef]
4. Carlsson, A.S. Plant oils as feedstock alternatives to petroleum—A short survey of potential oil crop platforms. *Biochimie* **2009**, *91*, 665–670. [CrossRef]
5. Natelson, R.H.; Wang, W.C.; Roberts, W.L.; Zering, K.D. Technoeconomic analysis of jet fuel production from hydrolysis, decarboxylation, and reforming of camelina oil. *Biomass Bioenergy* **2015**, *75*, 23–34. [CrossRef]
6. Larsson, M. Cultivation and processing of Linum usitatissimum and Camelina sativa in southern Scandinavia during the Roman Iron Age. *Veg. Hist. Archaeobot.* **2013**, *22*, 509–520. [CrossRef]
7. Krzyżaniak, M.; Stolarski, M.J.; Tworkowski, J.; Puttick, D.; Eynck, C.; Załuski, D.; Kwiatkowski, J. Yield and seed composition of 10 spring camelina genotypes cultivated in the temperate climate of Central Europe. *Ind. Crops Prod.* **2019**, *138*, 111443. [CrossRef]
8. Eidhin, D.N.; Burke, J.; O'Beirne, D. Oxidative stability of ω3-rich camelina oil and camelina oil-based spread compared with plant and fish oils and sunflower spread. *J. Food Sci.* **2003**, *68*, 345–353. [CrossRef]
9. Halmemies-Beauchet-Filleau, A.; Shingfield, K.J.; Simpura, I.; Kokkonen, T.; Jaakkola, S.; Toivonen, V.; Vanhatalo, A. Effect of incremental amounts of camelina oil on milk fatty acid composition in lactating cows fed diets based on a mixture of grass and red clover silage and concentrates containing camelina expeller. *J. Dairy Sci.* **2017**, *100*, 305–324. [CrossRef]
10. Hixson, S.M.; Parrish, C.C.; Wells, J.S.; Winkowski, E.M.; Anderson, D.M.; Bullerwell, C.N. Inclusion of camelina meal as a protein source in diets for farmed salmonids. *Aquac. Nutr.* **2016**, *22*, 615–630. [CrossRef]
11. Lawrence, R.D.; Anderson, J.L. Ruminal degradation and intestinal digestibility of camelina meal and carinata meal compared with other protein sources. *Prof. Anim. Sci.* **2018**, *34*, 10–18. [CrossRef]
12. Betancor, M.B.; MacEwan, A.; Sprague, M.; Gong, X.; Montero, D.; Han, L.; Napier, J.A.; Norambuena, F.; Izquierdo, M.; Tocher, D.R. Oil from transgenic Camelina sativa as a source of EPA and DHA in feed for European sea bass (*Dicentrarchus labrax* L.). *Aquaculture* **2021**, *530*, 735759. [CrossRef]
13. Ciubota-Rosie, C.; Ruiz, J.R.; Ramos, M.J.; Pérez, Á. Biodiesel from Camelina sativa: A comprehensive characterisation. *Fuel* **2013**, *105*, 572–577. [CrossRef]
14. Corporan, E.; Edwards, T.; Shafer, L.; DeWitt, M.J.; Klingshirn, C.; Zabarnick, S.; West, Z.; Striebich, R.; Graham, J.; Klein, J. Chemical, thermal stability, seal swell, and emissions studies of alternative jet fuels. *Energy Fuels* **2011**, *25*, 955–966. [CrossRef]

15. Kim, N.; Li, Y.; Sun, X.S. Epoxidation of Camelina sativa oil and peel adhesion properties. *Ind. Crops Prod.* **2015**, *64*, 1–8. [CrossRef]
16. Allen, B.L.; Vigil, M.F.; Jabro, J.D. Camelina growing degree hour and base temperature requirements. *Agron. J.* **2014**, *106*, 940–944. [CrossRef]
17. Berti, M.; Wilckens, R.; Fischer, S.; Solis, A.; Johnson, B. Seeding date influence on camelina seed yield, yield components, and oil content in Chile. *Ind. Crops Prod.* **2011**, *34*, 1358–1365. [CrossRef]
18. Johnson, J.M.F.; Gesch, R.W. Calendula and camelina response to nitrogen fertility. *Ind. Crops Prod.* **2013**, *43*, 684–691. [CrossRef]
19. Román-Figueroa, C.; Padilla, R.; Uribe, J.; Paneque, M. Land Suitability Assessment for Camelina (*Camelina sativa* L.) Development in Chile. *Sustainability* **2017**, *9*, 154. [CrossRef]
20. Krzyżaniak, M.; Stolarski, M.J. Life cycle assessment of camelina and crambe production for biorefinery and energy purposes. *J. Clean. Prod.* **2019**, *237*, 117755. [CrossRef]
21. Brentrup, F.; Küsters, J.; Lammel, J.; Kuhlmann, H. Methods to estimate on-field nitrogen emissions from crop production as an input to LCA studies in the agricultural sector. *Int. J. Life Cycle Assess.* **2000**, *5*, 349. [CrossRef]
22. Zanetti, F.; Gesch, R.W.; Walia, M.K.; Johnson, J.M.F.; Monti, A. Winter camelina root characteristics and yield performance under contrasting environmental conditions. *Field Crops Res.* **2020**, *252*, 107794. [CrossRef]
23. Berti, M.; Gesch, R.; Eynck, C.; Anderson, J.; Cermak, S. Camelina uses, genetics, genomics, production, and management. *Ind. Crops Prod.* **2016**, *94*, 690–710. [CrossRef]
24. Chen, C.; Bekkerman, A.; Afshar, R.K.; Neill, K. Intensification of dryland cropping systems for bio-feedstock production: Evaluation of agronomic and economic benefits of Camelina sativa. *Ind. Crops Prod.* **2015**, *71*, 114–121. [CrossRef]
25. Gesch, R.W.; Archer, D.W. Double-cropping with winter camelina in the northern Corn Belt to produce fuel and food. *Ind. Crops Prod.* **2013**, *44*, 718–725. [CrossRef]
26. Berti, M.; Samarappuli, D.; Johnson, B.L.; Gesch, R.W. Integrating winter camelina into maize and soybean cropping systems. *Ind. Crops Prod.* **2017**, *107*, 595–601. [CrossRef]
27. Royo-Esnal, A.; Valencia-Gredilla, F. Camelina as a Rotation Crop for Weed Control in Organic Farming in a Semiarid Mediterranean Climate. *Agriculture* **2018**, *8*, 156. [CrossRef]
28. Peterson, A.T.; Berti, M.T.; Samarappuli, D. Intersowing cover crops into standing soybean in the US upper midwest. *Agronomy* **2019**, *9*, 264. [CrossRef]
29. Zanetti, F.; Christou, M.; Alexopoulou, E.; Berti, M.T.; Vecchi, A.; Borghesi, A.; Monti, A. Innovative double cropping systems including camelina [*Camelina sativa* (L.) crantz] a valuable oilseed crop for bio-based applications. In Proceedings of the European Biomass Conference and Exhibition Proceedings, Lisbon, Portugal, 27–30 May 2019; pp. 127–130.
30. Christopher, L.P.; Kumar, H.; Zambare, V.P. Enzymatic biodiesel: Challenges and opportunities. *Appl. Energy* **2014**, *119*, 497–520. [CrossRef]
31. Bušić, A.; Kundas, S.; Morzak, G.; Belskaya, H.; Mardetko, N.; Šantek, M.I.; Komes, D.; Novak, S.; Šantek, B. Recent trends in biodiesel and biogas production. *Food Technol. Biotechnol.* **2018**, *56*, 152–173. [CrossRef]
32. Latterini, F.; Stefanoni, W.; Suardi, A.; Alfano, V.; Bergonzoli, S.; Palmieri, N.; Pari, L. A GIS Approach to Locate a Small Size Biomass Plant Powered by Olive Pruning and to Estimate Supply Chain Costs. *Energies* **2020**, *13*, 3385. [CrossRef]
33. Pari, L.; Latterini, F.; Stefanoni, W. Herbaceous Oil Crops, a Review on Mechanical Harvesting State of the Art. *Agriculture* **2020**, *10*, 309. [CrossRef]
34. McVay, K.A.; Lamb, P.F. Camelina production in Montana. *Bull. MT200701AG Mont. State Univ.* **2008**.
35. Zubr, J. Qualitative variation of Camelina sativa seed from different locations. *Ind. Crops Prod.* **2003**, *17*, 161–169. [CrossRef]
36. Vollmann, J.; Moritz, T.; Kargl, C.; Baumgartner, S.; Wagentristl, H. Agronomic evaluation of camelina genotypes selected for seed quality characteristics. *Ind. Crops Prod.* **2007**, *26*, 270–277. [CrossRef]
37. Leclère, M.; Jeuffroy, M.-H.; Butier, A.; Chatain, C.; Loyce, C. Controlling weeds in camelina with innovative herbicide-free crop management routes across various environments. *Ind. Crops Prod.* **2019**, *140*, 111605. [CrossRef]
38. Obour, K.A.; Sintim, H.J.; Obeng, E.; Jeliazkov, V.D. Oilseed Camelina (*Camelina sativa* L. Crantz): Production Systems, Prospects and Challenges in the USA Great Plains. *Adv. Plants Agric. Res.* **2015**, *2*, 00043. [CrossRef]
39. Stefanoni, W.; Latterini, F.; Ruiz, J.P.; Bergonzoli, S.; Attolico, C.; Pari, L. Mechanical Harvesting of Camelina: Work Productivity, Costs and Seed Loss Evaluation. *Energies* **2020**, *13*, 5329. [CrossRef]
40. Sintim, H.Y.; Zheljazkov, V.D.; Obour, A.K.; Garcia y Garcia, A. Managing harvest time to control pod shattering in oilseed camelina. *Agron. J.* **2016**, *108*, 656–661. [CrossRef]
41. Stolarski, M.J.; Krzyżaniak, M.; Tworkowski, J.; Załuski, D.; Kwiatkowski, J.; Szczukowski, S. Camelina and crambe production—Energy efficiency indices depending on nitrogen fertilizer application. *Ind. Crops Prod.* **2019**, *137*, 386–395. [CrossRef]
42. NSAI ISO 18134-2:2017 Solid Biofuels—Determination of Moisture Content—Oven Dry Method—Part 2: Total Moisture—Simplified Method. Available online: https://www.iso.org/standard/71536.html (accessed on 6 July 2020).
43. ISO 17828:2015 ISO 17828:2015 Solid Biofuels—Determination of Bulk Density. Available online: https://www.iso.org/obp/ui/#iso:std:iso:17828:ed-1:v1:en (accessed on 23 July 2020).
44. Reith, S.; Frisch, J.; Winkler, B. Revision of the working time classification to optimize work processes in modern agriculture. *Chem. Eng. Trans.* **2017**, *58*, 121–126. [CrossRef]
45. Assirelli, A.; Pignedoli, S. Costo di esercizio delle macchine agricole. *Cent. Ric. Prod. Anim.* **2005**, *5*, 1–10.

46. Suardi, A.; Stefanoni, W.; Bergonzoli, S.; Latterini, F.; Jonsson, N.; Pari, L. Comparison between Two Strategies for the Collection of Wheat Residue after Mechanical Harvesting: Performance and Cost Analysis. *Sustainability* **2020**, *12*, 4936. [CrossRef]
47. Suardi, A.; Stefanoni, W.; Alfano, V.; Bergonzoli, S.; Pari, L. Equipping a Combine Harvester with Turbine Technology Increases the Recovery of Residual Biomass from Cereal Crops via the Collection of Chaff. *Energies* **2020**, *13*, 1572. [CrossRef]
48. Suardi, A.; Saia, S.; Stefanoni, W.; Gunnarsson, C.; Sundberg, M.; Pari, L. Admixing Chaff with Straw Increased the Residues Collected without Compromising Machinery Efficiencies. *Energies* **2020**, *13*, 1766. [CrossRef]
49. Banca d'Italia Banca d'Italia Lending Rate. Available online: https://www.bancaditalia.it/ (accessed on 11 July 2020).
50. R Development Core Team. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing: Vienna, Austria, 2010. Available online: http://www.r-project.org/ (accessed on 6 August 2020).
51. Mauri, P.V.; Mostaza, D.; Plaza, A.; Ruiz-Fernandez, J.; Prieto, J.; Capuano, A. Variability of camelina production in the center of Spain in two years of cultivation, a new profitable and alternative crop. In Proceedings of the 27th European Biomass Conference and Exhibition, Lisbon, Portugal, 27–30 May 2019; pp. 196–200.
52. Schillinger, W.F. Camelina: Long-term cropping systems research in a dry Mediterranean climate. *Field Crop. Res.* **2019**, *235*, 87–94. [CrossRef]
53. Imbrea, F.; Jurcoane, S.; Hălmăjan, H.V.; Duda, M.; Botoş, L. Camelina sativa: A new source of vegetal oils. *Rom. Biotechnol. Lett.* **2011**, *16*, 6263–6270.
54. Lohaus, R.H.; Neupane, D.; Mengistu, M.A.; Solomon, J.K.Q.; Cushman, J.C. Five-Year Field Trial of Eight Camelina sativa Cultivars for Biomass to be Used in Biofuel under Irrigated Conditions in a Semi-Arid Climate. *Agronomy* **2020**, *10*, 562. [CrossRef]
55. Grady, K.; Nleya, T. Camelina Production. *Ext. Extra South Dakota State Univ.* **2010**, *8167*, 1–3.
56. Kuai, J.; Sun, Y.; Zuo, Q.; Huang, H.; Liao, Q.; Wu, C.; Lu, J.; Wu, J.; Zhou, G. The yield of mechanically harvested rapeseed (*Brassica napus* L.) can be increased by optimum plant density and row spacing. *Sci. Rep.* **2015**, *5*, 1–14. [CrossRef]
57. Zhu, L.H.; Krens, F.; Smith, M.A.; Li, X.; Qi, W.; Van Loo, E.N.; Iven, T.; Feussner, I.; Nazarenus, T.J.; Huai, D.; et al. Dedicated Industrial Oilseed Crops as Metabolic Engineering Platforms for Sustainable Industrial Feedstock Production. *Sci. Rep.* **2016**, *6*, 1–11. [CrossRef] [PubMed]
58. Gómez-Monedero, B.; Bimbela, F.; Arauzo, J.; Faria, J.; Ruiz, M.P. Pyrolysis of Red Eucalyptus, Camelina Straw, and Wheat Straw in an Ablative Reactor. *Energy Fuels* **2015**, *29*, 1766–1775. [CrossRef]
59. Pagnotta, E.; Ugolini, L.; Matteo, R.; Lazzeri, L.; Foschi, L.; Angelini, L.G.; Tavarini, S. Exploring the Camelina sativa value chain: A new opportunity for bio-based products and overall crop sustainability. *Riv. Ital. Delle Sostanze Grasse* **2019**, *96*, 259–268.
60. Pari, L.; Suardi, A.; Stefanoni, W.; Latterini, F.; Palmieri, N. Environmental and Economic Assessment of Castor Oil Supply Chain: A Case Study. *Sustainability* **2020**, *12*, 6339. [CrossRef]
61. Bergonzoli, S.; Suardi, A.; Rezaie, N.; Alfano, V.; Pari, L. An innovative system for Maize Cob and wheat chaff harvesting: Simultaneous grain and residues collection. *Energies* **2020**, *13*, 1265. [CrossRef]
62. Startsev, A.S.; Makarov, S.A.; Nesterov, E.S.; Kazakov, Y.F.; Terentyev, A.G. Comparative evaluation of the operation of a combine harvester with an additional sieve with adjustable holes for sunflower harvesting. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *433*. [CrossRef]
63. Shaforostov, V.D.; Makarov, S.S. The header for a breeding plot combine for sunflower harvesting. *Acta Technol. Agric.* **2019**, *22*, 60–63. [CrossRef]
64. Asoodar, A.M.; Izadinia, Y.; Desbiolles, J. Benefits of harvester front extension in reducing canola harvest losses. *Int. Agric. Eng. J.* **2012**, *21*, 32–37.
65. Pari, L.; Assirelli, A.; Suardi, A.; Civitarese, V.; Del Giudice, A.; Costa, C.; Santangelo, E. The harvest of oilseed rape (*Brassica napus* L.): The effective yield losses at on-farm scale in the Italian area. *Biomass Bioenergy* **2012**, *46*, 453–458. [CrossRef]
66. Hobson, R.N.; Bruce, D.M. Seed loss when cutting a standing crop of oilseed rape with two types of combine harvester header. *Biosyst. Eng.* **2002**, *81*, 281–286. [CrossRef]

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

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

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

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.

