

Article

Environmental and Economic Assessment of Castor Oil Supply Chain: A Case Study

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Abstract: Among the species currently cultivated for industrial vegetable oil production, castor could be a good candidate for future investments due to the good resistance to pests, tolerance to drought, and suitability for marginal lands cultivation. In addition, the production of castor oil from *Ricinus* generates a large quantity of press cake, husks, and crop residues that, in a framework of bioeconomy, could be used as by-products for different purposes. Using a case study approach, the work presents results of the environmental impact assessment and economic feasibility of the production of castor oil from two different castor hybrids comparing four by-products management scenarios and two harvesting systems (manual vs. mechanical). Castor hybrid C-856 harvested manually and that involved only the soil incorporation of press cake obtained by the oil extraction resulted as the most sustainable. The hybrid C-1030 resulted as more profitable than C-856 when harvested with the combine harvester. The ratio between gross margin and GWP emissions was applied to calculate the economic performance (gross margin) per unit of environmental burden. Findings showed that Sc1B scenario in case of C-856 cultivar hybrid had a better ratio between economic performance and greenhouse gas (GHG) emitted into the atmosphere (€3.75 per kg CO₂eq).

Keywords: bioeconomy; life cycle assessment; life cycle costing; *Ricinus communis*, L.; castor oil; harvesting; by-product; residue management

1. Introduction

The world's population is estimated to exceed 9 billion people by 2050 according to FAO (2009). Thus, increasing in food and energy demand worldwide cannot be avoided: projections show that the overall food production is expected to rise by 70% [1] while the global demand for energy will increase by more than a quarter to 2040 [2]. Bioenergy production primarily aims at the greenhouse gas (GHG) reduction and achieving such a goal may lead to indirect land use change. Competition for land use among food and non-food crops is a serious issue that European Commission has been addressing for decades, and more stringent policy measures regarding sustainable production of food and energy are on the Agenda. On 1 January 2021 the proposed new directive RED II will enter into force, setting the new thresholds for minimum renewable energy share [3]. Investments on biofuel production from non-food feedstock are largely promoted by UE. New policy measures aim to achieve a 27% renewable energy share consumed by the electricity, heating and cooling, and transportation sectors by 2030 [3]. The adoption of energy crops could generate benefits from the reduction of fossil energy dependence, improvement of rural economies, and the achievement of environmental goals [4]. Biodiesel production from vegetable oils is feasible and widely accepted as an alternative strategy to meet these goals: It has

similar properties to oil-derived diesel and, furthermore, it produces lower sulfur emission. Among the species currently cultivated for industrial vegetable oil production, castor could be a good candidate for future investments due to the good resistance to pests, tolerance to drought, and suitability for marginal lands cultivation [5]. According to FAO, in 2017, almost 1.8 million tons of castor seed had been produced worldwide, and Europe is the main user [6]. Furthermore, according to industry executives, the worldwide castor oil market is growing: The global castor oil market was \$1180 million in 2018 and is expected to reach \$1470 million by the end of 2025, growing at a compound annual growth rate (CAGR) of 2.8 percent between 2019 and 2025, according to international reports [7]. The price of castor oil in the beginning of 2019 in the international market reached 1600 dollars per ton compared with 1300 dollars per ton of 2018 [8].

In addition, the production of castor oil from *Ricinus* generates a large quantity of press cakes, husks, and crop residues [9] that, in a framework of bioeconomy, could be used as by-products for different purposes. In this framework, the European Project MAGIC (Marginal lands for Growing Industrial Crops—Grant Agreement number: 727698-MAGIC-H2020-RUR-2016-2017/H2020-RUR-2016-2) aims towards the development of resource-efficient and economically profitable industrial crops to be grown on marginal land. Among industrial crops considered in the Project, there is *Ricinus communis*, L. (castor) that is cultivated for its seed oil, which is employed extensively in medicine, pharmaceuticals, and biorefineries [10]. Castor is a vigorous fast-growing herbaceous plant native to tropical Africa [11,12] which is tolerant to salinity and drought stresses, with additional benefits of providing a multi-purpose oilseed production [13]. In the world, the most productive country is India (more than 80% of the worldwide production) along with Mozambique, China, Brazil, Myanmar, Ethiopia, Paraguay, and Vietnam. These are all developing countries that benefit from low labor costs, and the economic impact of the harvesting phase is thus sustainable. The lack of possibility to harvest the seeds mechanically is dictated by a high amount of aboveground biomass produced by wild cultivars that cannot be processed by common combine harvesters. In fact, clogging may occur in the case of a high quantity of aerial biomass production, and high seed losses. In order to solve this problem, breeders around the world are struggling to produce hybrids of castor exhibiting high productivity but shorter in height and with homogeneous ripening of the capsules.

To our knowledge, limited studies have been dedicated to the environmental and economic sustainability of castor [14,15]. Some studies are focused on the sustainability assessment of the residue biomass utilization [16] or biodiesel production [17] without investigating in detail the impact of the various castor agricultural stages and different residue management. In particular, a comparison of the environmental sustainability between different castor hybrids, harvesting methods, and by-products management have not been presented in the literature. Using a case study approach [18,19], the work aimed to present results concerning the estimation of the environmental impacts caused by two different castor hybrids harvested both manually and mechanically (manual vs. mechanical harvestings). Both hybrids had similar seed yields, even though hybrid C-856 is shorter than hybrid C-1030. The latter reported a higher amount of epigeal biomass. Various scenarios of on-farm by-products managements were analyzed. Starting by the same approach, the study carried out an economic assessment to identify the most advantageous scenario for each castor variety and residue management.