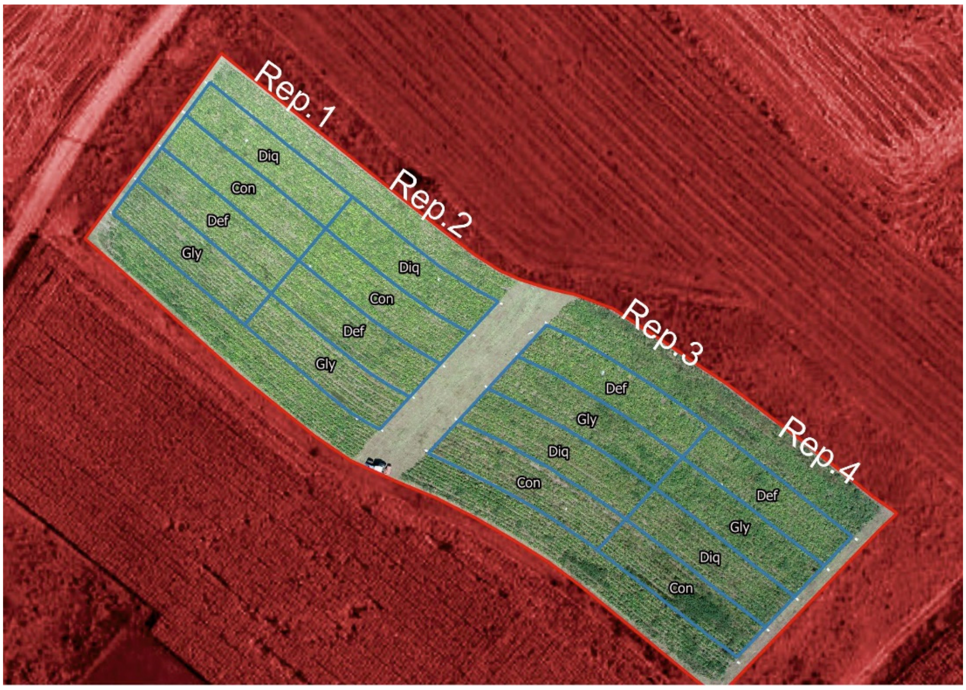

Figure 1. Aerial picture of the field trial with indication of the experimental design Gly = Glyphosate, Def = Defoliant, Diq = Diquat, Con = Control.

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.

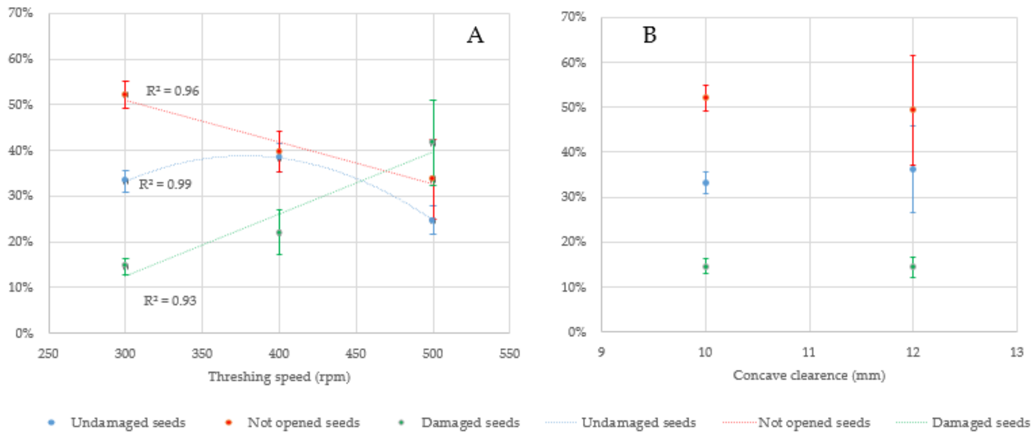

Figure 2. Percentage of undamaged, not opened and damaged seeds in relation to the rotational speed of the thrashing drum (**A**) and the clearance (**B**).

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.

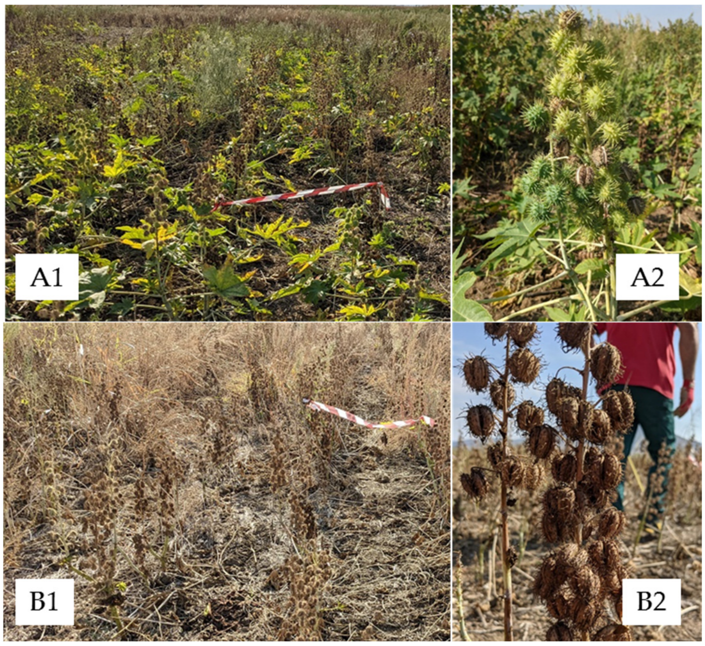

Figure 4. Difference between control (**A1**,**A2**) and terminated castor plants (**B1**,**B2**).

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 cardunculus* 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.

References

1. Carrino, L.; Visconti, D.; Fiorentino, N.; Fagnano, M. Biofuel Production with Castor Bean: A Win–Win Strategy for Marginal Land. *Agronomy* **2020**, *10*, 1690. [CrossRef]
2. European Union (EU). Renewable Energy Directive II (EU) 2018/2001. 11 December 2018. Available online: https://eur-lex.europa.eu/legal-content/IT/TXT/PDF/?uri=CELEX:32018L2001&from=IT (accessed on 10 July 2020).
3. Bateni, H.; Karimi, K.; Zamani, A.; Benakashani, F. Castor plant for biodiesel, biogas, and ethanol production with a biorefinery processing perspective. *Appl. Energy* **2014**, *136*, 14–22. [CrossRef]
4. Scholz, V.; Silva, J. Prospects and risks of the use of castor oil as a fuel. *Biomass Bioenergy* **2008**, *32*, 95–100. [CrossRef]
5. Polito, L.; Bortolotti, M.; Battelli, M.G.; Calafato, G.; Bolognesi, A. Ricin: An ancient story for a timeless plant toxin. *Toxins* **2019**, *11*, 324. [CrossRef] [PubMed]
6. Alexopoulou, E.; Papatheohari, Y.; Zanetti, F.; Tsiotas, K.; Papamichael, I.; Christou, M.; Namatov, I.; Monti, A. Comparative studies on several castor (Ricinus communis L.) hybrids: Growth, yields, seed oil and biomass characterization. *Ind. Crops Prod.* **2015**, *75*, 8–13. [CrossRef]
7. Zanetti, F.; Monti, A.; Berti, M.T. Challenges and opportunities for new industrial oilseed crops in EU-27: A review. *Ind. Crops Prod.* **2013**, *50*, 580–595. [CrossRef]
8. Pari, L.; Latterini, F.; Stefanoni, W. Herbaceous Oil Crops, a Review on Mechanical Harvesting State of the Art. *Agriculture* **2020**, *10*, 309. [CrossRef]
9. Fernández, J.; Pari, L.; Müller, M.; Márquez, L.; Fedrizzi, M.; Curt, M. Strategies for the mechanical harvesting of Cynara. In Proceedings of the 15th European Biomass Conference & Exhibition, Berlin, Germany, 7–11 May 2007; pp. 7–11.
10. Chan, A.P.; Crabtree, J.; Zhao, Q.; Lorenzi, H.; Orvis, J.; Puiu, D.; Melake-Berhan, A.; Jones, K.M.; Redman, J.; Chen, G.; et al. Draft genome sequence of the oilseed species Ricinus communis. *Nat. Biotechnol.* **2010**, *28*, 951–956. [CrossRef] [PubMed]

11. Baldanzi, M.; Pugliesi, C. Selection for non-branching in castor, Ricinus communis L. *Plant Breed.* **1998**, *117*, 392–394. [CrossRef]
12. Baldanzi, M.; Myczkowski, M.L.; Salvini, M.; Macchia, M. Description of 90 inbred lines of castor plant (*Ricinus communis* L.). *Euphytica* **2015**, *202*, 13–33. [CrossRef]
13. Anjani, K. Castor genetic resources: A primary gene pool for exploitation. *Ind. Crops Prod.* **2012**, *35*, 1–14. [CrossRef]
14. Zanetti, F.; Chieco, C.; Alexopoulou, E.; Vecchi, A.; Bertazza, G.; Monti, A. Comparison of new castor (Ricinus communis L.) genotypes in the mediterranean area and possible valorization of residual biomass for insect rearing. *Ind. Crops Prod.* **2017**, *107*, 581–587. [CrossRef]
15. Roberts, T.R.; Hutson, D.H.; Lee, P.W.; Nicholls, P.H.; Plimmer, J.R.; Roberts, M.C.; Croucher, L. *Metabolic Pathways of Agrochemicals: Part 1: Herbicides and Plant Growth Regulators*; Royal Society of Chemistry: Cambridge, United Kingdom, 2007; ISBN 1847551386.
16. International Agency for Research on Cancer. Evaluation of five organophosphate insecticides and herbicides. *IARC Monogr.* **2015**, *112*. Available online: https://www.iarc.who.int/news-events/iarc-monographs-volume-112-evaluation-of-five-organophosphate-insecticides-and-herbicides (accessed on 20 October 2021).
17. Myers, J.P.; Antoniou, M.N.; Blumberg, B.; Carroll, L.; Colborn, T.; Everett, L.G.; Hansen, M.; Landrigan, P.J.; Lanphear, B.P.; Mesnage, R.; et al. Concerns over use of glyphosate-based herbicides and risks associated with exposures: A consensus statement. *Environ. Health* **2016**, *15*, 19. [CrossRef] [PubMed]
18. Basi, S.; Noga, G.; Hunsche, M. Relevance of the deposit structure for the uptake and bio-efficacy of diquat, as monitored by the spatially resolved chlorophyll fluorescence. *Pestic. Biochem. Physiol.* **2013**, *107*, 218–225. [CrossRef]
19. Anastasiadis, B.; Garcia, B.A.; Laffranque, J.P.; Shires, S.W. Carfentrazone-Ethyl (F8426): A New Low-Dose Cotton Defoliant. In Proceedings of the World Cotton Research Conference-2, Athens, Greece, 6–12 September 1998; pp. 1175–1178.
20. StatSoft, Inc. *STATISTICA (Data Analysis Software System)*, version 7.0; StatSoft, Inc.: Round Rock, TX, USA, 2007. Available online: www.statsoft.com (accessed on 1 October 2021).
21. Sadeghi-Bakhtavari, A.R.; Hazrati, S. Growth, yield, and fatty acids as affected by water-deficit and foliar application of nitrogen, phosphorus, and sulfur in castor bean. *J. Crop Improv.* **2021**, *35*, 453–468. [CrossRef]
22. Severino, L.S.; Auld, D.L. A framework for the study of the growth and development of castor plant. *Ind. Crops Prod.* **2013**, *46*, 25–38. [CrossRef]
23. Reddy, K.R.; Matcha, S.K. Quantifying nitrogen effects on castor bean (*Ricinus communis* L.) development, growth, and photosynthesis. *Ind. Crops Prod.* **2010**, *31*, 185–191. [CrossRef]
24. de Carvalho Teixeira Vasconcelos, P.; Loureiro, M.B.; Lima, Á.M.M.F.; Ribeiro, P.R.; Bernal, D.T.; Moreno, M.L.V.; Fernandez, L.G.; de Castro, R.D. New insights into the mechanism underlying Ricinus communis L. tolerance to drought stress during germination. *Ind. Crops Prod.* **2017**, *103*, 99–106. [CrossRef]
25. Bewley, J.D.; Bradford, K.; Hilhorst, H.; Nogonaki, H. *Seeds: Physiology of Development, Germination and Dormancy*; Finch-Savage, B., Ed.; Springer Science & Business Media: New York, NY, USA; Heidelberg, Germany; Dordrecht, The Netherlands; London, UK, 2012; ISBN 1461446929.
26. Merkouropoulos, G.; Kapazoglou, A.; Drosou, V.; Jacobs, E.; Krolzig, A.; Papadopoulos, C.; Hilioti, Z. Dwarf hybrids of the bioenergy crop Ricinus communis suitable for mechanized harvesting reveal differences in morpho-physiological characteristics and seed metabolic profiles. *Euphytica* **2016**, *210*, 207–219. [CrossRef]
27. Evogene Ltd. Evofuel and Fantini s.r.l Announce Breakthrough in Mechanical Harvesting for Castor Bean. 2018. Available online: https://www.globenewswire.com/news-release/2018/10/29/1638116/32507/en/Evofuel-and-Fantini-s-r-l-Announce-Breakthrough-in-Mechanical-Harvesting-for-Castor-Bean.html (accessed on 25 October 2021).
28. Goneli, A.L.D.; Corrêa, P.C.; Oliveira, A.P.L.R.; Filho, C.P.H.; Oba, G.C. Castor beans quality subjected to different storage temperatures and periods. *Eng. Agric.* **2018**, *38*, 361–368. [CrossRef]
29. Pari, L.; Assirelli, A.; Suardi, A.; Civitarese, V.; Del Giudice, A.; Costa, C.; Santangelo, E. The harvest of oilseed rape (Brassica napus L.): The effective yield losses at on-farm scale in the Italian area. *Biomass Bioenergy* **2012**, *46*, 453–458. [CrossRef]
30. Latterini, F.; Stefanoni, W.; Sebastiano, S.; Baldi, G.M.; Pari, L. Evaluating the suitability of a combine harvester equipped with the sunflower header to harvest cardoon seeds: A case study in central Italy. *Agronomy* **2020**, *10*, 1981. [CrossRef]
31. Stefanoni, W.; Latterini, F.; Ruiz, J.P.; Bergonzoli, S.; Attolico, C.; Pari, L. Mechanical harvesting of camelina: Work productivity, costs and seed loss evaluation. *Energies* **2020**, *13*, 5329. [CrossRef]
32. Stefanoni, W.; Latterini, F.; Ruiz, J.P.; Bergonzoli, S.; Palmieri, N.; Pari, L. 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. *Sustainability* **2021**, *13*, 195. [CrossRef]

energies

Communication

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

Citation: Stefanoni, W.; Latterini, F.; Malkogiannidis, V.; Salpiggidis, V.; Alexopoulou, E.; Pari, L. Mechanical Harvesting of Castor Bean (*Ricinus communis* L.) with a Combine Harvester Equipped with Two Different Headers: A Comparison of Working Performance. *Energies* **2022**, *15*, 2999. https://doi.org/10.3390/en15092999

Academic Editors: Fernando Rubiera González and Alok Kumar Patel

Received: 11 March 2022
Accepted: 19 April 2022
Published: 20 April 2022

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.

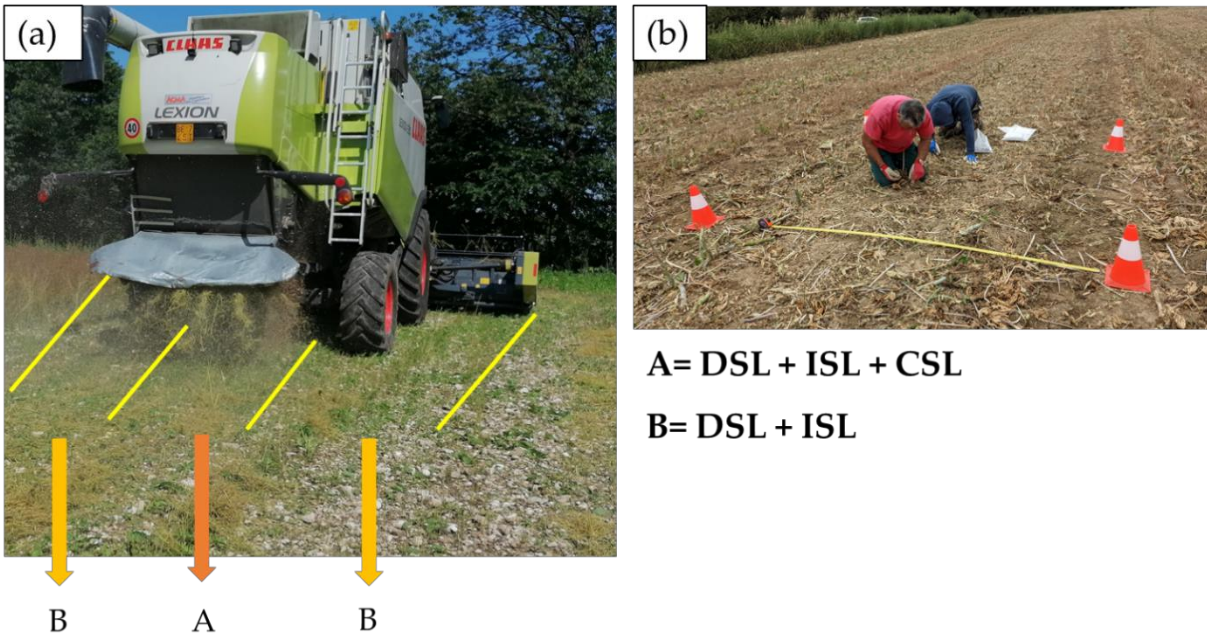

Figure 3. (**a**) Identification of the different zones behind the machinery, image from Stefanoni et al. [25]. (**b**) Sample plot to determine ISL and CSL.

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.

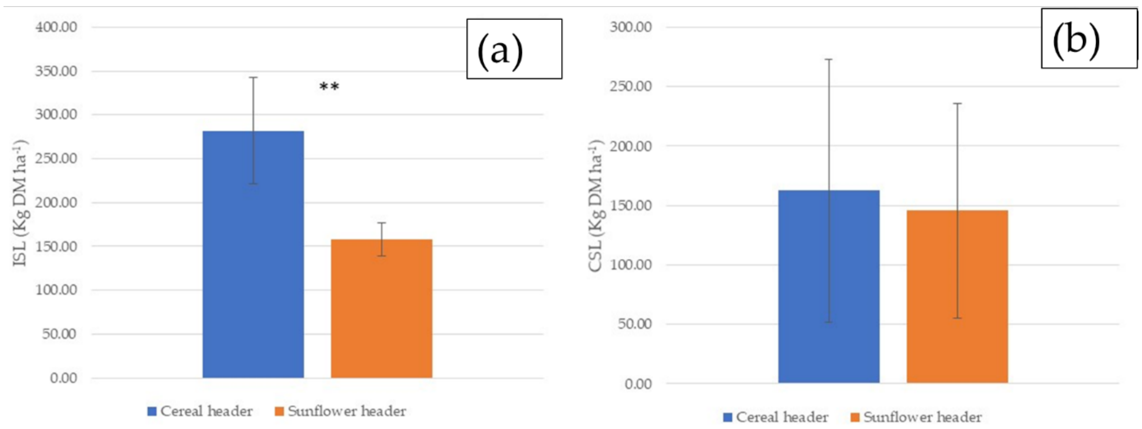

Figure 4. (**a**) Comparison of ISL between the two headers. (**b**) Comparison of CSL between the two headers. "**" indicates statistically significant differences at 0.01% according to *t*-test.

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.

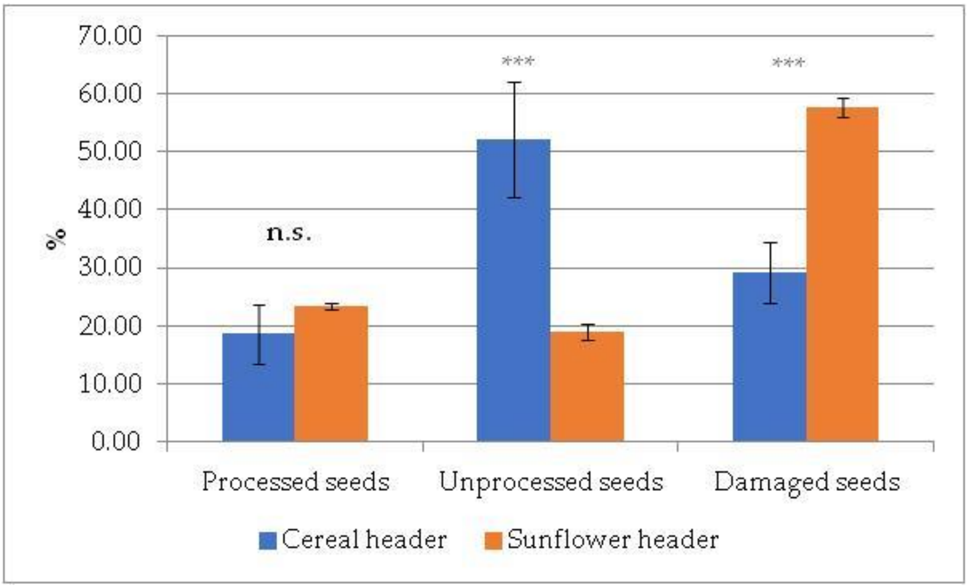

Figure 5. Percentage share of correctly processed seeds, unprocessed seeds, and damaged seeds for both treatments. "***" indicates statistically significant difference at $p < 0.001$ according to *t*-test. "n.s." indicates no significant difference between the treatments according to *t*-test.

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.

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

Funding: The work was performed in the framework of the European project "BeCool" (grant agreement No. 744821). The BeCool project is financed by the EU H2020 programme. This research was also funded by ERANETMED 2017 "EURO-MEDITERRANEAN—Cooperation through ERANET joint activities and beyond—Joint Transnational Call 2017—Fostering sustainable water management for the economic growth and sustainability of the Mediterranean region". MediOpuntia Project. Decreto Direttoriale n. 230 del 12/02/2019 e pubblicato in GU. il 12/04/2019 con n. 87.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available from corresponding author.

Acknowledgments: The authors would like to thank Sandu Lazar and all the staff of Bios Agrosystem for the valuable help provided in the organization and the conduction of both field and lab activities.

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

References

1. European Commission. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Closing the Loop—An EU Action Plan for the Circular Economy*; COM/2015/0614; European Commission: Bruxelles, Belgium, 2015.
2. Janiszewska, D.; Olchowski, R.; Nowicka, A.; Zborowska, M.; Marszałkiewicz, K.; Shams, M.; Giannakoudakis, D.A.; Anastopoulos, I.; Barczak, M. Activated biochars derived from wood biomass liquefaction residues for effective removal of hazardous hexavalent chromium from aquatic environments. *GCB Bioenergy* **2021**, *13*, 1247–1259. [CrossRef]
3. Wydra, S.; Hüsing, B.; Köhler, J.; Schwarz, A.; Schirrmeister, E.; Voglhuber-Slavinsky, A. Transition to the bioeconomy—Analysis and scenarios for selected niches. *J. Clean. Prod.* **2021**, *294*, 126092. [CrossRef]
4. Park, K.; Sanjaya, S.A.; Quach, T.; Cahoon, E.B. Toward sustainable production of value-added bioenergy and industrial oils in oilseed and biomass feedstocks. *GCB Bioenergy* **2021**, *13*, 1610–1623. [CrossRef]
5. Román-Figueroa, C.; Cea, M.; Paneque, M.; González, M.E. Oil Content and Fatty Acid Composition in Castor Bean Naturalized Accessions under Mediterranean Conditions in Chile. *Agronomy* **2020**, *10*, 1145. [CrossRef]
6. Gelfand, I.; Sahajpal, R.; Zhang, X.; Izaurralde, R.C.; Gross, K.L.; Robertson, G.P. Sustainable bioenergy production from marginal lands in the US Midwest. *Nature* **2013**, *493*, 514–517. [CrossRef] [PubMed]
7. D'Avino, L.; Di Bene, C.; Farina, R.; Razza, F. Introduction of Cardoon (*Cynara cardunculus* L.) in a Rainfed Rotation to Improve Soil Organic Carbon Stock in Marginal Lands. *Agronomy* **2020**, *10*, 946. [CrossRef]
8. Von Cossel, M.; Lewandowski, I.; Elbersen, B.; Staritsky, I.; Van Eupen, M.; Iqbal, Y.; Mantel, S.; Scordia, D.; Testa, G.; Cosentino, S.L.; et al. Marginal Agricultural Land Low-Input Systems for Biomass Production. *Energies* **2019**, *12*, 3123. [CrossRef]
9. Zanetti, F.; Monti, A.; Berti, M.T. Challenges and opportunities for new industrial oilseed crops in EU-27: A review. *Ind. Crops Prod.* **2013**, *50*, 580–595. [CrossRef]
10. Alexopoulou, E.; Papatheohari, Y.; Zanetti, F.; Tsiotas, K.; Papamichael, I.; Christou, M.; Namatov, I.; Monti, A. Comparative studies on several castor (*Ricinus communis* L.) hybrids: Growth, yields, seed oil and biomass characterization. *Ind. Crops Prod.* **2015**, *75*, 8–13. [CrossRef]

11. Carrino, L.; Visconti, D.; Fiorentino, N.; Fagnano, M. Biofuel Production with Castor Bean: A Win–Win Strategy for Marginal Land. *Agronomy* **2020**, *10*, 1690. [CrossRef]
12. Bateni, H.; Karimi, K. Biodiesel production from castor plant integrating ethanol production via a biorefinery approach. *Chem. Eng. Res. Des.* **2016**, *107*, 4–12. [CrossRef]
13. Ogunniyi, D.S. Castor oil: A vital industrial raw material. *Bioresour. Technol.* **2006**, *97*, 1086–1091. [CrossRef]
14. Pędzik, M.; Janiszewska, D.; Rogoziński, T. Alternative lignocellulosic raw materials in particleboard production: A review. *Ind. Crops Prod.* **2021**, *174*, 114162. [CrossRef]
15. Singh, A.K. Castor oil-based lubricant reduces smoke emission in two-stroke engines. *Ind. Crops Prod.* **2011**, *33*, 287–295. [CrossRef]
16. Anjani, K. Castor genetic resources: A primary gene pool for exploitation. *Ind. Crops Prod.* **2012**, *35*, 1–14. [CrossRef]
17. Vallejos, M.; Rondanini, D.; Wassner, D.F. Water relationships of castor bean (*Ricinus communis* L.) seeds related to final seed dry weight and physiological maturity. *Eur. J. Agron.* **2011**, *35*, 93–101. [CrossRef]
18. Koutroubas, S.D.; Papakosta, D.K.; Doitsinis, A. Adaptation and yielding ability of castor plant (*Ricinus communis* L.) genotypes in a Mediterranean climate. *Eur. J. Agron.* **1999**, *11*, 227–237. [CrossRef]
19. Polito, L.; Bortolotti, M.; Battelli, M.G.; Calafato, G.; Bolognesi, A. Ricin: An ancient story for a timeless plant toxin. *Toxins* **2019**, *11*, 324. [CrossRef]
20. Baldanzi, M.; Myczkowski, M.L.; Salvini, M.; Macchia, M. Description of 90 inbred lines of castor plant (*Ricinus communis* L.). *Euphytica* **2015**, *202*, 13–33. [CrossRef]
21. Chan, A.P.; Crabtree, J.; Zhao, Q.; Lorenzi, H.; Orvis, J.; Puiu, D.; Melake-Berhan, A.; Jones, K.M.; Redman, J.; Chen, G.; et al. Draft genome sequence of the oilseed species Ricinus communis. *Nat. Biotechnol.* **2010**, *28*, 951–956. [CrossRef] [PubMed]
22. Pari, L.; Latterini, F.; Stefanoni, W. Herbaceous Oil Crops, a Review on Mechanical Harvesting State of the Art. *Agriculture* **2020**, *10*, 309. [CrossRef]
23. Zhao, H.; Zhang, C.; Zhao, H. Analysis on The Research Status and Structure Characteristics of Castor Harvester. In Proceedings of the 2019 IEEE International Conference on Mechatronics and Automation (ICMA), Tianjin, China, 4–7 August 2019; pp. 415–420.
24. 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. [CrossRef]
25. Stefanoni, W.; Latterini, F.; Ruiz, J.P.; Bergonzoli, S.; Palmieri, N.; Pari, L. 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. *Sustainability* **2021**, *13*, 195. [CrossRef]
26. *STATISTICA (Data Analysis Software System)*, Version 7.0.; StatSoft, Inc.: Tulsa, OK, USA, 2007.
27. Zanetti, F.; Chieco, C.; Alexopoulou, E.; Vecchi, A.; Bertazza, G.; Monti, A. Comparison of new castor (*Ricinus communis* L.) genotypes in the mediterranean area and possible valorization of residual biomass for insect rearing. *Ind. Crops Prod.* **2017**, *107*, 581–587. [CrossRef]
28. Bewley, J.D.; Bradford, K.; Hilhorst, H.; Nogonaki, H. *Seeds: Physiology of Development, Germination and Dormancy*; Finch-Savage, B., Ed.; Springer Science & Business Media: New York, NY, USA; Berlin/Heidelberg, Germany; London, UK, 2012; ISBN 1461446929.
29. Mudryk, K.; Hutsol, T.; Wrobel, M.; Jewiarz, M.; Dziedzic, B. Determination of friction coefficients of fast-growing tree biomass. *Eng. Rural Dev.* **2019**, *18*, 1568–1573. [CrossRef]
30. Romuli, S.; Karaj, S.; Correa, C.R.; Kruse, A.; Müller, J. Physico-mechanical properties and thermal decomposition characteristics of pellets from *Jatropha curcas* L. *residues as affected by water addition. Biofuels* **2019**, *12*, 1–8. [CrossRef]
31. Drumond, A.A.L.; de Fátima Sales, J.; Zuchi, J.; Resende, O.; Camelo, G.N.; Souza, M.M.V. Physiological quality of castor bean seed genotypes stored at two temperatures. *Acta Sci. Agron.* **2019**, *42*, 1–10. [CrossRef]
32. Liu, R.K.; Cheng, X.X.; Xiao, Z.H.; Li, C.Z.; Huang, Z.H.; Ye, H.Q. Finite element simulation on mechanical property of castor capsule during husking. *J. Chin. Cereals Oils Assoc.* **2015**, *30*, 62–66.
33. Yeboah, A.; Ying, S.; Lu, J.; Xie, Y.; Amoanimaa-Dede, H.; Boateng, K.G.A.; Chen, M.; Yin, X. Castor oil (*Ricinus communis*): A review on the chemical composition and physicochemical properties. *Food Sci. Technol.* **2021**, *41*, 399–413. [CrossRef]
34. Stefanoni, W.; Latterini, F.; Ruiz, J.P.; Bergonzoli, S.; Attolico, C.; Pari, L. Mechanical Harvesting of Camelina: Work Productivity, Costs and Seed Loss Evaluation. *Energies* **2020**, *13*, 5329. [CrossRef]

forests

Communication

Assessment of Working Performance and Costs of Two Small-Scale Harvesting Systems for Medium Rotation Poplar Plantations

Francesco Latterini, Walter Stefanoni *, Vincenzo Alfano, Nadia Palmieri, Paolo Mattei and Luigi Pari

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.); vincenzo.alfano@crea.gov.it (V.A.); nadia.palmieri@crea.gov.it (N.P.); paolo.mattei@crea.gov.it (P.M.); luigi.pari@crea.gov.it (L.P.)
* Correspondence: walter.stefanoni@crea.gov.it

Abstract: Considering the increasing need to produce energy from renewable sources, the interest towards Medium Rotation Coppices (MRC) plantations has increased. One of the main issues that require tackling for the comprehensive sustainability of these plantations is related to the development of sustainable harvesting systems. Indeed, as a consequence of the average tree diameters at a breast height (dbh) of about 15 cm, single-pass harvesting typical of short rotation coppice is not applicable. Therefore, these plantations are generally harvested with machinery specifically developed for forest operations, as for instance harvesters, feller-bunchers and forwarders. In the Mediterranean area, the availability of such machines is still limited to a few big forest enterprises. Indeed, the majority of forest contractors carry out their activities in the framework of small-scale forestry, without the financial possibility of purchasing expensive machineries. Thus, the present study had the objective to evaluate the performance of two small-scale harvesting systems in a 7-year-old poplar plantation in Central Italy. The difference between the two systems was the different machinery applied for wood extraction, i.e., a forestry-fitted farm tractor equipped with winch (WINCH) and a fork lift prototype, attached to a crawler tractor (CFL). Extraction via CFL system reached very high working performance with about 21.5 m^3 SMH^{-1} (Scheduled Machine Hours, including delays), comparable to the productivities reported in the literature for forwarders working in similar plantations. Harvesting costs with CFL were 24.74 EUR m^{-3}, of which 4.48 EUR m^{-3} was for felling with chainsaw, 4.61 EUR m^{-3} for extraction with CFL prototype and 15.64 EUR m^{-3} for wood chipping. WINCH showed unsatisfactory results instead, possessing a wood chip production cost of 41.95 EUR m^{-3}, which is practically equivalent to the market price of wood chips.

Keywords: work productivity; harvesting costs; sustainable forest operations; whole tree harvesting

Citation: Latterini, F.; Stefanoni, W.; Alfano, V.; Palmieri, N.; Mattei, P.; Pari, L. Assessment of Working Performance and Costs of Two Small-Scale Harvesting Systems for Medium Rotation Poplar Plantations. *Forests* **2022**, *13*, 569. https://doi.org/10.3390/f13040569

Academic Editors: Andrea Laschi, Dalia Abbas and Piotr S. Mederski

Received: 21 March 2022
Accepted: 1 April 2022
Published: 2 April 2022

1. Introduction

Enhancing the supply of renewable energy is fundamental in order to meet the expected increase in global energy demand in the following years, as well as fighting climate change through the reduction in pollutants [1–4].

In this framework, lignocellulosic biomass has been considered as a promising renewable and sustainable source of energy, considering its neutral or even negative carbon budget [5–8].

Moreover, in the frame of the growing development of the bioeconomy sector, the demand for lignocellulosic biomass has been increasing for different industrial purposes: for instance, building materials, wood pulp, wood-based panels and other biomaterials [9–11].

Fast growing woody plantations are of particular interest in this context, being able to supply the woody biomass that traditional agroforestry systems cannot provide [5,12]. Fast growing plantations consist of woody cultivation, characterised by a high planting density of fast-growing species, such as poplar (*Populus* spp.), willow (*Salix* spp.) and eucalyptus (*Eucalyptus* spp.) capable of sprouting from the stump after being cut and which can provide high biomass yield in short periods of time (usually less than 7 years).

According to the harvesting cycle and plantation scheme, it is possible to distinguish between Short Rotation Coppice (SRC), where plants are harvested at 2–3-year intervals reaching an average diameter of 5–8 cm at cut levels with a planting density of 6000–7000 plants ha^{-1}; and Medium Rotation Coppice (MRC), with a harvesting cycle up to 5–7 years, a planting density of 1000–1500 plants ha^{-1} and trees with a diameter in the range of 15–20 cm at harvesting [13].