2. Materials and Methods

2.1. Study Sites

The study area is located in Geaca Municipality, Cluj District (Romania). Cluj District lies in the northwestern half of the country, between parallels 47°28' in North and 46°24' in South, meridians 23°39' in west and 24°13' in east, respectively. It is located in the contact zone of three representative natural units: Apuseni Mountains, Someș Plateau, and Transylvanian Plain. Cluj District is the 12th largest in the country and accounts for almost 3% of Romania's area. It is bordered to the northeast by

Maramureş and Bistriţa-Năsăud counties, to the east by Mureş District, to the south by Alba District, and to the west by Bihor and Sălaj counties.

The trials were carried out on the 8th and 9th of October 2019 in two different experimental fields where castor was harvested (Figure 1).

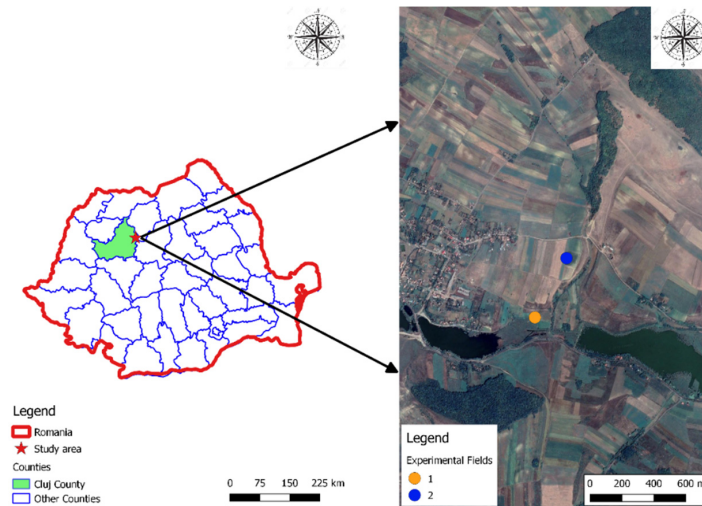


Figure 1. Study area and experimental field location (Geaca Municipality, Cluj District, Romania).

Main features of the experimental fields are given in Table 1. Data were taken both from GIS analysis and from field relieves with clinometer.

As highlighted in Table 1, all fields have southern exposition and the prevalent altitude of 313 m a.s.l. was recorded in Field 2 while the maximum slope was recorded in Field 1. However, both fields can be considered flat terrains. The surface of the field 2 was 0.27 ha higher than Field 1. A view of experimental fields positioning on Sentinel-2 image dated 3 September 2019 is given in Figure 2.

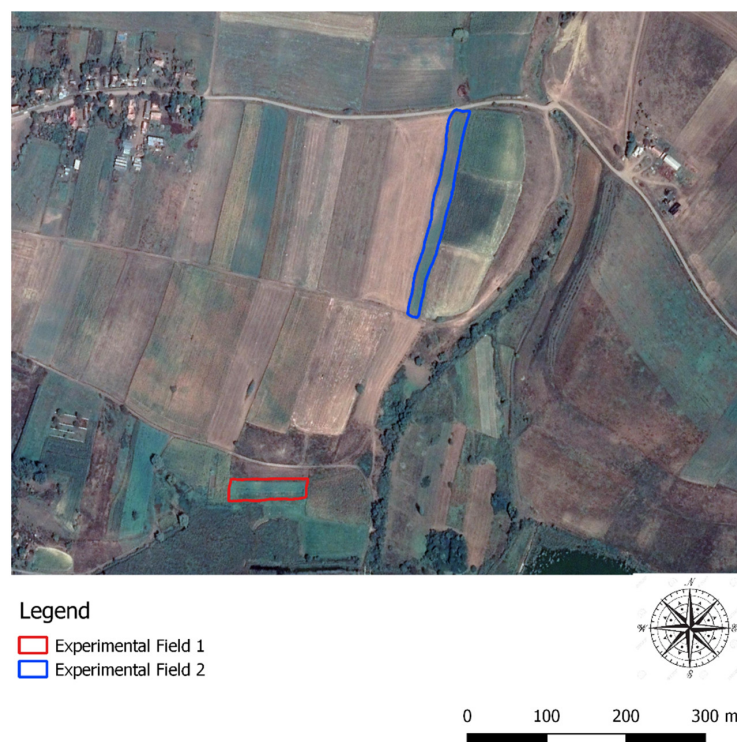


Figure 2. Experimental fields positioning. Base map Google Satellite Images dated 3 September 2019.

Table 1. Main features of the experimental fields for castor harvesting.

Experimental Field	Prevalent Slope [%]	Minimum Slope [%]	Maximum Slope [%]	Prevalent Exposition	Prevalent Altitude [m a.s.l.]	Surface [ha]
1	8.5	7.9	8.7	South	294	0.25
2	5.7	4.1	7.2	South	313	0.47

2.2. Crop Characteristics and Management of the by-Products

The main data of two dwarf hybrids of *Ricinus communis* (C-856 and C-1030) collected during the trials are reported in Table 2. Plants were cultivated in Romania, and seeds were provided to local farmer (Ecoricinus—National association of Ricinus growers) by the Israeli company KAIIMA.

Table 2. Primary data: Two castor hybrids. Pre-harvest data collection: Height of the plants, aerial biomass produced, and Harvest Index.

Hybrid Cultivar	Height of Plants [cm]	Husks [Mg ha ⁻¹]	Seed [Mg ha ⁻¹]	Straw Fresh Weight [Mg ha ⁻¹]		Harvest Index [%]
		d.w.	ssf.w.	f.w.	d.w.	
C-856	74.4 c	1.40	2.80 a	4.13 b	0.87 b	52.5 a
C-1030	112.8 a	1.60	2.90 a	8.35 a	1.61 a	43.4 b

Note: Common letters within columns denote the absence of significant difference ($p < 0.05$).

The dwarf hybrids tested were two of the various chosen by the association Ecoricinus to evaluate their behavior and productivity in Romania. Although hybrid C-856 has already been analyzed in productive and morphological terms by Alexopoulou et al. [6] in Greece and Italy, hybrid C-1030 has never been described in the literature and in the present study, it has been analyzed only to assess its productivity and the amount of epigeal biomass available for the LCA study.