In recent years, there has been a growing interest in MRC cropping system. This is due to the higher biomass yield achievable by extending the harvesting age, along with a better biofuel quality given by a reduced bark/fiber ratio [13,14].

The length of the harvesting cycle influences the harvesting system, the level and type of mechanisation and its costs. In fact, harvesting is the part of the cropping cycle which shows the highest cost, and the amount of costs is largely affected by the level of mechanisation [9,15].

In SRC, it is possible to use a high productivity-modified forage harvester that performs cutting and chipping in a single pass. In MRC, due to the larger size of stems, it is instead necessary to use double passage biomass collection. Generally, these forms of plantations are harvested with machineries usually applied in forest utilisation, such as feller-bunchers, skidders and forwarders [16].

In MRC harvesting, partially to fully mechanised levels of mechanisation, they can be adopted for tree cutting and extraction to the landing area, with varying work productivity and related costs.

In semi-mechanised systems, felling is performed manually with a chainsaw while extraction is performed with forestry-fitted farm tractors, skidders or forwarders. In fully mechanised harvesting, in addition to dedicated logging machines, feller-bunchers (shear, disc saw or chainsaw head) are used [16].

To reach higher working performances, fully mechanised systems should be adopted, even if these systems rely on expensive machinery [17]. However, in the Mediterranean area, the availability of such machines is still limited to a few large forest enterprises. Thus, the growing demand from woody processing industry and bioenergy plants for good quality lignocellulosic biomass makes it crucial to look for alternative solutions that may guarantee high levels of productivity by using simple and inexpensive machinery, which is attractive to small-scale operators with limited capital availability [18].

Thus, the objective of the present short communication was to carry out a preliminary evaluation of the performance of two small-scale harvesting systems in a 7-year poplar plantation in Central Italy. In addition to estimating the cost of the full harvesting systems (felling + extraction + wood chipping), a particular focus was placed on extraction operation, comparing the performance of a forestry-fitted farm tractor equipped with a winch (WINCH) and a fork lift prototype attached to a crawler tractor (CFL).

The research hypothesis behind the experimental design was as follows: in the common situation of poplar plantations in flat terrains with sufficient manoeuvre space, CFL performs similarly to machineries that are much more expensive, similarly to forwarders and grapple skidders. A lower productivity is instead expected for forestry-fitted farm tractors equipped with a winch.

The novel aspect of the study consists of investigating the performance of a prototype, which has never been evaluated in the current literature.

2. Materials and Methods

2.1. Study Area and Dendrometric Characteristic of the Plant

The study area was located in Monterotondo Municipality (Latium, Italy), and it consisted of an experimental poplar (clone AF-8) plant with an overall area of 0.42 ha (Coordinates in WGS84UTM33T 303994 E; 4663859 N). Terrain has a plain morphology and no roughness.

The plantation was 7 years old and the intervention carried out represented the first harvest; therefore, the plants showed a single-stem structure.

Planting density was 1666 N ha^{-1} (2 m on the row and 3 m between rows). Average diameter at breast height (dbh) was 13 cm, and the average height was 13.2 m, resulting in an average plant volume of 0.08 m^3 according to the national allometric equations developed for poplar. Average wood density was derived by cutting 15 wood samples from different trees after felling, measuring their top diameter and base diameter with a caliper and length with a measure tape to determine volume, then weighing each sample with a precision scale. Derived fresh wood density was 0.869 Mg FM (fresh matter) m^{-3}. A further 15 wood samples were taken from the same trees for wood moisture assessment via oven drying at 105 °C until constant weight. Average wood moisture was 54.05%; therefore, the dry wood density resulted in 0.399 Mg DM (dry matter) m^{-3}. Therefore, the average whole tree weight was 0.070 Mg FM and 0.032 Mg DM. The resulting biomass yield was 108.132 m^3 ha^{-1}, corresponding to 93.975 Mg FM ha^{-1} and 43.178 Mg DM ha^{-1}.

2.2. Experimental Design and Machineries Involved

The plantation consisted of 14 rows prior to starting the working time evaluations, and the two external rows were removed in order to avoid edge effects. The same applied to the first and the last plant of the remaining 12 rows. Randomly, 6 rows were subsequently extracted with a forestry-fitted farm tractor equipped with winch (WINCH) and 6 rows with the crawler fork lift prototype (CFL). The two experimental treatments differed for extraction system, while felling and chipping were carried out with the same machineries. The felling operation was performed by a single operator using a Stihl 201TX chainsaw (Waiblingen, Germany). Single trees were directionally felled perpendicularly to the rows' direction. WINCH extraction was carried out with a 60 kW Landini tractor (Fabbrico, Italy) equipped with a Schwarz Tajfun kN 45 forest winch (Frangarto, Italy). The tractor did not enter directly into the stand, but it stood at the limit of the plantation winching trees outside the field, thus limiting the possibility of triggering substantial disturbance to soil and stumps. Considering that the dimension of the plantation winching distance ranged from 10 to 100 m, CFL extraction was performed with a Fiat 80C crawler tractor (Torino, Italy) equipped with the fork lift prototype. This consisted of a fork lift attached at the front loader of the tractor. The fork lift was equipped with a metal structure attached to a hydraulic piston in order to facilitate unloading harvested trees.

Extraction via CFL was carried out by felling half a row with the trees perpendicular to the row's direction. The crawler tractor then moved towards the trees, loading them or simply pushing them outside the field. The extraction distance was, therefore, 50 m (half of the length of a row). A vision of CFL is provided in Figure 1.

Chipping operations were performed with a Farmi forest chipper CH260 (Iisalmi, Finland) powered by a 104 kW Landini tractor (Fabbrico, Italy), discharging the material into a trailer attached to the mentioned above 60 kW Landini tractor (Fabbrico, Italy).

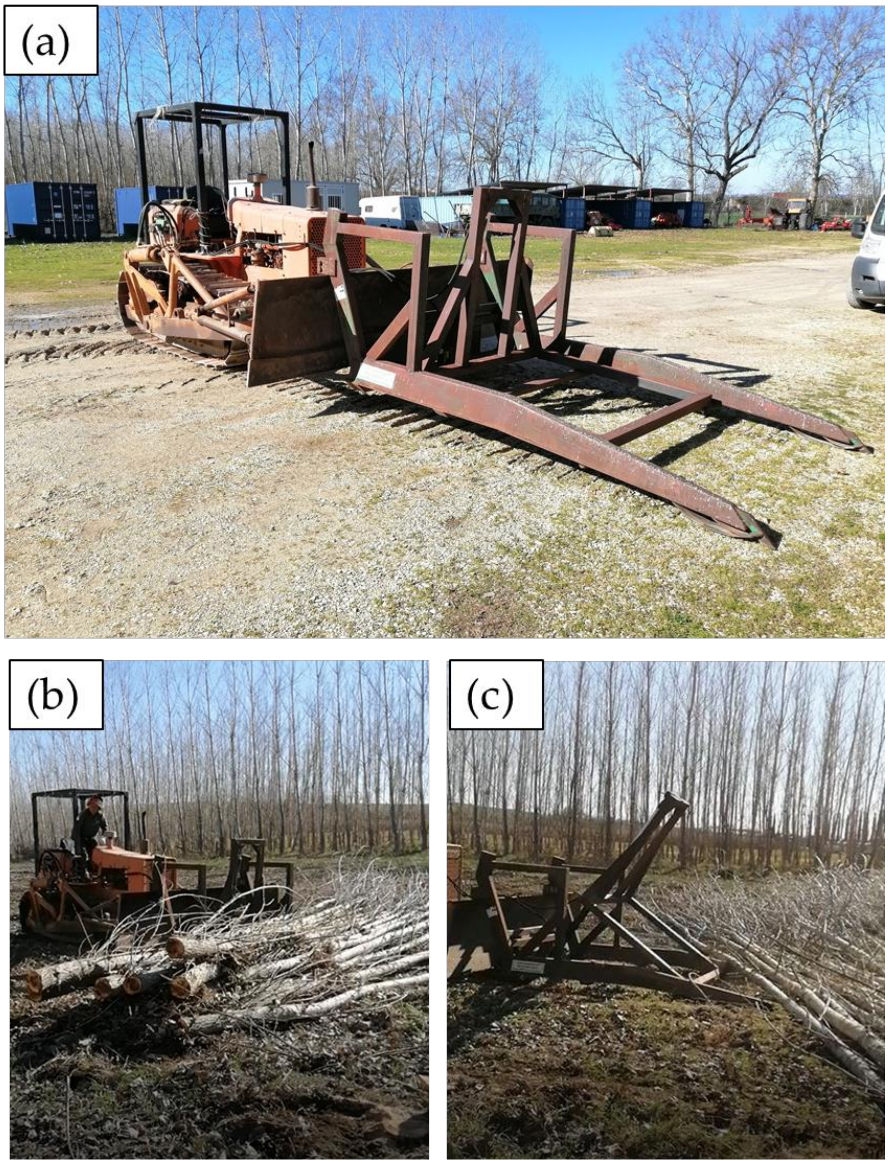

Figure 1. (**a**) Vision of CFL. (**b**) CFL while loading trees. (**c**) CFL while unloading trees.

2.3. Work Productivity and Costs Evaluation

The experimental field was subdivided into 12 blocks of 300 m^2 each, corresponding to the various rows. Each block corresponded to about 45 trees. The dbh of all the plants in each block was measured and recorded, while a height-to-diameter equation was developed using 45 sample trees (felled and measured in height with a measuring tape). Each plant was subsequently identified with paint mark. Half of the blocks were randomly assigned to WINCH, while the others were assigned to CFL. The working cycles analysed for work productivity evaluation were as follows: 10 plants for felling, one block for extraction and the single tree for chipping. The time to carry out each working cycle was measured and recorded with a handheld chronometer with an accuracy of 1/100 min, separating work time from delay time [19]. Since delay time is typically erratic and there is a high possibility that a short-term study performed on small study areas can fail to represent the actual incidence of delay time in the long-term perspective, a 20% delay factor, revealed by long-term studies, was added to extraction and chipping working times [20], as suggested by several previous research studies on a similar topic [17,18,21].

This value for the delay factor was selected in order to represent the favorable work conditions constituted by a rational plantation in flat terrain, close to all maintenance and repair facilities [18,21].

A 40% delay factor was adopted for motor-manual felling via chainsaw, considering the need of recuperation as a consequence of the heavy physiological workload [22].

Knowing working times and the volume of the trees in each working cycle, it was possible to derive the net work productivity measured in m^3 PMH^{-1} (productive machine hour, calculated not accounting for delay) and gross productivity measured in m^3 SMH^{-1} (scheduled machine hour, calculated accounting for delay). The presence of statistically significant differences between the working productivity in extraction operation with WINCH and CFL was investigated by using an unpaired sample *t*-test, after checking for normality and homoscedasticity of the data, respectively, with Shapiro–Wilk and Levene's tests.

Machine costs were estimated by applying the Harmonized European Costing Model developed within EU COST Action FP0902 [23]. Costing assumptions were obtained from previously conducted interviews from local forest enterprises. Calculated scheduled machine hour (SMH) costs and component for cost calculations are provided in Table 1.

Table 1. Components of cost calculations for the machines. SMH refers to scheduled machine hour, inclusive of delays.

Cost Component	Unit	Chainsaw	Tractor for Winch and Trailer	Winch	Crawler Tractor	Fork Lift Prototype	Tractor for Chipper	Chipper
Investment price	EUR	1000	59,071.00	6000.00	55,717.00	6000.00	122,020.00	20,000.00
Salvage value	EUR	0.00	17,448.64	1131.78	16,457.92	1131.78	36,042.77	2954.81
Service life	Years	4	10	10	10	10	10	12
Annual use	SMH	500	1000	1000	150	150	1000	1000
Operator wage	EUR SMH^{-1}	16.00	16.00	16.00	16.00	0.00	16.00	0.00
Interest	%	4	8	8	8	8	8	8
Depreciation	EUR $year^{-1}$	250.00	4162.24	486.82	3925.91	486.82	8597.72	1420.43
Interest	EUR $year^{-1}$	20.00	3060.79	285.27	2887.00	285.27	6322.51	918.19
Insurance	EUR $year^{-1}$	2.50	147.78	15.00	139.29	15.00	305.05	50.00
Maintenance	EUR $year^{-1}$	200.00	4730.00	480.00	51.00	270.00	9760.00	1330.00
Fuel and lubricant	EUR $year^{-1}$	1660.00	6200.00	0.00	1914.00	0.00	13,610.00	0.00
Personnel	EUR $year^{-1}$	8000.00	16,000.00	16,000.00	2400.00	0.00	16,000.00	0.00
Overhead and profit	%	20	20	20	20	20	20	20
Overhead and profit	EUR $year^{-1}$	2026.15	6863.73	3453.82	2268.23	215.02	10,923.78	745.99
Total	EUR $year^{-1}$	12,156.90	41,180.00	20,720.00	13,609.38	1290.11	65,542.10	4475.95
Total	EUR SMH^{-1}	24.31	41.18	20.72	90.73	8.60	65.54	4.48

3. Results and Discussion

The obtained values of working productivity for felling operations, including delays, are provided in Table 2. The results were only slightly lower than the findings of Spinelli et al. 2011, i.e., 6.3 m^3 SMH^{-1} [24], and Tavankar et al. 2020, i.e., 7.101 m^3 SMH^{-1} [25], notwithstanding the smaller dbh of the trees in the present study (average dbh 13 cm vs. 32–38 cm). Tree size is generally positively related to work productivity, i.e., the higher the average tree volume, the higher the productivity [16,26,27], but the application of entire tree harvesting system, therefore avoiding delimbing and bucking, allowed obtaining comparable values of productivity [28].

Table 2. Productivity SMH (including delays) of felling operation.

	AVG	ST.DEV
m^3 SMH^{-1}	5.43	1.46
Mg FM SMH^{-1}	4.72	1.27
Mg DM SMH^{-1}	1.88	0.51

The share of working times (without considering delays) for the two different investigated extraction systems is provided in Figure 2. As it is possible to notice, for CFL, there were only two working phases: travel loaded (including loading and unloading of trees), which accounted for more than 60% of total net time; and travel unloaded, which corresponded to about 40%. Regarding WINCH, the share of working times is more complex, referring to four different phases, of which the one that accounted for the major percentage of working times was winching.

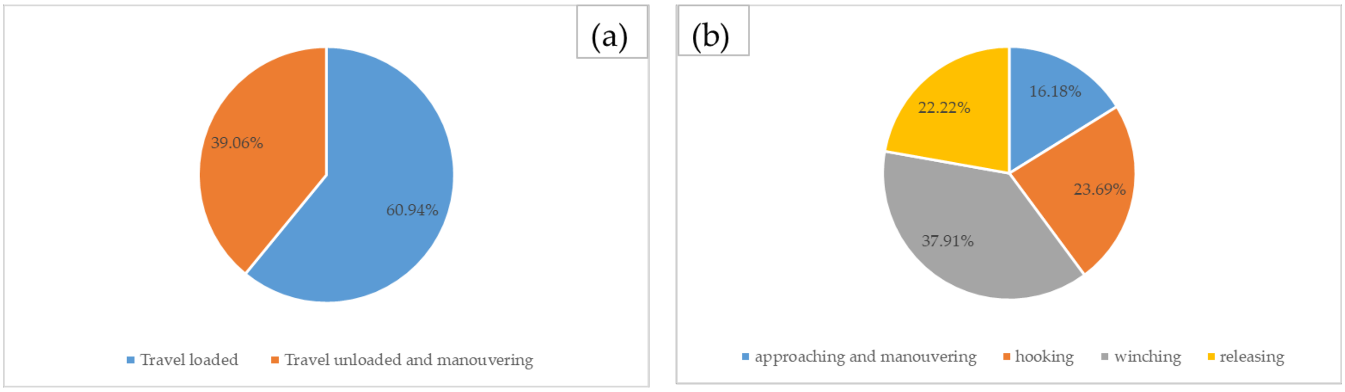

Figure 2. Share of working time without considering delays for CFL (**a**) and WINCH (**b**).

The results of working performance for the two investigated extraction systems are reported in Table 3. As it is possible to notice, CFL performed much better than WINCH. A forestry-fitted farm tractor equipped with a winch revealed, therefore, to not be a valid option for extracting timber from this kind of stand, characterised by low tree dimensions, showing unsatisfactory productivity. Winching is, however, a suitable solution for poplar plants but only dealing with plantations dedicated to high value timber, where the average tree dimension is substantially higher [25]. Furthermore, the application of machineries specifically dedicated to forest operations is recommended, replacing forestry-fitted farm tractors with skidders. A cable skidder in a poplar plantation for high-value timber production in Northern Italy achieved a productivity of 28.846 m^3 h^{-1} [25], while grapple skidder productivity was 20.7 Mg FM SMH^{-1} in a plantation with an average dbh of 15 cm and mean height of 16.5 m [18].

On the other hand, CFL showed very interesting results, with performances that are in line with those of much more expensive extraction machineries, thus confirming the research hypothesis. Magagnotti et al. reported a productivity of 24 m^3 h^{-1} SMH for a forwarder working in very similar conditions to the ones of the present study, with the same planting density and average tree dimensions [21]. In another similar plantation, a second-hand forwarder reached a productivity value ranging from 7.8 to 11.2 Mg FM SMH^{-1} [17], which is, therefore, even lower than what was revealed for CFL. However, in this last case, the landing was located at a distance between 400 and 700 m from the harvesting site [17], obviously leading to increased working time in comparison to the situation in the present trial, where there was not a proper landing but the trees were unloaded just outside the plantation.

Table 3. Work productivity SMH (including delays) for the two investigated extraction systems. "***" indicates statistically significant differences at $p > 0.001$ between the mean values of the treatments.

	CFL		WINCH		Significance
	Avg.	**St.Dev**	**Avg.**	**St.Dev**	
m^3 SMH^{-1}	21.524	3.839	2.836	0.728	***
Mg FM SMH^{-1}	18.706	3.337	2.465	0.633	***
Mg DM SMH^{-1}	8.595	1.533	1.132	0.291	***

Work productivity for the chipping operation is shown in Table 4. The results were in line with those reported in the current literature for the wood chipper of limited dimension, such as the tested Farmi Forest CH260 [29].

Table 4. Work productivity SMH (including delays) for chipping operation.

	Avg.	St.Dev
m^3 SMH^{-1}	4.477	1.057
Mg FM SMH^{-1}	3.891	0.919
Mg DM SMH^{-1}	1.787	0.422

The results of cost analysis for producing wood chips with the investigated harvesting systems are provided in Figure 3. The substantial difference in extraction productivity between the two systems led to a much lower cost for CFL in comparison to WINCH. Cost for extraction with CFL was indeed 4.61 EUR m^{-3}, while in WINCH, the cost was 21.83 EUR m^{-3}.

The combined cost for felling and extraction in CFL was 9.10 EUR m^{-3} (10.46 EUR MG FM^{-1} and 22.77 EUR Mg DM^{-1}), in line with 9.1–9.4 EUR m^{-3} reported for a system based on the harvester and forwarder [21] and slightly lower than the value of 8.0 EUR Mg FM^{-1} revealed for a system based on the feller buncher and grapple skidder [18]. In CFL, harvesting the chipping operation had the highest cost; therefore, a possible improvement of the system could be the adoption of a larger wood chipper that is able to guarantee higher performance [30]. A shift to mechanised felling with the application of a feller-buncher could also be as well a suitable option to further reduce harvesting costs.

The application of the WINCH harvesting system was, instead, not economically sustainable as the cost of wood chips production was very close to the market value of wood chips in the zone, i.e., 50.00 EUR Mg FM^{-1} [31–33].

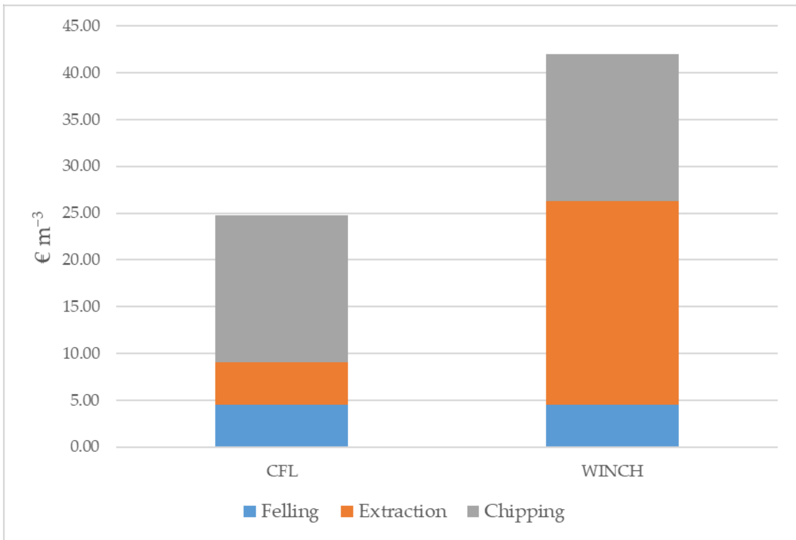

Figure 3. Costs of the two investigated harvesting systems.

In summary, CFL was revealed to be a very interesting solution in harvesting medium rotation poplar plantations in the framework of small-scale forestry. The obtained productivity and costs are in line with those reported in the literature for other harvesting systems, based on much more expensive machineries such as forwarders. It is, however, worth highlighting some limitations of CFL system. Firstly, the crawler tractor equipped with the fork lift prototype allows only unidirectional movement. Thus, it is applicable in fields where there is enough space to accumulate trees in the headland that do not constitute a real landing site, a situation of which is, however, common in poplar plantations. If the trees have to be accumulated on a dedicated site outside the plantation, CFL is not applicable. Furthermore, a lower wood chip quality in comparison to the one obtained from material extracted via forwarding is expected. This is related to the fact that trees are extracted touching the terrain, with the possibility of ground particles remaining attached to the stems resulting in increased ash content during combustion. This aspect has to be, however, evaluated in further dedicated studies.

4. Conclusions

Medium rotation coppices represent an interesting source of renewable energy and good quality lignocellulosic biomass for other industrial purposes. However, this kind of plantation requires particular attention to be paid to harvesting operations. Indeed, as a consequence of the dimension reached from the trees, single-pass harvesting typical of short rotation coppice is not a suitable option. Currently, these stands are harvested by relying on machineries specifically developed for forest operations such as harvesters, feller-bunchers and forwarders. In the context of Mediterranean forestry, particularly in Central and Southern Italy, the availability of such machines is still limited. Indeed, the major part of forest contractors operates in the framework of small-scale forestry and do not possess financial ability of purchasing expensive machineries. Taking this into account, the present study aimed to evaluate the performance of two small-scale harvesting systems in a 7-year poplar plantation. The investigated harvesting systems were based on motor-manual felling with a chainsaw and chipping via a stationary chipper. The difference between the systems consisted of the different machineries used for extraction operations, which were a forestry-fitted farm tractor equipped with a winch (WINCH) and a fork lift prototype attached to a crawler tractor (CFL).

The obtained results revealed the unsuitability of the WINCH system in the study context. On the other hand, CFL reached very satisfactory working performance, comparable to those reported in the literature for harvesting systems based on much more expensive machines. Therefore, CFL represents a very interesting harvesting system for these plantations; in this case, there is no need to shift the trees to a landing site, but it is possible to accumulate the trees in the headland before chipping.

Author Contributions: F.L.: Conceptualisation, methodology, formal analysis, investigation, writing—original draft, and writing—review and editing. W.S.: Conceptualisation, methodology, formal analysis, investigation, writing—original draft, and writing—review and editing. V.A.: Conceptualisation, methodology, investigation, writing—original draft, and writing—review and editing. N.P.: Formal analysis. P.M.: Methodology. L.P.: Supervision and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: The work was performed in the framework of the European project "BeCool" (grant agreement No. 744821). The BeCool project is financed by the EU H2020 programme.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Acknowledgments: The authors gratefully acknowledge Cesare Cervellini, Franco Bernardini, Gino Branetti, Sandu Lazar and Alberto Sestili for helpful collaboration during the harvesting operations.

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

References

1. European Union Renewable Energy Directive 2018/2001/EU. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN (accessed on 10 February 2020).
2. European Commission Communication from The Commission to The European Parliament, The Council, The European Economic And Social Committee and The Committee of The Regions Energy Roadmap 2050. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:5 (accessed on 10 February 2020).
3. Reinhardt, J.; Hilgert, P.; Von Cossel, M. A review of industrial crop yield performances on unfavorable soil types. *Agronomy* **2021**, *11*, 2382. https://doi.org/10.3390/agronomy11122382.
4. Reinhardt, J.; Hilgert, P.; Von Cossel, M. Yield performance of dedicated industrial crops on low-temperature characterized marginal agricultural land in Europe—A review. *Biofuels*, *Bioprod. Biorefining* **2022**, *16*, 609–622. https://doi.org/10.1002/bbb.2314.
5. Rodrigues, A.M.; Costa, M.M.G.; Nunes, L.J.R. Short rotation woody coppices for biomass production: An integrated analysis of the potential as an energy alternative. *Curr. Sustain. Energy Rep.* **2021**, *8*, 70–89.
6. Fuertes, A.; Oliveira, N.; Cañellas, I.; Sixto, H.; Rodríguez-Soalleiro, R. An economic overview of Populus spp. in Short Rotation Coppice systems under Mediterranean conditions: An assessment tool for decision-making. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111577. https://doi.org/10.1016/j.rser.2021.111577.
7. Sperandio, G.; Suardi, A.; Acampora, A.; Civitarese, V. Environmental Sustainability of Heat Produced by Poplar Short-Rotation Coppice (SRC) Woody Biomass. *Forests* **2021**, *12*, 878. https://doi.org/10.3390/f12070878.
8. Perdomo E., E.A.; Schwarzbauer, P.; Fürtner, D.; Hesser, F. Life Cycle Assessment of Agricultural Wood Production—Methodological Options: A Literature Review. *Bioenergy Res.* **2021**, *14*, 492–509. https://doi.org/10.1007/s12155-021-10266-4.
9. Eisenbies, M.H.; Volk, T.A.; DeSouza, D.; Hallen, K.; Stanton, B.; Espinoza, J.; Himes, A.; Shuren, R.; Stonex, R.; Summers, B.; et al. An assessment of the harvesting and fuel performance of a single-pass cut-and-chip harvester in commercial-scale short-rotation poplar crops as influenced by crop and weather conditions. *Biomass Bioenergy* **2021**, *149*, 106075. https://doi.org/10.1016/j.biombioe.2021.106075.
10. Fortier, J.; Truax, B.; Gagnon, D.; Lambert, F. Thinning and Gap Harvest Effects on Soil, Tree and Stand Characteristics in Hybrid Poplar Bioenergy Buffers on Farmland. *Forests* **2022**, *13*, 194. https://doi.org/10.3390/f13020194.
11. Olba-Zięty, E.; Stolarski, M.J.; Krzyżaniak, M. Economic Evaluation of the Production of Perennial Crops for Energy Purposes—A Review. *Energies* **2021**, *14*, 7147. https://doi.org/10.3390/en14217147.
12. Alesso, S.P.; Tapias, R.; Alaejos, J.; Fernández, M. Biomass Yield and Economic, Energy and Carbon Balances of Ulmus pumila L., Robinia pseudoacacia L. and Populus × euroamericana (Dode) Guinier Short-Rotation Coppices on Degraded Lands under Mediterranean Climate. *Forests* **2021**, *12*, 1337. https://doi.org/10.3390/f12101337.
13. Santangelo, E.; Scarfone, A.; Del Giudice, A.; Acampora, A.; Alfano, V.; Suardi, A.; Pari, L. Harvesting systems for poplar short rotation coppice. *Ind. Crops Prod.* **2015**, *75*, 85–92. https://doi.org/10.1016/j.indcrop.2015.07.013.
14. Saulino, L.; Allevato, E.; Rossi, S.; Minotta, G.; Fiorentino, N.; Saracino, A. Lengthening single-stem rotation improves biomass yield and water use efficiency in black poplar genotype multi-stem rotation coppice plantations. *Biomass Bioenergy* **2021**, *154*, 106256. https://doi.org/10.1016/j.biombioe.2021.106256.
15. Stanton, B.J.; Bourque, A.; Coleman, M.; Eisenbies, M.; Emerson, R.M.; Espinoza, J.; Gantz, C.; Himes, A.; Rodstrom, A.; Shuren, R.; et al. The practice and economics of hybrid poplar biomass production for biofuels and bioproducts in the Pacific Northwest. *Bioenergy Res.* **2021**, *14*, 543–560. https://doi.org/10.1007/s12155-020-10164-1.

16. Sperandio, G.; Acampora, A.; Del Giudice, A.; Civitarese, V. Models for the Evaluation of Productivity and Costs of Mechanized Felling on Poplar Short Rotation Coppice in Italy. *Forests* **2021**, *12*, 954. https://doi.org/10.3390/f12070954.
17. Spinelli, R.; Magagnotti, N.; Lombardini, C.; Mihelič, M. A Low-Investment Option for the Integrated Semi-mechanized Harvesting of Small-Scale, Short-Rotation Poplar Plantations. *Small-Scale For.* **2021**, *20*, 59–72. https://doi.org/10.1007/s11842-020-09456-3.
18. Spinelli, R.; Magagnotti, N.; Lombardini, C. Low-Investment Fully Mechanized Harvesting of Short-Rotation Poplar (populus spp.) Plantations. *Forests* **2020**, *11*, 502. https://doi.org/10.3390/f11050502.
19. Bjorheden, R.; Thompson, M.A. An international nomenclature for forest work study. In Proceedings of the IUFRO 1995, 20th World Congress, Tampere, Finland, 6–15 August 1995; pp. 190–215.
20. Spinelli, R.; Visser, R. Analyzing and Estimating Delays in Harvester Operations. *Int. J. For. Eng.* **2008**, *19*, 36–41. https://doi.org/10.1080/14942119.2008.10702558.
21. Magagnotti, N.; Spinelli, R.; Kärhä, K.; Mederski, P.S. Multi-tree cut-to-length harvesting of short-rotation poplar plantations. *Eur. J. For. Res.* **2021**, *140*, 345–354. https://doi.org/10.1007/s10342-020-01335-y.
22. Spinelli, R.; Magagnotti, N. Comparison of two harvesting systems for the production of forest biomass from the thinning of Picea abies plantations. *Scand. J. For. Res.* **2010**, *25*, 69–77.
23. Ackerman, P.; Belbo, H.; Eliasson, L.; de Jong, A.; Lazdins, A.; Lyons, J. The COST model for calculation of forest operations costs. *Int. J. For. Eng.* **2014**, *25*, 75–81. https://doi.org/10.1080/14942119.2014.903711.
24. Spinelli, R.; Magagnotti, N.; Sperandio, G.; Cielo, P.; Verani, S.; Zanuttini, R. Cost and productivity of harvesting high-value hybrid poplar plantations in Italy. *For. Prod. J.* **2011**, *61*, 64–70. https://doi.org/10.13073/0015-7473-61.1.64.
25. Tavankar, F.; Nikooy, M.; Latterini, F.; Venanzi, R.; Bianchini, L.; Picchio, R. The Effects of Soil Moisture on Harvesting Operations in Populus spp. Plantations: Specific Focus on Costs, Energy Balance and GHG Emissions. *Sustainability* **2021**, *13*, 4863. https://doi.org/10.3390/su13094863.
26. Marčeta, D.; Petković, V.; Ljubojević, D.; Potočnik, I. Harvesting system suitability as decision support in selection cutting forest management in northwest Bosnia and Herzegovina. *Croat. J. For. Eng.* **2020**, *41*, 251–265. https://doi.org/10.5552/crojfe.2020.744.
27. Francesco, L.; Stefanoni, W.; Venanzi, R.; Tocci, D.; Picchio, R. GIS-AHP approach in forest logging planning to apply sustainable forest operations. *Forests* **2022**, *13*, 484.
28. Carbone, F.; Picchio, R. Operative Machinery Costs Analysis within Forest Management Implementation Frame. In *Timber Buildings and Sustainability*; IntechOpen: London, UK, 2019; p. 32.
29. Spinelli, R.; Eliasson, L.; Magagnotti, N. Determining the repair and maintenance cost of wood chippers. *Biomass Bioenergy* **2019**, *122*, 202–210. https://doi.org/10.1016/j.biombioe.2019.01.024.
30. Laitila, J.; Prinz, R.; Sikanen, L. Selection of a chipper technology for small-scale operations—A Finnish case. *J. For. Sci.* **2019**, *65*, 121–133. https://doi.org/10.17221/26/2019-JFS.
31. Suardi, A.; Latterini, F.; Alfano, V.; Palmieri, N.; Bergonzoli, S.; Pari, L. Analysis of the Work Productivity and Costs of a Stationary Chipper Applied to the Harvesting of Olive Tree Pruning for Bio-Energy Production. *Energies* **2020**, *13*, 1359. https://doi.org/10.3390/en13061359.
32. Suardi, A.; Latterini, F.; Alfano, V.; Palmieri, N.; Bergonzoli, S.; Karampinis, E.; Kougioumtzis, M.A.; Grammelis, P.; Pari, L. Machine Performance and Hog Fuel Quality Evaluation in Olive Tree Pruning Harvesting Conducted Using a Towed Shredder on Flat and Hilly Fields. *Energies* **2020**, *13*, 1713. https://doi.org/10.3390/en13071713.
33. Latterini, F.; Stefanoni, W.; Suardi, A.; Alfano, V.; Bergonzoli, S.; Palmieri, N.; Pari, L. A GIS Approach to Locate a Small Size Biomass Plant Powered by Olive Pruning and to Estimate Supply Chain Costs. *Energies* **2020**, *13*, 3385. https://doi.org/10.3390/en13133385.

energies

Perspective

Perennial Grass Species for Bioenergy Production: The State of the Art in Mechanical Harvesting

Walter Stefanoni [1,*], Francesco Latterini [2] 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
[2] Institute of Dendrology, Polish Academy of Sciences, Parkowa 5, 62-035 Kórnik, Poland
* Correspondence: walter.stefanoni@crea.gov.it; Tel.: +39-069-067-5250

Abstract: Future European strategies to reduce dependence on foreign markets for energy supply and energy production will rely on the further exploitation of the primary sector. Lignocellulosic feedstock for bioenergy production is a valuable candidate, and dedicated crops such as giant reed (*Arundo donax* L.), miscanthus (*Miscanthus* × *giganteus*), reed canary grass (*Phalaris arundinacea* L.), and switchgrass (*Panicum virgatum* L.) have been proven to be suitable for extensive cultivation on marginal lands. The present review aimed at providing a comprehensive picture of the mechanical strategies available for harvesting giant reed, miscanthus, reed canary grass, and switchgrass that are suitable for the possible upscaling of their supply chain. Since harvesting is the most impactful phase of a lignocellulosic supply chain in dedicated crops, the associated performance and costs were taken into account in order to provide concrete observations and suggestions for future implementation. The findings of the present review highlighted that the investigated species have a sufficient technology readiness level concerning mechanical harvesting for the upscaling of their cultivation. All the species could indeed be harvested with existing machinery, mostly derived from the context of haymaking, without compromising the work productivity.