Despite the significant difference found in height, straw production, and the harvest index (HI) between the two hybrids, in both cases, the aboveground biomass produced was lower than the quantity produced by wild varieties commonly cultivated in Romania (data not shown). Therefore, more suitable for mechanical harvesting. The farmer reported that fertilization and plowing took place in 2018 between week 47 and 48, while harrowing and sowing occurred in week 23 and 24 2019 at the depth of 8–10 cm with the sowing density of 3.6 seeds m⁻². Mature cow manure was applied at the quantity of 6 Mg ha⁻¹ and no irrigation was provided. No chemicals were used for both weed control and desiccation of leaves.

On the basis of farmer's survey, two scenarios for each castor variety with a different mix of by-products management were considered (Table 3).

Table 3. Scenarios analyzed in the study for each castor variety (Sc1 = scenario 1; Sc2 = scenario 2).

Harvesting Systems		Manual Harvesting		Mechanical Harvesting	
Scenarios		Sc1A	Sc1B	Sc2A	Sc2B
Products and co-products	Straw	Soil incorporation	Sale	Soil incorporation	Sale
	Husk	Sale	Sale	Soil incorporation	Soil incorporation
	Press cake	Soil incorporation	Soil incorporation	Soil incorporation	Soil incorporation
	Castor oil	Sale	Sale	Sale	Sale

In the case of manual harvesting (Sc1A and Sc1B), the castor fruit is harvested as whole, and the separation of the spiny capsules from the seeds takes place on the farm. According to Parascanu (2017), castor husk might be deemed as the best candidate for the combustion process due to its high heat release [20]. Therefore, in the Sc1A and Sc1B scenarios, the sale of spiny capsules has been assumed at a

market price of crushed olive stones due to similar lower heating value (LHV) that results in 16.48 [20] and 16.50 MJ/kg [21], respectively.

In the scenarios Sc2A and Sc2B involving castor mechanical harvesting, castor husk has always been considered incorporated into the soil because it was discharged on the ground by the combine harvester as residue and not collected. Castor straw is a residue with an LHV of 17.68 MJ/kg and an ash content of 1.70 wt% [20]. For this reason, both manual and mechanical harvesting scenarios have been considered, both sold as solid biofuel (Sc1B and Sc2B) and incorporated into the soil (Sc1A and Sc2A). According to the farmer, press cake that resulted during the oil extraction phase is used as fertilizer and for this reason was always considered incorporated into the soil. Castor oil is the main product in the supply chain, and it has always been considered as sold.

2.3. Data Sampling and Measurements

Pre-harvest tests were conducted directly in the field. Four plots of 1.5m x 2m each were randomly selected within the two experimental fields in order to measure the growth of the plants and estimate the aboveground biomass produced. In each plot, plants were counted and cut at the collect level, then brought outside the field for height measurements as well as straw and capsules fresh weight determination. The height of the plant was taken by measuring the distance between the collect and the tip of the longest raceme. Samples of straw and the total capsules collected in each plot were put in sealed bags and brought to the laboratory for dry weight determination. In the laboratory, capsules were separated manually from the seeds. Thus, seeds were weighed for seed yield estimation. Simultaneously, samples of straw and empty capsules (husks) were dried at constant temperature of 105 °C in a ventilated oven until constant weight was reached (EN ISO 18134-2:2015). Then, the dry matter and humidity content were calculated. All data were subjected to the analysis of variance (ANOVA) to separate statistically different means ($P < 0.05$).

2.4. Life Cycle Assessment of Castor Oil Supply Chain

An environmental impact analysis of castor oil production was carried out using the life cycle assessment methodology (LCA) according to UNI EN ISO 14040: 2006 [22] and UNI EN ISO 14044: 2006 [23], by means an attributional approach [24–27], including the following statements: (a) Goal definition and scoping: Defining the goals of the study, the functional units, the boundaries of the system, and the required data; (b) life cycle inventory: data collection; (c) life cycle impact assessment: Estimation of the potential environmental impacts; (d) life cycle interpretation and improvement: Final step where the risks are evaluated and checked to draw conclusions.

2.4.1. Goal Definition and Scoping

The considered system is defined by all the agricultural processes that occurred during the *Ricinus communis* growing phase and subsequent oil extraction phase carried out at farm level.

The boundary of the system (Figure 3) is given by the life cycle stages of castor to be included in the LCA. Cultivation phases and extraction phase of oil were studied from cradle-to-farm gate.

The functional unit represents the reference unit used to quantify all inputs and outputs from the boundaries of the system. It is defined as 1 Mg of castor oil produced by the farm.

Firstly, the environmental impact of each single hybrid cultivar was separately analyzed for each scenario; then, each scenario was assessed to identify the best hybrid cultivar.

Allocation describes how environmental impacts are shared between the main product and co-products along the supply chain [28]. Castor oil is the main product, while crop residues (castor husks and straw) and press cakes are considered co-products [9]. In an LCA study, the co-product handling is a crucial issue because it could impact on the final results [29]. Agricultural products are particularly sensitive to allocation methods because of the different share that their co-products can have. In our case, an economic allocation method that takes into account market prices and mass of product and by-products per each scenario was used [30] (Table 4). Castor market prices are not easy

to be found, especially for castor co-products that do not have a market. For this reason, the selling price of castor seed was considered to be 600 euros per Mg, while the price of castor oil for cosmetic purposes was 30 euros per liter according to informal local market. As described above, in the absence of a market, husk and straw prices for energy purposes have been assimilated to solid biomass with similar characteristics (olive stones and wheat straw) used for energy purposes and with known market prices. In fact, following information from the informal local market as happen in other studies [31], the price of husks for energy purposes was 180 euros per Mg, while the price of straw was considered 55 euros per Mg. The prices used are those indicated by the Ricinum producers National Association of Romania (Ecoricinus Productie Comert Srl, Cluj-Napoca, 10, Fanatelor st. jud, Cluj, Romania). Even if the press cake corresponds to an important amount of biomass, due to its returns to the soil as fertilizer internally at the farm, according to the economic allocation type used and due to an absence of a market and a market price, the impact generated by the press cake was assumed to be very low (0.07%) with a minimum price of 0.1 € per Mg of by-product.