Keywords: *Arundo donax*; *Miscanthus* × *giganteus*; *Phalaris arundinacea*; *Panicum virgatum*; machine performance; supply chain

Citation: Stefanoni, W.; Latterini, F.; Pari, L. Perennial Grass Species for Bioenergy Production: The State of the Art in Mechanical Harvesting. *Energies* **2023**, *16*, 2303. https://doi.org/10.3390/en16052303

Academic Editor: Adam Smoliński

Received: 30 January 2023
Revised: 14 February 2023
Accepted: 25 February 2023
Published: 27 February 2023

1. Introduction

Climate action has become one of the priorities in Europe after the presentation of the new Green Deal policy programme in 2019. As a consequence of the new geopolitical challenges that the EU is facing nowadays, it is even more important for this continent to drive the energy transition and become independent from foreign markets as soon as possible. The overall energy consumption in the EU in 2020 amounted to 37,086 PJ, and 22.1% of this derived from renewable sources [1,2]. However, energy independence is the main goal of Europe, which currently imports 97 and 83.6% of its petrol and natural gas, respectively, for domestic consumption [2]. Nor is the European renewable energy sector completely independent from foreign markets, since, for instance, the majority of photovoltaic panels used in Europe are made in Asia, and uranium for nuclear energy is imported from foreign countries [3].

Therefore, during the last few years, Europe has experienced rising concerns regarding energy security, which have stimulated the adoption of future strategies aimed at reducing dependency on foreign energy supplies [4]. The domestic production of primary sources for bioenergy production is fundamental.

Agriculture could strongly contribute to European energy security by providing renewable energies from both dedicated energy crops and agricultural residues [5–11]. Dedicated energy crops can be subdivided into two main categories: oilseeds and lignocellulosic crops. Among the latter, perennial grasses have gained more and more interest over annual crops as a potential sustainable source of bioenergy in Europe [12]. Their high biomass yield is a favorable characteristic [13,14], but they have also been proven to grow and thrive on marginal lands, thus partially avoiding the competition with food crops while being cultivated, for instance, on polluted soils [15]. Furthermore, perennial grasses require less intensive management and lower agronomic inputs in comparison to annual crops, with subsequently lower environmental impacts in terms of nitrogen leaching and GHG emissions [16]. Finally, scientific research has highlighted how perennial grass cropping promotes greater biodiversity and related ecosystem services—for instance, major pollinator abundance and the greater storage of organic carbon in the soil [17,18]. Furthermore, the possibility of intercropping with other food or non-food crops may help to increase farmers' revenue, farm biodiversity, and the sustainability of agricultural systems.

On the other hand, the sustainable implementation of bioenergy production from perennial grasses still faces some major issues, mostly related to the high production costs, which are largely due to biomass harvesting and logistics [19].

Lignocellulosic feedstocks generally exhibit a low bulk density and high moisture content, two features that contribute to increasing both the supply chain's costs and potential losses during storage [20–22]. The harvesting strategy adopted may play a fundamental role in trying to address these issues.

The goal of the present review was to delineate the state of the art of the mechanical strategies currently adopted for harvesting the following perennial grasses: giant reed (*Arundo donax* L.), miscanthus (*Miscanthus* × *giganteus*), reed canary grass (*Phalaris arundinacea* L.), and switchgrass (*Panicum virgatum* L.). In this way, we wanted to test the following hypothesis: the technology readiness level concerning the mechanical harvesting of these four species is sufficient to allow the upscaling of their cultivation.

The authors aimed at selecting the perennial grass species most suitable for cultivation in Europe and which also allow for mechanical harvesting, in order to provide a clear picture of the possible upscaling of these crops.

2. Materials and Methods

A systematic literature review was carried out within the Google Scholar, Scopus, and Web of Science databases. No time restriction was applied, but only manuscripts in the English language were considered. The research keywords were the scientific and common names of the various species, linked via the Boolean operators "AND" or "OR" with other keywords such as "harvesting", "harvest", "swathing", "chopping", "shredding", "self-propelled forage harvester", "baler", "baling", "mower", "mowing".

After this operation, articles were refined by reading the title, abstract, and (when needed) the main text, in order to select only manuscripts dealing with the mechanical harvesting of the target crops, reporting the working performance and/or the costs of the investigated harvesting system. In this way, 35 papers were selected, and the percentage of papers for each investigated species is reported in Figure 1.

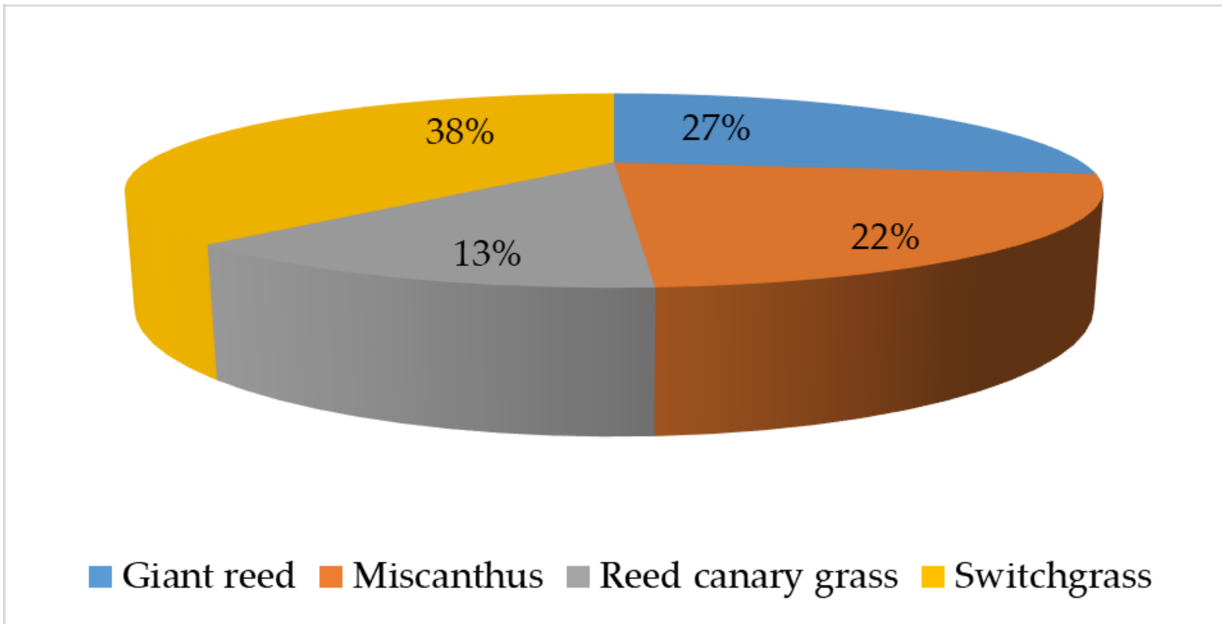

Figure 1. Percentage of papers per species dealing with mechanical harvesting identified after systematic literature search.

3. Results

3.1. Giant Reed

3.1.1. General Features of the Crop

Giant reed is a herbaceous perennial crop belonging to the *Poaceae* family that can tolerate diverse ecological and edaphic conditions, is resistant to many pests and diseases, and can provide relatively high yields of biomass with lower agronomic inputs [23]. These features have made giant reed attractive for bioenergy production in many regions of the world. Giant reed is considered a sterile plant; the propagation is performed via either hydroponic or in vitro techniques [24]. On the other hand, giant reed can act as an invasive species in flooded areas. Currently, this crop is grown for grassland management; phytoremediation; and, mostly, bioenergy production [24–26].

Arundo donax presents several advantages in comparison to other energy crops, for instance, its high plasticity in relation to environmental, soil, and growing conditions; high biomass yield; and ability to be grown as a low-input crop [27,28]. Furthermore, it has been demonstrated that giant reed can also achieve a substantial biomass yield under high-salinity conditions [29]. It is moreover suitable for cultivation on marginal or sub-marginal lands, such as polluted areas and poor soils [30]. The biomass yield of this species is in the range of 30–40 Mg DM ha^{-1} per year [29]. Regarding its bioenergy features, the higher heating value of giant reed ranges between 18 and 20 MJ kg^{-1} [31,32]. The ash percentage is in the range of 5.0–8.0% [28].

3.1.2. Mechanical Harvesting

The first issue to be taken into account when selecting a harvesting system for giant reed is the final destination of the biomass. Indeed, giant reed can be used for both thermochemical processes and second-generation biofuels. In this last case, the biomass can be processed with a high moisture content, while for combustion a drying period is needed [33].

Therefore, *Arundo donax* harvesting can be performed with a single- or double-passage operation [34]. Regarding single-passage harvesting for second-generation biofuel production, harvesting takes place during summer, considering that anaerobic digestion is fostered by a high moisture content and the presence of leaves [35].

The most common system for the single-passage harvesting of giant reed consists of a self-propelled forage harvester (SPFH), a machine commonly applied in silage maize harvesting. In this system, biomass is flanked by a tractor–trailer unit receiving the chopped material, which is then shipped to a collection point [36].

The work productivity of SPFH for giant reed reached a field capacity of 1.34 ha h^{-1} with an operative speed of 3.90 km h^{-1}, thus resulting in harvesting costs of EUR 17.9 Mg $^{-1}$ DM [33]. The same system can, however, be strongly limited in the case of lodged crops, with harvesting costs more than doubled [34]. Furthermore, it is important to underline how the intrinsic developing pattern of giant reed causes the messy development of the cultivation, with a layout not as ordered as maize crop, leading to operational difficulties in applying such harvesting systems in older giant reed fields. To reduce such problems, a row-independent attachment is strongly recommended.

Biomass harvesting for thermochemical conversion takes place during winter, when plants are in quiescence and have a low moisture content. The possible alternatives for giant reed biomass harvesting in winter period consist of mowing and shredding or shredding and baling [34]. A typical haymaking harvesting system consisting of mowing and baling is not applicable to giant reed, considering the dimensions and hardness of the stems. Mowing and shredding can be applied with a conventional mower powered by a tractor, followed by a shredding and collecting phase using a self-propelled forage harvester, which discharges the biomass onto a tractor–trailer. In a field trial with this harvesting system, the field capacity of mowing was 0.86 ha h^{-1}, and that of shredding was 1.01 ha h^{-1}. The consequent harvesting costs were EUR 378.94 ha^{-1} and EUR 26.40 Mg^{-1} DM [33]. A similar harvesting system was also tested in Spain, applying a SPFH equipped with a Kemper header to mow the crop; the header was modified, allowing it to leave the cut and windrowed plants on the ground prior to baling (one and a half months later). This system showed a field capacity of about 1 ha h^{-1} for mowing, crushing, and windrowing and about 0.3 ha h^{-1} for baling, leading to overall harvesting costs of EUR 34.4 Mg^{-1} DM [33].

Regarding shredding and baling systems, the literature reports a working speed of about 4–5 km h^{-1} for a shredder powered by a tractor, with a varying field capacity depending on the working width of the machinery, i.e., 0.69 ha h^{-1} [34] to 1.77 ha h^{-1} [37]. The effective field capacity of baling shredded biomass of giant reed varied as well between 0.44 ha h^{-1} [34] and 0.95 ha h^{-1} [37].

Harvesting costs for this system were reported as about EUR 200 ha^{-1}, corresponding to EUR 10.4 Mg^{-1} DM in an experimental trial carried out in Italy [38]. Interestingly, in the same working conditions, the possibility of single-pass harvesting through shredding and baling was tested. This required a tractor with frontal power take off (PTO), to which the shredder was attached, and the baler was instead linked to the conventional rear PTO. However, the results for the working productivity and costs were poorer than those of the two-passage system [38]. It is interesting to note that the shredding and baling system showed the lowest harvesting costs among the possible alternatives; however, it is important to note that to power a shredder that is able to efficiently work on giant reed, a tractor of at least 200 kW is needed [39].

In summary, technologies for the efficient harvesting of giant reed are already available on the market and do not need modifications, apart from row-independent equipment; only a tractor with sufficient power to manage the hardness and dimensions of giant reed stems is required. Considering that the machinery applicable to this species is derived from silage production, it is possible to recommend the cultivation of giant reed on farms that produce silage maize and already have in their fleet tractors with a power equal to or higher than 200 kW.

3.2. Miscanthus

3.2.1. General Features of the Crop

Miscanthus (*Miscanthus × giganteus*) is a sterile, rhizomatous perennial C4 grass [40,41]. It shows a very high potential biomass yield of up to 44 Mg ha^{-1} yr^{-1} [28]. In European climate conditions, it shows cold resistance and the ability to grow with low-input management, especially in terms of fertilizers and herbicides [42]. Miscanthus biomass can be used for a wide range of purposes—for instance, combustion, or the production of bioethanol or bio-based products such as paper, materials for the building sector, or basic chemicals [43]. The miscanthus yields reported in the literature also show great variability as a consequence of the plethora of different environmental conditions in which this species has been tested. In an irrigation regime in Southern Europe, the yield could achieve values of up to 30 Mg DM ha^{-1}, while in Central European conditions, the yield was in the range between 10 and 25 Mg DM ha^{-1} [40]. The heating value of miscanthus biomass is generally around 17 MJ kg^{-1} [40]. The ash content reported in the literature is lower than for other herbaceous energy crops, being in the range between 1.6 and 4.0%, with an ash fusion temperature of 1020 °C [40].

3.2.2. Mechanical Harvesting

Biomass harvesting is a crucial phase in miscanthus supply chains [19]. As for giant reed, different harvesting strategies are also applicable for miscanthus. Each of these strategies is based on existing machinery, such as self-propelled forage harvesters (SPFHs) and other silage-making and haymaking machinery. However, it is worth highlighting that these machines usually operate with a lower working productivity than when used for forage, as a consequence of the higher density and hardness of miscanthus biomass [44].

The harvesting strategies for miscanthus can be based on single-passage or double-passage harvesting. In single-phase harvesting, biomass is picked up, chopped, or mowed and directly loaded onto a trailer or a baler (Figure 2). The most common single-phase harvesting system for miscanthus consists of the application of a self-propelled forage harvester. In miscanthus crops that have already experienced a harvesting operation, the original rows are not distinguishable anymore, so a row-independent mowing attachment is required [45].

Multi-phase systems consist of mowing and conditioning followed by raking/swathing, picking up, and baling. The typical two-step system requires a mower–conditioner that cuts the crop, rakes it to create a swath on the ground, and bales [46]. A conditioning operation is recommended in order to facilitate the baling operation [47].

The various harvesting systems for this species derive from haymaking or silage-making machinery, but some modifications are needed to optimize the work performance [48]. Focusing on mowers, several studies highlighted that a higher angle of the blades allows one to improve the working productivity and reduce energy requirements [49,50]. The mowing–conditioning productivity for miscanthus biomass was reported to be 1.8 ha h^{-1}, while baling with a large square baler showed a productivity of 1.4 ha h^{-1} [46]. Harvesting costs with this system have been reported to be about EUR 94.00 ha^{-1} [51].

Focusing on harvesting losses, the two-step harvesting system showed losses more than double those of single-passage harvesting, increasing from about 5% to about 12% [52].

Miscanthus can therefore be harvested with conventional machinery, but some modifications are recommended to optimize the working performance. Single-passage harvesting via an SPFH is particularly efficient when a row-independent mowing attachment is applied. Therefore, as is the case for giant reed, miscanthus cultivation could be suitable for farms cultivating silage maize. Double-passage harvesting is applicable based on haymaking machinery, and the productivity can be improved after the modification of the mower's blades. It is, however, expected that the higher hardness of miscanthus stems in comparison to typical haymaking species could increase the rate of deterioration of the machinery elements, thus increasing the maintenance costs. The cultivation of miscanthus is therefore recommended for haymaking farms only in such cases when it is possible to establish a short energy chain using miscanthus biomass to produce energy for the farm itself. A short transport distance between the fields and the main buildings of the farm is required; in this case, the optimization of the costs for energy could overcome the higher expenses needed for machinery maintenance costs.

Figure 2. Miscanthus harvesting in a single pass using a self-propelled forage harvester.

3.3. Reed Canary Grass

3.3.1. General Features of the Crop

Reed canary grass belongs to the *Gramineae* family. It is a native perennial grass of the temperate regions of Europe, Asia, and North America. In Europe, it is particularly common in Nordic countries. Wet areas such as lake shores are typical environments where this grass can be found.

Reed canary grass (*Phalaris arundinacea*) is used as a forage crop mainly in North America, even if nowadays the main function of interest for this species is energy production [28].

It is particularly suitable for cultivation in poorly drained soils, as it is able to tolerate flooding; however, it also shows good drought resistance [28]. In suitable conditions, the biomass yield ranges between 7.5 and 9 Mg DM ha^{-1} [53]. Heating values for reed canary grass biomass have been reported in the range between 16.6 and 19.3 MJ kg^{-1} [54].

3.3.2. Mechanical Harvesting

In contrast to the reports for giant reed and miscanthus, the harvesting operations for reed canary grass in the current literature are described only with reference to double-passage harvesting carried out with haymaking machinery, consisting of mowing and then baling [55,56].

The harvesting costs for this harvesting system have been reported as about EUR 559 ha^{-1} [55], based on a working productivity in the range between 8 and 21 Mg h^{-1} [57]. It is important to highlight that harvesting reed canary grass with this system can cause harvesting losses of up to 25% DM [54].

Considering the above, the cultivation of reed canary grass could be suitable for farms in Northern Europe that usually carry out haymaking activities.

3.4. Switchgrass

3.4.1. General Features of the Crop

Like reed canary grass, switchgrass also belongs to the *Graminae* family. Its natural range is in North America, from a latitude of 55° North to Central Mexico. In the central USA, it has been largely cultivated as fodder grass [28]. Switchgrass shows adaptability to a wide range of soils and a marked drought tolerance [58]. The highest yields can be reached with one or two harvests per year, with values ranging from 16 to 22 Mg DM ha^{-1} [59]. The heating value for the biomass of this species has been reported as 17 MJ kg^{-1} [60,61]. The percentage of ash after combustion has been reported to range between 4.5 and 10.5%, with an ash melting point of about 1016 °C [60,61].

3.4.2. Mechanical Harvesting

Similarly to other herbaceous energy crops, switchgrass can be harvested with commercially available haying equipment, such as mowers, rakes, and balers. Bales can be either round or square-shaped. Due to the high quantity of fresh biomass produced (higher than 10 Mg ha^{-1}), self-propelled swathers with rotary headers should be preferred, due to their ability to handle a high volume of material. The cutting height is set at 10–15 cm to facilitate air movement in order to decrease the moisture content below 20% before baling. Material losses during outside storage are lower in round bales than in rectangular bales, although the latter shape is easier to handle and transport in cases where there are no width restrictions [62].

The large-scale production of switchgrass was also investigated by [63] in 2009, introducing the possibility of using a loafer instead of a common baler to reduce the cost of production. Loafing is performed through a piece of machinery named a loafer (or stacker), which picks up the switchgrass from the windrow (max moisture content at 15% *w*/*w*) and packs the biomass into large packages (2.4 m wide, up to 6 m long, and 3.6 m high) that weigh as much as 4 Mg, approximately. Although loafs have a lower density compared to bales, the transportation costs are lower than those recorded for loose material. In the abovementioned study, the loafing strategy was compared with baling, and the harvesting costs changed significantly according to the yield. Three yield values were considered: 10, 20, and 30 Mg ha^{-1}. The respective costs per Mg of biomass for loafing were estimated to be EUR 14.86, 12.07, and 9.29, whilst for baling, the costs were EUR 22.29, 16.72, and 14.86. The authors of [64] reported EUR 82.20 dry Mg^{-1} for mowing, raking, and baling with large square bales, whilst the authors of [65] reported about EUR 11.15 and 12.07 FM Mg^{-1} for round and square bales, respectively. Additionally, the authors of [38] reported a production cost of EUR 9.9–12.1 Mg^{-1} dry biomass, though they used a prototype for shredding switchgrass before baling.

Depending on the harvest strategy adopted (high-density versus loose chopped material), a partial drying process might be necessary during field operations in order to reduce spontaneous fermentation. The use of both mower–conditioner and tedder harvest treatments promoted rapid switchgrass drying from 67% to 18% moisture content (wet basis) within 48 h after cutting [66]. According to [67], during baling, the loss in DM can range from 1 to 5% depending on the moisture content: the lower the humidity, the higher the loss.

Concerning machinery performance, the mower–conditioner can operate at speeds of up to 16.4 km h^{-1} and process 57 Mg DM h^{-1}. However, in extremely lodged switchgrass, the speed must be reduced to prevent clogging. On the other hand, a high volume of material does not affect the performance of a rotary rake. Once dried, the round baler can bale switchgrass at speeds as high as 14.0 km h^{-1}, corresponding to a material capacity of 48 Mg DM h^{-1} [66].

The authors of [38] proposed the combination of a shredder and a baler connected to the same tractor as a promising strategy for collecting switchgrass in small farms in a single pass. The shredder used was a prototype biotriturator RM 280 BIO, which combined cutting, shredding, and crop windrowing. The strategy proposed provided interesting results in terms of cost and performance; however, in larger farms (>200 ha), the reduced EFC (0.61 ha h^{-1}) dictated by the baler does not allow one to level-off the extra cost for labor in a dual-stage harvesting strategy. Therefore, the two-pass strategy must be adopted.

Alternatively to baling, switchgrass can be transported to the plant as loose chopped biomass. In this case, a self-loading forage-chopping wagon can be used, which picks up windrows prepared by a mower and windrow merger or rake. The effective field capacity ranges between 0.93 and 1.03 ha h^{-1}, whilst the material capacity ranges between 3.58 and 11.86 Mg h^{-1}, depending on the distance from the processing site [68]. Harvesting switchgrass as a loose material with a forage wagon costs EUR 4.10 FM Mg^{-1} [65].

Regardless of the system adopted, harvesting is the most impactful phase of the switchgrass supply chain. Establishment accounts for almost a third of the total cost. In fact, a comprehensive study on lignocellulosic feedstock production performed in 2020 [19] reported the following cost breakdown, expressed as the percentage of switchgrass delivery: establishment 32.46, harvest 41.36, storage 4.77, processing 2.24, and transportation 19.17.

In summary, switchgrass cultivation can be efficiently carried out with haymaking machinery. Considering the high amount of biomass, it is recommended to use self-propelled swathers. This kind of machine is not so common, being typically present only in the fleets of large haymaking farms. This type of farm could therefore be particularly suitable for switchgrass cultivation. Smaller farms could, however, cultivate switchgrass and carry out harvesting with conventional haymaking technology by mowing, raking, and baling.

3.5. Summary Table

In the current literature, a comprehensive review work focused on the topic of the mechanical harvesting of perennial grasses is still missing. This represents an important research gap, considering that harvesting is probably one of the most expensive phases of the cropping cycle [9,10,69,70].

Taking the above into account, we focused our literature review on four perennial grasses: giant reed, miscanthus, reed canary grass, and switchgrass. These are the species that have shown the highest potential in terms of yield and the possibility of successful growth on marginal lands [71].

The main findings of the present review work are presented in Table 1. As is noticeable, the harvesting costs per hectare were rather similar for miscanthus, reed canary grass, and switchgrass, while the costs per surface unit for giant reed harvesting were much higher. However, the costs per biomass unit were very similar among the various crops, considering that giant reed compensates for its high surface unit costs with a very high yield.

The main contribution of this review work was to highlight how the harvesting operations for all the investigated crops are already well-developed. All the crops can indeed be harvested with widely available machinery taken from forage- or silage-making systems. Some modifications could be helpful to improve the productivity, but such machines could essentially be applied as-is for all the investigated crops without excessively compromising the working performance or increasing the harvesting costs. This is a great advantage of lignocellulosic crops in comparison to several oilseeds, such as castor bean (*Ricinus communis* L.), for which the full development of mechanical harvesting is still a challenging topic [5]. The possibility of applying existing and widely used machines for harvesting operations represents another advantage of lignocellulosic perennial grasses, i.e., its easy integration into intercropping systems [72], with positive effects on biodiversity and the resilience of agro-ecosystems [73,74].

Table 1. Harvesting strategies and associated costs per species.

Species	Harvesting Strategy	Machinery Performance	Harvesting Cost	Ref.	Notes
Giant Reed	Self-propelled forage harvester + tractor–trailer unit	1.34 ha h^{-1}	EUR 537 ha^{-1} and EUR 17.9 Mg^{-1} DM	[33]	Row-independent attachment recommended after the first harvesting
	Mowing and shredding or shredding and baling	0.46 ha h^{-1}	EUR 378.94 ha^{-1} and EUR 26.40 Mg^{-1} DM	[33]	A tractor with at least 200 kW is needed to power a shredder able to efficiently work on giant reed biomass
	SPFH equipped with kemper header + baling	0.23 ha h^{-1}	EUR 1032 ha^{-1} and EUR 34.4 Mg^{-1} DM	[33]	To allow for biomass drying, the header has to be modified so that it can leave the cut and windrowed plants on the ground prior to baling
Miscanthus	Self-propelled forage harvesters (single pass)	1.05 ha h^{-1}	-	[46,51]	Row-independent attachment recommended after the first harvesting
	Haymaking machinery (multi-phase)	0.79 ha h^{-1}	EUR 94.00 ha^{-1}	[46,51]	A higher angle of the blades of the mower is recommended. Farmers have to take into consideration possible higher maintenance costs when applying common mowers and balers on miscanthus biomass as a consequence of the higher hardness of the stems in comparison to typical haymaking grasses
Red canary grass	Haymaking machinery (multi-phase)	0.57 ha h^{-1}	EUR 90 ha^{-1}	[55]	High harvesting losses (about 25%) have been experienced
Switchgrass	Haymaking machinery (multi-phase) for round bales, square bales, or loaf production		EUR 89.1 ha^{-1} round bales, EUR 84.3 ha^{-1} square bales, EUR 49.1 ha^{-1} loafs	[63] [64] [63]	Considering the high biomass yield, large machinery such as self-propelled rotary mowers are recommended. Loafs should be preferred in the case of a greater transport distance to the biomass plant in order to lower the transport costs.
	Single pass with biotriturator RM 280 BIO + baler	0.61 ha h^{-1}	EUR 137.7 ha^{-1}	[38]	To feed a shredder suitable for switchgrass, the tractor should have a power of at least 150 kW
	Multi-phase + self-loading forage-chopping wagon	1.0 ha h^{-1}	EUR 49.1 ha^{-1}	[68]	Indicated for very short transport distance

4. Conclusions

Producing renewable energy from agriculture is fundamental to tackle the issue of energy independence for European countries. In this framework, the cultivation of perennial grasses has shown potential, mostly thanks to the presence of species that are fast-growing and can achieve high biomass yields. However, the mechanical harvesting of perennial grasses is still an issue to be comprehensively investigated in the scientific literature. Therefore, we conducted a review of the mechanical harvesting of four perennial grass species that are particularly suitable for cultivation in Europe. These species were giant reed, miscanthus, reed canary grass, and switchgrass. The investigated lignocellulosic perennial grasses are ready for cultivation upscaling from the point of view of the technological readiness level of mechanical harvesting. All the investigated species could indeed be harvested with conventional machinery mostly deriving from forage-making technologies, without an excessive decrease in working productivity or increase in harvesting costs. Concerning the future research directions, it is recommended on the one hand to focus attention on increasing the possibility of growing such species in marginal land conditions, working on agronomic solutions to allow the crop to also reach a sustainable biomass yield in difficult edaphic situations. On the other hand, research in the framework of agriculture engineering should now be focused on the following parts of the supply chain: the optimization of transport and storage operations.

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

Funding: This research was funded by the European Union's Horizon 2020-MIDAS-Utilization of Marginal lands for growing sustainable industrial crops and developing innovative bio-based products. Grant agreement ID: 101082070.

Data Availability Statement: Data available on request from the corresponding author.

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

References

1. Eionet Share of Energy Consumption from Renewable Sources in Europe. Available online: https://www.eea.europa.eu/ims/share-of-energy-consumption-from#:~:text=Witha22.1%25shareof,accordingtodatafromEurostat (accessed on 12 December 2022).
2. Eurostat Energy Statistics—An Overview. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview#Primary_energy_production (accessed on 10 November 2022).
3. IAEA Nuclear Technology. In *The New Crusaders*; Routledge: London, UK, 2020; pp. 77–86.
4. Buonomano, A.; Barone, G.; Forzano, C. Advanced Energy Technologies, Methods, and Policies to Support the Sustainable Development of Energy, Water and Environment Systems. *Energy Rep.* **2022**, *8*, 4844–4853. https://doi.org/10.1016/j.egyr.2022.03.171.
5. Pari, L.; Latterini, F.; Stefanoni, W. Herbaceous Oil Crops, a Review on Mechanical Harvesting State of the Art. *Agriculture* **2020**, *10*, 309. https://doi.org/10.3390/agriculture10080309.
6. Suardi, A.; Saia, S.; Stefanoni, W.; Gunnarsson, C.; Sundberg, M.; Pari, L. Admixing Chaff with Straw Increased the Residues Collected without Compromising Machinery Efficiencies. *Energies* **2020**, *13*, 1766. https://doi.org/10.3390/en13071766.
7. Bergonzoli, S.; Suardi, A.; Rezaie, N.; Alfano, V.; Pari, L. An Innovative System for Maize Cob and Wheat Chaff Harvesting: Simultaneous Grain and Residues Collection. *Energies* **2020**, *13*, 1265. https://doi.org/10.3390/en13051265.
8. Suardi, A.; Stefanoni, W.; Alfano, V.; Bergonzoli, S.; Pari, L. Equipping a Combine Harvester with Turbine Technology Increases the Recovery of Residual Biomass from Cereal Crops via the Collection of Chaff. *Energies* **2020**, *13*, 1572. https://doi.org/10.3390/en13071572.
9. Latterini, F.; Stefanoni, W.; Sebastiano, S.; Baldi, G.M.; Pari, L. Evaluating the Suitability of a Combine Harvester Equipped with the Sunflower Header to Harvest Cardoon Seeds: A Case Study in Central Italy. *Agronomy* **2020**, *10*, 1981. https://doi.org/10.3390/agronomy10121981.
10. Stefanoni, W.; Latterini, F.; Malkogiannidis, V.; Salpiggidis, V.; Alexopoulou, E.; Pari, L. Mechanical Harvesting of Castor Bean (*Ricinus Communis* L.) with a Combine Harvester Equipped with Two Different Headers: A Comparison of Working Performance. *Energies* **2022**, *15*, 2999. https://doi.org/10.3390/en15092999.
11. 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.
12. Zahorec, A.; Reid, M.L.; Tiemann, L.K.; Landis, D.A. Perennial Grass Bioenergy Cropping Systems: Impacts on Soil Fauna and Implications for Soil Carbon Accrual. *GCB Bioenergy* **2022**, *14*, 4–23. https://doi.org/10.1111/gcbb.12903.
13. Kantola, I.B.; Masters, M.D.; Blanc-Betes, E.; Gomez-Casanovas, N.; DeLucia, E.H. Long-term Yields in Annual and Perennial Bioenergy Crops in the Midwestern United States. *GCB Bioenergy* **2022**, *14*, 694–706. https://doi.org/10.1111/gcbb.12940.
14. Sacristán, D.; Cifre, J.; Llompart, M.; Jaume, J.; Gulias, J. Lignocellulosic Biomass Production and Persistence of Perennial Grass Species Grown in Mediterranean Marginal Lands. *Agronomy* **2021**, *11*, 2060. https://doi.org/10.3390/agronomy11102060.
15. Scordia, D.; Papazoglou, E.G.; Kotoula, D.; Sanz, M.; Ciria, C.S.; Pérez, J.; Maliarenko, O.; Prysiazhniuk, O.; von Cossel, M.; Greiner, B.E.; et al. Towards Identifying Industrial Crop Types and Associated Agronomies to Improve Biomass Production from Marginal Lands in Europe. *GCB Bioenergy* **2022**, *14*, 710–734. https://doi.org/10.1111/gcbb.12935.