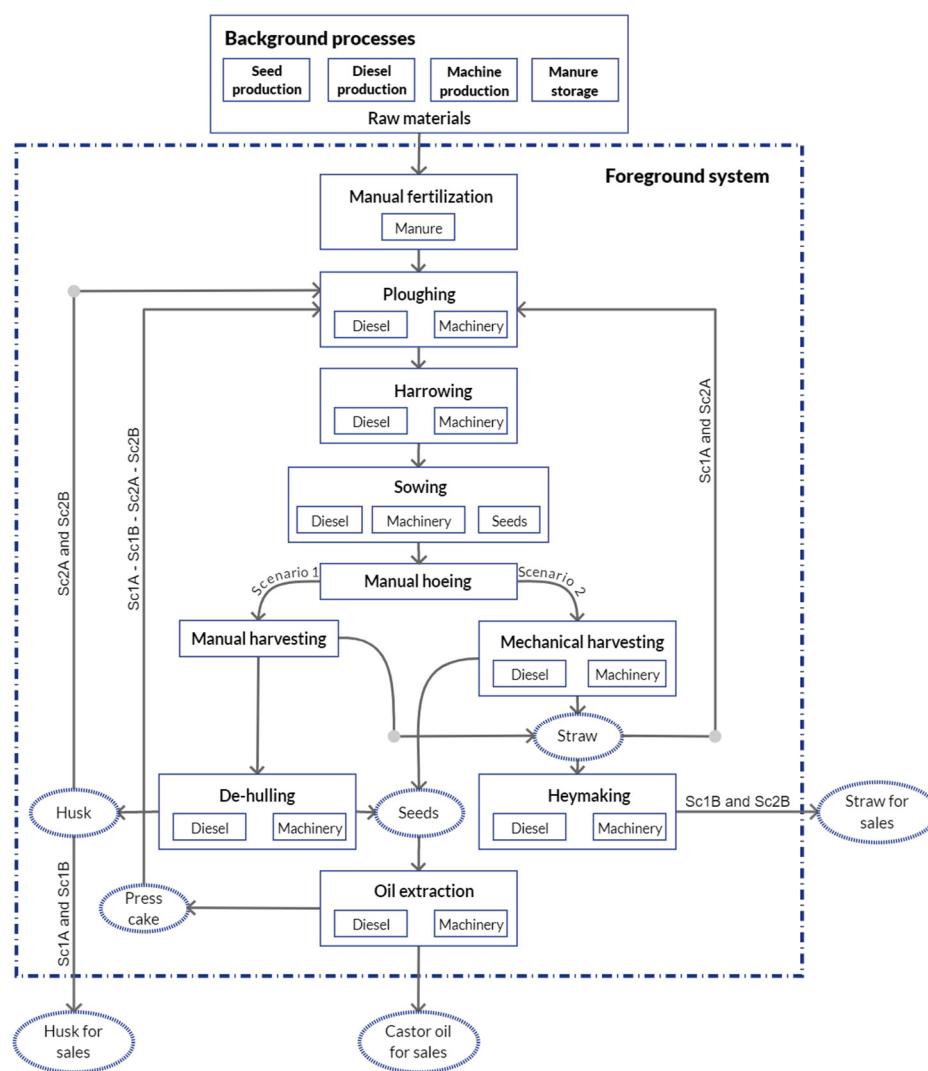


Figure 3. System boundary.

Table 4. Economic allocation factors for each castor variety.

Phases	Product and by-Products	Cultivar Hybrids	
		C-856	C-1030
Agricultural phases	Husks with seed	97.50%	95.84%
	Straw	2.50%	4.16%
	Total	100.00%	100.00%
Dehulling	Castor seed	86.96%	85.80%
	Husks	13.04%	14.20%
	Total	100.00%	100.00%
Oil extraction phase	Castor oil	99.93%	99.93%
	Press cake	0.07%	0.07%
	Total	100.00%	100.00%

Source: CREA elaboration.

2.4.2. Life Cycle Inventory Analysis

Data resulting from a survey carried out by field technicians were utilized for the life cycle inventory analysis. The Simapro code database 8.0.2 (Prè Consultants, Amersfoort, The Netherlands) was used for data not identifiable by survey.

The primary data were relative to the technical characteristics of the tractors and agricultural equipment utilized and diesel consumption (Table 5). Regarding the hypothesis of mechanical harvesting, all data for the costs, performance, and specifications of a conventional combine harvester were derived from personal communication and literature. Moreover, the primary data were relative to different castor varieties.

Table 5. Technical characteristics of the machineries, diesel consumption, and agricultural phases.

Agricultural Operation	Manual Fert.	Plough.	Harr.	Sow.	Manual Hoeing	Manual Harv.*	Mech Harv.**	Dehull.	Oil Extrac.
Machinery									
Machinery power (kW)	-	78	78	78	-	-	146	7.7	3
Machinery weight (kg)	-	3750	3750	3750	-	-	10700	250	1900
Fuel consumption (l ha ⁻¹)	-	45	15	5	-	-	25	5.1	-
Lubrificant consumption (l ha ⁻¹)	-	0.10	0.07	0.03	-	-	0.05	0.18	-
Lifetime (h ha ⁻¹)	-	12,000	12,000	12,000	-	-	3000	2000	-
Instrument used (type)	Shovel	Moldboard plow	Rolmako	Row planter	-	-	-	-	-
Instrument power (kW)	-	66	63	44	-	-	-	-	-
Weight instruments (kg)	1.5	795	2860	830	-	-	-	-	-
Lifetime (h)	4000	2000	2000	1500	-	-	-	-	-
Product utilized (type)	Manure	-	-	Seeds	-	-	-	-	-
Quantity (kg ha ⁻¹)	6000	-	-	15	-	-	-	-	-

Source: CREA elaboration on survey data. *Scenario 1. ** Scenario 2.