16. Robertson, G.P.; Hamilton, S.K.; Barham, B.L.; Dale, B.E.; Izaurralde, R.C.; Jackson, R.D.; Landis, D.A.; Swinton, S.M.; Thelen, K.D.; Tiedje, J.M. Cellulosic Biofuel Contributions to a Sustainable Energy Future: Choices and Outcomes. *Science* **2017**, *356*, eaal2324. https://doi.org/10.1126/science.aal2324.
17. Landis, D.A.; Gratton, C.; Jackson, R.D.; Gross, K.L.; Duncan, D.S.; Liang, C.; Meehan, T.D.; Robertson, B.A.; Schmidt, T.M.; Stahlheber, K.A.; et al. Biomass and Biofuel Crop Effects on Biodiversity and Ecosystem Services in the North Central US. *Biomass Bioenergy* **2018**, *114*, 18–29. https://doi.org/10.1016/j.biombioe.2017.02.003.
18. McGowan, A.R.; Nicoloso, R.S.; Diop, H.E.; Roozeboom, K.L.; Rice, C.W. Soil Organic Carbon, Aggregation, and Microbial Community Structure in Annual and Perennial Biofuel Crops. *Agron. J.* **2019**, *111*, 128–142. https://doi.org/10.2134/agronj2018.04.0284.
19. Wang, Y.; Wang, J.; Schuler, J.; Hartley, D.; Volk, T.; Eisenbies, M. Optimization of Harvest and Logistics for Multiple Lignocellulosic Biomass Feedstocks in the Northeastern United States. *Energy* **2020**, *197*, 117260. https://doi.org/10.1016/j.energy.2020.117260.
20. Pari, L.; Alfano, V.; Mattei, P.; Santangelo, E. Pappi of Cardoon (*Cynara Cardunculus* L.): The Use of Wetting during the Harvesting Aimed at Recovering for the Biorefinery. *Ind. Crop. Prod.* **2017**, *108*, 722–728. https://doi.org/10.1016/j.indcrop.2017.07.037.
21. Alfano, V.; Stefanoni, W.; Latterini, F.; Liuzzi, F.; de Bari, I.; Viola, E.; Ciancolini, A.; Pari, L. Inulin Content in Chipped Roots of Cardoon Stored at Different Initial Moisture Contents After Six-Month Storage. *Front. Energy Res.* **2022**, *10*, 448. https://doi.org/10.3389/fenrg.2022.834443.
22. Pari, L.; Alfano, V.; Stefanoni, W.; Latterini, F.; Liuzzi, F.; de Bari, I.; Valerio, V.; Ciancolini, A. Inulin Content in Chipped and Whole Roots of Cardoon after Six Months Storage under Natural Conditions. *Sustainability* **2021**, *13*, 3902.
23. Fernando, A.L.; Barbosa, B.; Costa, J.; Papazoglou, E.G. Giant Reed (*Arundo Donax* L.). In *Bioremediation and Bioeconomy*; Prasad, M.N.V., Ed.; Elsevier: Amsterdam, The Netherlands, 2016; pp. 77–95, ISBN 978-0-12-802830-8.
24. Popp, J.; Harangi-Rákos, M.; Gabnai, Z.; Balogh, P.; Antal, G.; Bai, A. Biofuels and Their Co-Products as Livestock Feed: Global Economic and Environmental Implications. *Molecules* **2016**, *21*, 285. https://doi.org/10.3390/molecules21030285.
25. Prochnow, A.; Heiermann, M.; Plöchl, M.; Amon, T.; Hobbs, P.J. Bioenergy from Permanent Grassland—A Review: 2. Combustion. *Bioresour. Technol.* **2009**, *100*, 4945–4954. https://doi.org/10.1016/j.biortech.2009.05.069.
26. Monti, A.; Zegada-Lizarazu, W.; Zanetti, F.; Casler, M. Nitrogen Fertilization Management of Switchgrass, Miscanthus and Giant Reed: A Review. In *Advances in Agronomy*; Sparks, D.L., Ed.; Academic Press: Cambridge, MA, USA, 2019; Volume 153, pp. 87–119.
27. Piccitto, A.; Scordia, D.; Corinzia, S.A.; Cosentino, S.L.; Testa, G. Advanced Biomethane Production from Biologically Pretreated Giant Reed under Different Harvest Times. *Agronomy* **2022**, *12*, 712. https://doi.org/10.3390/agronomy12030712.
28. Lewandowski, I.; Scurlock, J.M.O.; Lindvall, E.; Christou, M. The Development and Current Status of Perennial Rhizomatous Grasses as Energy Crops in the US and Europe. *Biomass Bioenergy* **2003**, *25*, 335–361. https://doi.org/10.1016/S0961-9534(03)00030-8.
29. Angelini, L.G.; Ceccarini, L.; Nassi o Di Nasso, N.; Bonari, E. Comparison of *Arundo Donax* L. and *Miscanthus x Giganteus* in a Long-Term Field Experiment in Central Italy: Analysis of Productive Characteristics and Energy Balance. *Biomass Bioenergy* **2009**, *33*, 635–643. https://doi.org/10.1016/j.biombioe.2008.10.005.
30. Cosentino, S.L.; Copani, V.; D'Agosta, G.M.; Sanzone, E.; Mantineo, M. First Results on Evaluation of *Arundo Donax* L. Clones Collected in Southern Italy. *Ind. Crop. Prod.* **2006**, *23*, 212–222. https://doi.org/10.1016/j.indcrop.2005.06.004.
31. Rabemanolontsoa, H.; Saka, S. Comparative Study on Chemical Composition of Various Biomass Species. *RSC Adv.* **2013**, *3*, 3946. https://doi.org/10.1039/c3ra22958k.
32. Bonanno, G.; Cirelli, G.L.; Toscano, A.; Giudice, R.L.; Pavone, P. Heavy Metal Content in Ash of Energy Crops Growing in Sewage-Contaminated Natural Wetlands: Potential Applications in Agriculture and Forestry? *Sci. Total Environ.* **2013**, *452–453*, 349–354. https://doi.org/10.1016/j.scitotenv.2013.02.048.
33. Pari, L.; Curt, M.D.; Sánchez, J.; Santangelo, E. Economic and Energy Analysis of Different Systems for Giant Reed (*Arundo Donax* L.) Harvesting in Italy and Spain. *Ind. Crop. Prod.* **2016**, *84*, 176–188. https://doi.org/10.1016/j.indcrop.2016.01.036.
34. Pari, L.; Suardi, A.; Scarfone, A.; Santangelo, E. Italian Experiences on Arundo Harvesting: Economic and Energy Appraisal. In *Perennial Biomass Crops for a Resource-Constrained World*; Barth, S., Murphy-Bokern, D., Kalinina, O., Taylor, G., Jones, M., Eds.; Springer International Publishing: Cham, Switzerland, 2016; pp. 77–86, ISBN 978-3-319-44530-4.
35. Dragoni, F.; o Di Nasso, N.N.; Tozzini, C.; Bonari, E.; Ragaglini, G. Aboveground Yield and Biomass Quality of Giant Reed (*Arundo Donax* L.) as Affected by Harvest Time and Frequency. *Bioenergy Res.* **2015**, *8*, 1321–1331. https://doi.org/10.1007/s12155-015-9598-x.
36. Pari, L.; Assirelli, A.; Acampora, A.; del Giudice, A.; Santangelo, E. A New Prototype for Increasing the Particle Size Of Chopped *Arundo Donax* (L.). *Biomass Bioenergy* **2015**, *74*, 288–295. https://doi.org/10.1016/j.biombioe.2015.01.025.
37. Assirelli, A.; Civitarese, V.; Caracciolo, G.; Sannino, M.; Faugno, S. Mechanical Harvesting Line Setting of Giant Reeds. *Appl. Sci.* **2019**, *9*, 5425. https://doi.org/10.3390/app9245425.
38. Bentini, M.; Martelli, R. Prototype for the Harvesting of Cultivated Herbaceous Energy Crops, an Economic and Technical Evaluation. *Biomass Bioenergy* **2013**, *57*, 229–237. https://doi.org/10.1016/j.biombioe.2013.07.008.
39. Faugno, S.; Quacquarelli, I.; Civitarese, V.; Crimaldi, M.; Sannino, M.; Ricciardiello, G.; Caracciolo, G.; Assirelli, A. Two Steps *Arundo Donax* L. Harvesting in South Italy. *Chem. Eng. Trans.* **2017**, *58*, 265–270. https://doi.org/10.3303/CET1758045.

40. Lewandowski, I.; Clifton-Brown, J.C.; Scurlock, J.M.O.; Huisman, W. Miscanthus: European Experience with a Novel Energy Crop. *Biomass Bioenergy* **2000**, *19*, 209–227. https://doi.org/10.1016/S0961-9534(00)00032-5.
41. Liang, K.; Peng, X.; Liu, F. Physiological Response of Miscanthus Genotypes to Salinity Stress under Elevated CO_2. *GCB Bioenergy* **2022**, *14*, 858–874. https://doi.org/10.1111/gcbb.12948.
42. Robson, P.; Mos, M.; Clifton-Brown, J.; Donnison, I. Phenotypic Variation in Senescence in Miscanthus: Towards Optimising Biomass Quality and Quantity. *Bioenergy Res.* **2012**, *5*, 95–105. https://doi.org/10.1007/s12155-011-9118-6.
43. Davis, L.C.; Pidlisnyuk, V.; Mamirova, A.; Shapoval, P.; Stefanovska, T. *Miscanthus for Bioenergy Production: Crop Production, Phytotechnology with Biomass Production: Sustainable Management of Contaminated Sites_Chapter 5*; Erickson, L.E., Pidlisnyuk, V., Eds.; CRC Press: Boca Raton, FL, USA, 2021; Volume 4, ISBN 9780367522803.
44. Anderson, E.; Arundale, R.; Maughan, M.; Oladeinde, A.; Wycislo, A.; Voigt, T. Growth and Agronomy of *Miscanthus × Giganteus* for Biomass Production. *Biofuels* **2011**, *2*, 167–183. https://doi.org/10.4155/bfs.10.80.
45. Venturi, P.; Huisman, W.; Molenaar, J. Mechanization and Costs of Primary Production Chains For *Miscanthus x Giganteus* in The Netherlands. *J. Agric. Eng. Res.* **1998**, *69*, 209–215. https://doi.org/10.1006/jaer.1997.0239.
46. Mathanker, S.K.; Hansen, A.C. Impact of Miscanthus Yield on Harvesting Cost and Fuel Consumption. *Biomass Bioenergy* **2015**, *81*, 162–166. https://doi.org/10.1016/j.biombioe.2015.06.024.
47. Fasick, G.T.; Liu, J. Lab Scale Studies of Miscanthus Mechanical Conditioning and Bale Compression. *Biosyst. Eng.* **2020**, *200*, 366–376. https://doi.org/10.1016/j.biosystemseng.2020.10.011.
48. Bilandžija, N.; Fabijanić, G.; Sito, S.; Grubor, M.; Krononc, Z.; Čopec, K.; Kovačev, I. Harvest Systems of *Miscanthus x Giganteus* Biomass: A Review. *J. Cent. Eur. Agric.* **2020**, *21*, 159–167. https://doi.org/10.5513/JCEA01/21.1.2511.
49. Gan, H.; Mathanker, S.; Momin, M.A.; Kuhns, B.; Stoffel, N.; Hansen, A.; Grift, T. Effects of Three Cutting Blade Designs on Energy Consumption during Mowing-Conditioning of *Miscanthus Giganteus*. *Biomass Bioenergy* **2018**, *109*, 166–171. https://doi.org/10.1016/j.biombioe.2017.12.033.
50. Maughan, M.; Bollero, G.; Lee, D.K.; Darmody, R.; Bonos, S.; Cortese, L.; Murphy, J.; Gaussoin, R.; Sousek, M.; Williams, D.; et al. *Miscanthus × Giganteus* Productivity: The Effects of Management in Different Environments. *GCB Bioenergy* **2012**, *4*, 253–265. https://doi.org/10.1111/j.1757-1707.2011.01144.x.
51. Kwaśniewski, D.; Płonka, A.; Mickiewicz, P. Harvesting Technologies and Costs of Biomass Production from Energy Crops Cultivated on Farms in the Małopolska Region. *Energies* **2022**, *15*, 131.
52. Meehan, P.G.; McDonnell, K.P.; Finnan, J.M. An Assessment of the Effect of Harvest Time and Harvest Method on Biomass Loss for *Miscanthus × Giganteus*. *GCB Bioenergy* **2013**, *5*, 400–407. https://doi.org/10.1111/j.1757-1707.2012.01205.x.
53. Becker, R.; Meyer, D.; Wagoner, P.; Saunders, R.M. Alternative Crops for Sustainable Agricultural Systems. *Agric. Ecosyst. Environ.* **1992**, *40*, 265–274. https://doi.org/10.1016/0167-8809(92)90097-U.
54. Hadders, G.; Olsson, R. Harvest of Grass for Combustion in Late Summer and in Spring. *Biomass Bioenergy* **1997**, *12*, 171–175. https://doi.org/10.1016/S0961-9534(96)00047-5.
55. Nilsson, D.; Rosenqvist, H.; Bernesson, S. Profitability of the Production of Energy Grasses on Marginal Agricultural Land in Sweden. *Biomass Bioenergy* **2015**, *83*, 159–168. https://doi.org/10.1016/j.biombioe.2015.09.007.
56. Lötjönen, T.; Paappanen, T. Bale Density of Reed Canary Grass Spring Harvest. *Biomass Bioenergy* **2013**, *51*, 53–59. https://doi.org/10.1016/j.biombioe.2012.12.041.
57. Shinners, K.J.; Boettcher, G.C.; Muck, R.E.; Weimer, P.J.; Casler, M.D. Harvest and Storage of Two Perennial Grasses as Biomass Feedstocks. *Trans. ASABE* **2010**, *53*, 359–370.
58. Douglas, J.; Lumonyon, J.; Wynia, R.; Salon, P. Planting and Managing Switchgrass as a Biomass Energy Crop. In *Alternative Energy and Shale Gas Encyclopedia*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2016; pp. 663–674.
59. Larnaudie, V.; Ferrari, M.D.; Lareo, C. Switchgrass as an Alternative Biomass for Ethanol Production in a Biorefinery: Perspectives on Technology, Economics and Environmental Sustainability. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112115. https://doi.org/10.1016/j.rser.2022.112115.
60. McLaughlin, S.B.; Samson, R.; Bransby, D.; Wiselogel, A. Evaluating Physical, Chemical, and Energetic Properties of Perennial Grasses as Biofuels. *Fuel Energy Abstr.* **1998**, *39*, 283. https://doi.org/10.1016/S0140-6701(98)96595-X.
61. Sladden, S.E.; Bransby, D.I.; Aiken, G.E. Biomass Yield, Composition and Production Costs for Eight Switchgrass Varieties in Alabama. *Biomass Bioenergy* **1991**, *1*, 119–122. https://doi.org/10.1016/0961-9534(91)90034-A.
62. Mitchell, R.; Schmer, M. Switchgrass Harvest and Storage. In *Switchgrass. Green Energy and Technology*; Monti, A., Ed.; Springer: London, UK, 2012; Volume 94, ISBN 978-1-4471-2902-8.
63. Sokhansanj, S.; Mani, S.; Turhollow, A.; Kumar, A.; Bransby, D.; Lynd, L.; Laser, M. Large-Scale Production, Harvest and Logistics of Switchgrass (*Panicum Virgatum* L.)—Current Technology and Envisioning a Mature Technology. *Biofuels Bioprod. Biorefining* **2009**, *3*, 124–141. https://doi.org/10.1002/bbb.129.
64. Manatt, R.K.; Hallam, A.; Schulte, L.A.; Heaton, E.A.; Gunther, T.; Hall, R.B.; Moore, K.J. Farm-Scale Costs and Returns for Second Generation Bioenergy Cropping Systems in the US Corn Belt. *Environ. Res. Lett.* **2013**, *8*, 035037. https://doi.org/10.1088/1748-9326/8/3/035037.
65. Brownell, D.; Liu, J. Field Test and Cost Analysis of Four Harvesting Options for Herbaceous Biomass Handling. *Int. J. Agric. Biol. Eng.* **2011**, *4*, 58–68. https://doi.org/10.3965/j.issn.1934-6344.2011.03.0-0.
66. Womac, A.; Hart, W.E.; Bitra, V.S.P.; Kraus, T. Biomass Harvesting of High-Yield Low-Moisture Switchgrass: Equipment Performance and Moisture Relations. *Appl. Eng. Agric.* **2012**, *28*, 775–786. https://doi.org/10.13031/2013.42469.

67. Sanderson, M.A.; Egg, R.P.; Wiselogel, A.E. Biomass Losses during Harvest and Storage of Switchgrass. *Biomass Bioenergy* **1997**, *12*, 107–114. https://doi.org/10.1016/S0961-9534(96)00068-2.
68. Brownell, D.K.; Liu, J.; Hilton, J.W.; Richard, T.L.; Cauffman, G.R.; MacAfee, B.R. Evaluation of Two Forage Harvesting Systems for Herbaceous Biomass Harvesting. *Trans. ASABE* **2012**, *55*, 1651–1658. https://doi.org/10.13031/2013.27802.
69. Griffel, L.M.; Vazhnik, V.; Hartley, D.S.; Hansen, J.K.; Roni, M. Agricultural Field Shape Descriptors as Predictors of Field Efficiency for Perennial Grass Harvesting: An Empirical Proof. *Comput. Electron. Agric.* **2020**, *168*, 105088. https://doi.org/10.1016/j.compag.2019.105088.
70. Stefanoni, W.; Latterini, F.; Ruiz, J.; Bergonzoli, S.; Attolico, C.; Pari, L. Mechanical Harvesting of Camelina: Work Productivity, Costs and Seed Loss Evaluation. *Energies* **2020**, *13*, 5329. https://doi.org/10.3390/en13205329.
71. Smeets, E.M.W.; Lewandowski, I.M.; Faaij, A.P.C. The Economical and Environmental Performance of Miscanthus and Switchgrass Production and Supply Chains in a European Setting. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1230–1245. https://doi.org/10.1016/j.rser.2008.09.006.
72. Kimura, E.; Fransen, S.C.; Collins, H.P.; Stanton, B.J.; Himes, A.; Smith, J.; Guy, S.O.; Johnston, W.J. Effect of Intercropping Hybrid Poplar and Switchgrass on Biomass Yield, Forage Quality, and Land Use Efficiency for Bioenergy Production. *Biomass Bioenergy* **2018**, *111*, 31–38. https://doi.org/10.1016/j.biombioe.2018.01.011.
73. Barros, A.P.; de Carvalho Silva, A.; de Souza Abboud, A.C.; Ricalde, M.P.; Ataide, J.O. Effect of Cosmos, Crotalaria, Foeniculum, and Canavalia Species, Single-Cropped or Mixes, on the Community of Predatory Arthropods. *Sci. Rep.* **2022**, *12*, 16013. https://doi.org/10.1038/s41598-022-20188-6.
74. Scott, D.; Freckleton, R.P. Crop Diversification and Parasitic Weed Abundance: A Global Meta-Analysis. *Sci. Rep.* **2022**, *12*, 19413. https://doi.org/10.1038/s41598-022-24047-2.