The secondary data referred to the emission generated by the machines during different agricultural phases and from fertilizers.

Emissions in air, soil, and underground water (leaching) due to manure storage, as well as by-products and manure incorporation into the soil per each scenario, were calculated using the model proposed by [32] and values of the references reported in Table 6.

Table 6. Secondary data: Source of the emissions considered in the study for storage and soil incorporation of the manure, and by-products (press cake, straw, and husk according to the scenario—Table 2).

Emissions	Source
Manure storage emissions	
Emissions of methane (CH ₄) and nitrous oxide (N ₂ O)	[33–35]
Ammonia (NH ₃) emissions due to manure storage	[35,36]
Nitrogen oxides (NO _x) emissions	[37], using the factor by [34]
Emissions related to soil incorporation different combinations of by-products	
CO ₂ emissions	[6,38]
N ₂ O emissions	[32]
Emissions due to soil incorporation of manure	
N ₂ O, NH ₃ , NO _x and nitrate leaching	[32]
Emission factor of Potassium, Copper and Zinc	[36]

The exhaust gases emissions from agricultural tractors and combine harvester were calculated using the standard emission factors for diesel engines reported by Directive 2004/26/EC for carbon-nitrogen oxides (g NO_x ha⁻¹), hydrocarbons (g HC ha⁻¹), monoxide (g CO ha⁻¹), and particulate matter (g PM ha⁻¹), according to the method reported by [39]. The amount of released carbon dioxide (kg CO₂ ha⁻¹) was calculated by multiplying the fuel consumption (kg ha⁻¹) by an air emission factor of 2.6 (kg CO₂ emitted per kg of diesel fuel consumed), according to [40,41].

2.4.3. Land Use Change (LUC)

The direct and indirect land use change (LUC) associated with crop production can produce changes in the carbon from soil and vegetation [42]. Castor oil can be in the form of herbaceous or arborescent plant, annual or perennial, depending on the climatic conditions of the region. In the present study, castor oil is cultivated as annual oil crop in cropland that had not undergone any land-use conversion for a period of more than 20 years [34]. Following the indications of the Intergovernmental Panel on Climate [34] there is no net accumulation of biomass carbon stocks for annual crops. On the other hand, emission from soil carbon mineralization per each scenario has been taken into consideration because there are changes in the management activities on croplands, and in particular, in the amount of biomass that has been considered incorporated into the soil according to the different scenario considered (Table 2). Even if the soil's organic carbon was considered in the steady state, and the farm analyzed employed crop rotations, different crop residue management considered in the study and the amount of GHG emitted during the different scenario were calculated according to the following formula:

$$GHG_{res} = \sum_{i=1}^3 (Res_i \times C_{res_i} \times C_{min_i} \times aw_{CO_2}) \quad (1)$$

where

GHG_{res} = Greenhouse gases emissions from soil incorporation of residue “*i*” per scenario (Mg CO₂ ha⁻¹)

Res_i = Amount of residue “*i*” incorporated into the soil (Mg ha⁻¹)

C_{res_i} = Organic carbon content in the residues “*i*” (%) [6]

$Cmin_i$ = Organic carbon in the residues “*i*” mineralized in soil (%) [38]

$awCO_2$ = atomic weight of carbon dioxide equal to 44/12

2.4.4. Life Cycle Impact Assessment

The environmental impact of 1 Mg of castor oil was based on GHG emissions. The carbon footprint was defined as the sum of all GHGs emitted within the system boundary and expressed in CO₂ equivalent applying the IPCC 2007 method (100-year life span).

A parallel economic assessment is integrated with LCA also using a life cycle perspective that covers all activities in the supply chain up to the farm gate. The economic sustainability is critical because when it comes to assessing the different products and by-products management, the attention of farmers does not fall solely on environmental impacts, but also (and mainly) on economic aspects. For this reason, an economic assessment was carried out.

2.5. Economic Assessment

The study followed the steps in LCA identified in the relevant international standard [22,23] with the corresponding steps in life cycle costing (LCC) introduced in parallel. Life cycle costing (LCC) is a methodology that aimed to assess the costs across the entire life cycle of a product, process, or service [43] concentrating on the economic cost at each stage [44]. A conventional cradle-to-gate LCC was applied here and includes the assessment of all costs associated with the life cycle of the castor-oil cultivation specific to each scenario. In particular, the LCC assessment is focused on internal costs (value of goods and services consumed, including raw materials, services, other operating expenses, and labor costs). It is important to underline that the contractors provide all phases of the preparation of the field up to sowing (bottom fertilization, ploughing, harrowing, and sowing). Everything afterwards (weed control and harvesting) is performed by the owners of the field for Sc1A and Sc1B. In Sc2A and Sc2B, all agricultural phases are in subcontractor account. Later, to evaluate the gross margin of farm, the revenues for each product (multiplying between prices and quantity of products) are calculated. Gross margin refers to the difference between revenue from crop sales and the variable costs related to the agricultural activities [44] and it is a profitability indicator of a farm. All data (Table 7) come from the budget (year 2018) of the farm studied.

Table 7. Economic data expressed in €/ha per year.

Costs (€/Year)	Cultivar Hybrids	
	C-856	C-1030
Manual fertilization	200.00	200.00
Ploughing	120.00	120.00
Harrowing	60.00	60.00
Sowing	60.00	60.00
Manual hoeing	375.00	375.00
Manual harvesting	625.00	625.00
Mechanical harvesting	180.00	180.00
Dehulling	150.00	150.00
Oil extraction	390.00	390.00
Revenues (€/year)		
Straw for sales	49.5	88.00
Husks for sales	255.00	288.00
Castor oil for sales	26,206.32	27,142.26

Source: CREA elaboration.

3. Results and Discussions

According to the literature, castor yield can change appreciably with genotype [45]. Arnaud (1990) observed a seed yield from 2000 to 2620 kg ha⁻¹ in France [46], while Anastasi (2015) reported a yield between 1790 to 4750 kg ha⁻¹ in Italy [47]. In the present research, the genotypes of castor grown showed similar productions of 2800 and 2900 kg ha⁻¹ for C-856 and C-1030, respectively. However, the C-1030 hybrid, which is higher than C-856 and has a significantly higher HI (Table 2), produced 85% more straw than C-856, with the same inputs used.

Alexopoulou et al. [6], from the comparison of various castor hybrids planted in Greece and Italy, found an average amount of stems and leaves of 1.08 Mg_{dm} ha⁻¹, and the hybrid C-856, that resulted as 133 cm tall (79% taller than in our study) in Greece (Aliartos area, Greece in 2014), allowed for obtaining 1.13 Mg_{dm} ha⁻¹ of stems and leaves against 0.87 Mg ha⁻¹ obtained in the present study. In the same study, the C-856 hybrid produced a straw quantity of 0.585 Mg ha⁻¹, much more similar to that obtained in this study in 2012 in Greece (Aliartos area, Greece in 2014) [6]. In general, Alexopoulou et al. [6] highlighted that C-856 resulted as the best-performing hybrid in Italy while in Greece, its yields were quite low, probably related to the high percentage of immature racemes (60%) at harvest. This suggests the influence of the climate and crop management on the phenotype expression of this hybrid. To the best of our knowledge, there is no information in the literature about the C-1030 hybrid.

The type of harvesting represents a critical phase that can also have a significant influence on the amount of product that can be collected per unit area. Mechanized harvesting allows for collecting about 3 t/h of castor oil seeds (considering a harvesting rate between 0.75 and 1.5 hectares per hour) ready to be pressed. On the other hand, according to farmers, manual harvesting shows extremely low losses <5%. On the contrary, castor mechanized harvesting needs to be improved due to the major losses, which can be up to 50% as evidenced by [48]. So far, only one machine manufacturer has started the first harvesting tests using a specific castor header, which would be able to reduce losses to 5% [48], and Zhao et al. [49] reported the possibility to harvest the capsules using a vibrating system instead of a cutting bar [49]. In the present study, losses were not considered given the uncertainty of the data to be scientifically verified in specific tests.

3.1. LCA

The impact analysis allowed for identifying the processes that had higher impacts on the environment.

What emerged from the analysis was that fertilization was the agricultural phase with the most impact. This result is common to various studies [50–56]. In the present study, for all cultivar hybrids and scenarios, the environmental impacts of fertilization phase were due to emissions of methane (CH₄), dinitrogen monoxide (N₂O), and carbon dioxide (CO₂) from manure management and its incorporation into the soil. In fact, fertilization emitted 74 to 89% of the GHG of the castor oil production. The LCA study of biodiesel production from rapeseed published by Malça et al. [57] reported that the cultivation stage impacted 66 to 79% and fertilization was the main cause of GHG emissions [57]. According to our results, the higher GHG emissions were mainly due to the characteristics, and the direct and indirect emissions were generated by manure itself. It should be highlighted that, as suggested by Aguilera et al. [58], organic fertilizers applied at similar N rates to synthetic fertilizers generally make smaller contributions to the leached NO₃⁻ pool, and can mitigate N₂O emissions [58]. The different by-product management also influenced the indirect emissions of GHG due to their degradations during soil incorporation.

In the case of castor oil produced by both C-856 and C-1030 cultivar hybrids, as expected, the manual harvesting resulted as more sustainable (Sc1A and Sc1B), and Sc1B scenario was always the least impactful, followed by scenarios 1A and 2B (Figures 4 and 5).

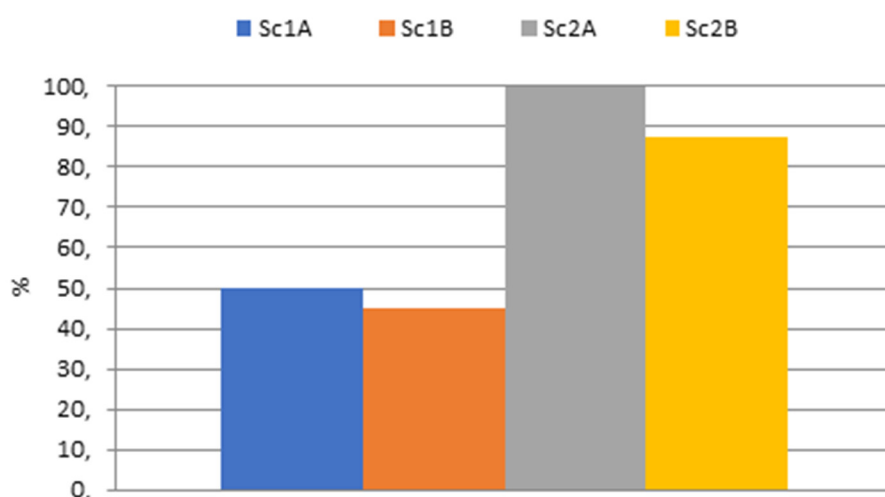


Figure 4. Carbon footprint of 1 Mg of castor oil hybrid C-856 for each scenario ((Sc1 = scenario 1; Sc2 = scenario 2).

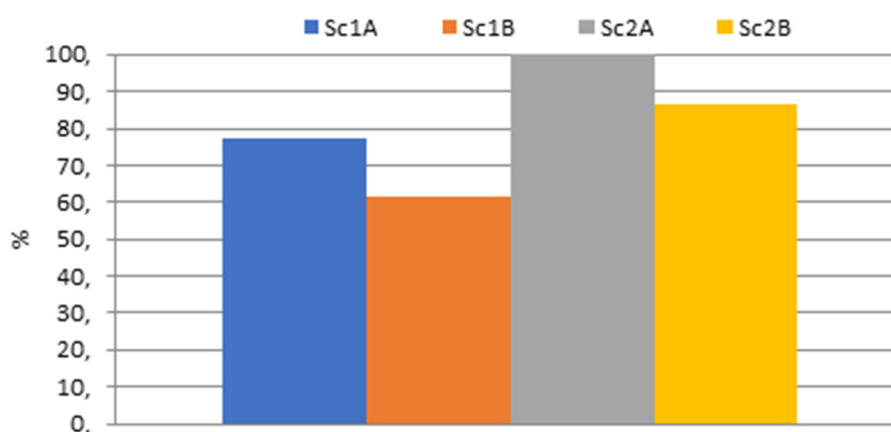


Figure 5. Carbon footprint of 1 Mg of castor oil hybrid C-1030 for each scenario (Sc1 = scenario 1; Sc2 = scenario 2).

Moreover, among cultivar hybrids and all scenarios, Sc2A_C-1030 is more impactful than the other treatments analyzed, while the Sc1B_C-856 is less burdensome than others. These results were due to both different combinations of on-farm by-products (castor press cake incorporation into the soil in case of 1B_C-856, and castor press cake, straw and husks incorporation into the soil in case of 2A_C-1030) and yields (2.8 Mg per ha in case of C-856 vs. 2.9 Mg per ha in case of C-1030). In general, the incorporation of by-products in the soil at farm level has resulted in higher GHG emissions than their sale. For this reason, the highest impact observed in the mechanized harvesting treatments (Sc2A and Sc2B) is largely due to the non-collection of husks that are left in the field by the combine and then buried (unlike manual harvesting where husks are separated from the seeds on the farm and then sold as solid fuel). Obviously, the study focused on the impacts related to the production of castor oil on the farm, not considering the whole process downstream of the supply chain and the related impacts that could completely reverse the results obtained.

The life cycle of scenario 1B, in which manual harvesting was assumed (less burdensome in the case of hybrid C-856, slightly less productive, and with less press cake), and with the incorporation of the pressed cake alone and the sale of the other by-products, resulted in the emission of 8.14 Mg CO₂eq per Mg of castor oil (8.14 kg CO₂eq per kg of castor oil extracted). On the other hand, the life cycle of scenario 2A_C-1030, in which mechanized harvesting with combine harvesters and the incorporation of straw, husks, and press cakes was assumed, resulted in the emission of 18.9 Mg CO₂eq per Mg of castor oil produced (18.9 kg CO₂eq per kg of castor oil extracted).

Although, in Sc1A and Sc1B scenarios, there is the de-hulling phase that there is not in Sc2A and Sc2B, this has a very small impact always <8% (on average 0.698 Mg CO₂eq Mg⁻¹ of castor oil produced) of the total CO₂ emissions. The oil extraction impacted less than 5% of the total CO₂ emitted (on average 0.412 Mg CO₂eq Mg⁻¹ of castor oil). Sanz Requena (2010) reported that for each ton of crude sunflower, rapeseed, and soybean oil extracted, an average of 2.2 Mg of CO₂ was emitted, but it should be highlighted that after the mechanical extraction, a treatment with a solvent (hexane) was included [54].

Spinelli (2012) reported a total emission of 13.7 Mg CO₂eq Mg⁻¹ of sunflower oil produced [59]. However, according to the study and the allocation used, the emissions became 4.52 Mg CO₂eq Mg⁻¹ of sunflower oil and 9.18 Mg CO₂eq Mg⁻¹ of sunflower cake produced. The lack of allocation of a higher share of emissions from the press cake makes castor oil production inevitably more impactful in GHG emitted than other vegetable oils, although the variety C-856 with manual harvesting have relatively low and promising overall emissions.

3.2. Economic Assessment

The economic gross margin is related mainly to the yield level (product and by-products) and to the cost of inputs for each scenario and cultivar hybrid. As far as the yield is concerned, the values for each farm and crop have been previously discussed and the data are reported in Table 8, showing higher yields per ha for C-1030 than for C-856 crops. For these reasons, the C-1030 cultivar shows lower total costs per Mg cultivated than C-856 ones (Table 8). Moreover, for both cultivar hybrids, the total costs of manual harvesting scenario are higher than mechanical harvesting scenario ones. This finding was due to labor costs in harvesting phase. In fact, in case of the manual harvesting scenario, five workers are required to harvest castor seed, contributing 32% to the total costs; while in case of mechanical scenario one worker (with machinery) is required contributing just 13% to the total costs. The impact that manual harvesting has on costs can be equated to that reported by Silalertruksa (2012) in Thailand, where manual harvesting accounts for 22% of total costs in the palm oil sector [60].

Table 8. Economic gross margin for each scenario expressed in €/FU (1 Mg of castor oil)—(Sc1 = scenario 1; Sc2 = scenario 2).

	Cultivar Hybrid: C-856 Scenarios				Cultivar Hybrid: C-1030 Scenarios			
	Manual		Mechanical		Manual		Mechanical	
	Sc1A	Sc1B	Sc2A	Sc2B	Sc1A	Sc1B	Sc2A	Sc2B
Costs (€/Mg) *								
Manual fertilization	72.42	71.42	71.42	71.42	68.96	68.96	68.96	68.96
Ploughing	42.85	42.85	42.85	42.85	41.38	41.38	41.38	41.38
Harrowing	21.43	21.43	21.43	21.43	20.69	20.69	20.69	20.69
Sowing	21.43	21.43	21.43	21.43	20.69	20.69	20.69	20.69
Manual hoeing	133.93	133.93	133.93	133.93	129.31	129.31	129.31	129.31
Harvesting	223.21	223.21	64.28	64.28	215.52	215.52	62.07	62.07
Dehulling	53.57	53.57	-	-	51.72	51.72	-	-
Oil extraction	139.28	139.28	139.28	139.28	134.48	134.48	134.48	134.48
Total Costs (€/Mg)	708.12	708.12	494.62	494.62	682.75	682.75	477.58	477.58
Revenues (€/Mg)								
Straw for sales	-	4.58	-	4.58	-	7.61	-	7.61
Husks for sales	76.24	76.24	-	-	81.57	81.57	-	-
Castor oil for sales	31,166	31,166	31,166	31,166	31,166	31,166	31,166	31,166
Total Revenues (€/Mg)	31,242	31,246	31,166	31,170	31,247	31,255	31,166	31,173
Gross Margin (€/Mg)	30,533	30,537	30,671	30,675	30,564	30,572	30,688	30,695

Source: CREA elaboration on budget data (year 2018). * For each agricultural phase are included the internal costs (i.e., value of goods and services consumed, including raw materials, services, other operating expenses and labor costs).

Table 9 shows that the 2B_C-1030 scenario had higher gross margin than other scenarios; while the 1A_C-856 scenario had the lowest gross margin.

Table 9. Gross margin and carbon footprint for each scenario, expressed in €/FU (1 Mg of castor oil)—(Sc1 = scenario 1; Sc2 = scenario 2).

	Unit	Cultivar Hybrid: C-856 Scenarios				Cultivar Hybrid: C-1030 Scenarios			
		Manual		Mechanical		Manual		Mechanical	
		Sc1A	Sc1B	Sc2A	Sc2B	Sc1A	Sc1B	Sc2A	Sc2B
Gross Margin	(€/FU)	30,533	30,537	30,671	30,675	30,564	30,572	30,688	30,695
GWP	(kg CO ₂ eq/FU)	9070	8140	18,100	15,800	14,600	11,600	18,900	16,300
Gross Margin/GWP ratio	(%)	3.37	3.75	1.69	1.94	2.09	2.63	1.62	1.88

Source: CREA elaboration on both budget data (year 2018) and environmental findings.

In addition, the ratio between gross margin and GWP emissions was applied to calculate the economic performance (gross margin) per unit of environmental burden (Table 9). The ratio is based on data from both environmental and economic accounting systems. The higher the ratio value, the higher the economic performance per unit of GWP emitted.

Findings showed that scenario 1B in the case of C-856 cultivar hybrid had a better ratio between economic performance and GHG emitted into the atmosphere (€3.75 per kg CO₂eq); while the 2A_C-1030 scenario showed the worst ratio between economic and environmental performances (€1.62 per kg CO₂-eq) confirming the environmental results. These results were due to different combinations of on-farm by-products (see Table 3), different revenues (see Table 8), and yields (see Table 2).

4. Conclusions

There has been a critical increment in interest for sustainable and biodegradable items so as to diminish reliance on petrochemicals. This is one of the essential elements which is driving the growth of the worldwide castor oil market. The research focused on the evaluation of the environmental and economic sustainability of two different castor hybrids (C-856 and C-1030) comparing manual and mechanical harvesting methods, and by-product management.

Comparing all the proposed scenarios, the cultivation of the manually harvested castor hybrid C-856 and the by-product management that involved only the soil incorporation of press cake obtained by the oil extraction resulted as the most sustainable. On the other hand, the mechanized harvesting of hybrid C-1030, which involved the incorporation of all the by-products of the cultivation of castor and production of castor oil (husk, straw, and press cake) showed the highest CO₂ emissions per Mg of castor oil (+132%). It is therefore clear how, with the same inputs used, the castor-oil cultivation method affects the management of by-products and how, while residues are a source of organic matter for the soil, they cause greenhouse gas emissions during the degradation process in the soil.

From an economic point of view, a difference in Gross Margin (€/Mg) between the hybrids used was only evident when comparing the scenarios in which mechanized harvesting was used, i.e., C-856_Sc2A vs. C-1030_Sc2A and C-856_Sc2B vs. C-1030_Sc2B, resulting in an increase in Gross Margin of 6 and 7%, respectively, using the hybrid C-1030. The two hybrids when harvested manually did not show appreciable increases in Gross Margin (0.1%). In general, the scenario that produced most Gross Margin was the C-1030_Sc2B where mechanized harvesting of the plants, the incorporation of husk and press cake, and the sale of castor oil and straw were carried out.

In the end, to determine the most economically and environmentally convenient scenario, the ratio between gross margin and GWP emissions was applied to calculate the economic performance (gross margin) per unit of environmental burden. Findings showed that scenario Sc1B in the case of C-856 cultivar hybrid had a better ratio between economic performance and GHG emitted into the atmosphere

(€3.75 per kg CO₂eq); while the Sc2A_C-1030 scenario showed the worst ratio between economic and environmental performances (€1.62 per kg CO₂eq) confirming the environmental results.

Although Sc1B represents a good economic–environmental compromise, including manual harvesting, it clashes both with the need to innovate the castor production chain, and with the costs and availability of labor that may vary over time, affecting the sustainability of the chain, costs, and market prices.

Furthermore, an important aspect that was not considered in the study is the loss of product during harvesting. This is particularly relevant in the case of very high losses that are reflected in the impacts per unit of product. With the implementation of well-functioning mechanized castor harvesting systems, the resulting seed losses will also necessarily have to be considered in future studies.

Moreover, it is important to highlight that the study did not consider the whole process downstream of the castor oil extraction and the related impacts that could completely reverse the results obtained, which should be investigated in future researches.

Ultimately, the lack of official economic data on the market prices of products and by-products, and the difficulty of finding the costs resulting from the various cultivation practices, within the castor production chain, as old as it is, currently undergoing improvement and modernization, represents a limit to obtaining exhaustive answers on its economic sustainability. For this reason, this research does not have the presumption to provide a definitive answer to the questions related to the environmental and economic sustainability of the castor-oil production chain, which will need further study and analysis as the production methods are refined.

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