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The Eco-Efficiency of Castor Supply Chain: A Greek Case Study

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Abstract: Castor is a candidate crop that grows in marginal lands in the Mediterranean area. It can be grown by utilizing minimal resources to provide unique industrial chemicals or to serve as an energy crop. However, it can be also cultivated with intensive inputs providing higher yields. Whether a high input or a low input scheme is more sustainable depends on the economic and environmental impacts of each case. The objective of the present study, therefore, was to evaluate these impacts under the Mediterranean climate and farming conditions by examining two alternative scenarios: a castor crop grown on a low-inputs field vs. a crop grown in a high-inputs one. The environmental impacts were estimated by following a Life Cycle Assessment (LCA) methodology based on GHG emissions. Furthermore, a sensitivity analysis was performed by switching the functional unit from 1 Mg of castor oil to 1 hectare. The economic feasibility of the castor crop production was assessed by calculating the gross margin, which is referred to the difference between revenues and the variable costs due to the agricultural phases. In addition, the ratio between gross margin and GWP (Global Warming Potential) emissions was applied to calculate the economic performance (gross margin) per unit of environmental burden. Findings showed that the castor oil produced by high inputs resulted in a more sustainable scenario due to its higher yield than low-inputs ones. On the other hand, sensitivity analysis showed that the field management with low inputs showed GHG emissions that were 27% lower than those emitted from the field management with high inputs. Moreover, from an economic point of view, by switching the field management from low inputs to high ones, the Gross Margin increased by about 73%. Finally, the high-inputs scenario showed the best ratio between economic performance and GHG emitted into the atmosphere.

Keywords: bioeconomy; castor oil; industrial vegetable sustainability; life cycle assessment (LCA); life cycle costing (LCC); *Ricinus communis* L.; sensitivity analysis

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1. Introduction

The world's population is expected to reach 9.1 billion people by 2050 [1] and therefore an increase in global food and energy demand cannot be avoided. In fact, food production will rise by 70% and the overall demand for energy is expected to increase by more than a quarter by 2040 [2,3]. In this framework, one of the major issues consists of the competition among food and non-food crops. The European Commission has been facing it with new measures in order to achieve sustainable production of both food and bio-energy. In fact, the RED II directive established the new requirements for minimum renewable energy share and it aims to achieve the 27% renewable energy share consumed by some sectors, such the electricity, heating and cooling ones, in 2030 [4]. The energy crops use could lead to benefits such as the reduction of fossil energy dependence, improvement of rural economies and the reduction of environmental impacts [5].

Among the species proposed for energy uses, castor is a promising candidate due to its tolerance to biotic and abiotic stresses, which makes the species suitable for cultivation on marginal areas [6]. Castor bean is a tropical plant with several wild and semiwild types which can differ both genotypically and phenotypically [7], with habitus ranging from a shrub to a little tree to even a small annual plant [8,9]. It shows high plasticity and adaptability to grow in several different climatic zones [10]. The European Project MAGIC (Marginal lands for Growing Industrial Crops) [11] demonstrated that castor is among the resource-efficient and economically profitable industrial crops that can be grown on marginal lands in Europe for its seed oil, which, thanks to the particular fatty acid composition [12], is employed extensively in biorefineries [13].

According to Pari's et al. study [3], the global castor oil market is growing; in fact, in 2018 it was worth USD 1180 million and it is expected to reach USD 1.470 million in 2025. Until recently, castor harvesting relied on hand-picking of the fruits so the main production came from countries with low labor costs such as India, China and Brazil. However, the recent advances in mechanical harvesting, along with the development of new dwarf hybrids adapted in mechanical manipulation, fostered interest in growing castor in marginal conditions in the Mediterranean area [14–18]. It is also worth mentioning that Europe is one of the main importers of castor oil and the demand has largely increased during the last few years [14]. Results of field trials carried out in different Mediterranean countries for the evaluation of different castor cultivars reported a seed yield potential up to 4 Mg ha^{-1} [19,20]. This promising finding, along with the increased demands for castor oil imports during the last few years, identifies castor bean as an ideal non-food crop [21] for Europe. However, the cultivation practices in terms of use of inputs should be optimized in order to promote sustainable and viable crop production.

Sustainable agricultural systems today imply the optimization of the inputs in order to reduce the ecological impacts [22]. The concept of sustainable agriculture is based on a set of ideas drawn from economic, social and environmental aspects whose main objective is to improve the efficiency of resources in order to balance the relationship between the economy, the environment and society [3,23,24]. In other words, sustainable agriculture requires the development of a balanced production system that takes economic, social and environmental aspects into consideration [23]. For these reasons, extended studies are necessary in order to assess the optimum balances [25–27]. To the best of our knowledge, notwithstanding the high interest of scientific community in castor bean, a few articles have been published analyzing the environmental and economic sustainability of castor (e.g., [3,28,29]) and only one [3] investigated the impacts of two different castor hybrids comparing four by-products management scenarios in Romania. Given that the agricultural phase is the step with the highest environmental impacts and the lowest economic value [25,30–32], a comparison of the environmental and economic impacts between different field managements has not been studied in the aforementioned literature [3]. In this realm, the present work aims to fill this gap by estimating the environmental and economic impacts of a conservative "low input" and an intensive "high-input" castor production system under Greek Mediterranean conditions. It is a case study approach [3,33,34], in which the authors try to identify the best field management system under environmental and economic point of view, on specific agroclimatic conditions. To that end, we estimated an eco-efficiency ratio (which measures the value added per 1 Mg of GHG emitted into the atmosphere [24]) to identify the most advantageous scenario.

2. Materials and Methods

2.1. Study Sites

Two study sites were selected in the University of Thessaly Farm in Central Greece (Figure 1). The two experimental fields were 500 m apart, but soil samples taken from both fields at a depth of 0.3 m and sent to laboratory for analysis indicated that the fields shared similar clayey soil features with average values of: 47.1% clay; 32.7% silt; 20.1% sand (Bouyoucos method [35]); 1.48% OM (Walkley and Black method [36]); PH 7.9. One field (0.94 ha; (39°24′4.84″ N; 22°45′37.65″ E; 68 m a.s.l.) was characterized as low input, and it received minimal field operations and reduced amounts of agricultural goods, while the other one (0.20 ha; 39°23′47.10″ N; 22°45′24.18″ E; 71 m a.s.l.) was characterized as high input, and inputs were based on data already mentioned in the literature [20,37].

Figure 1. Experimental fields in the University of Thessaly farm. Aerial photos taken at 23 August 2021.

Low inputs field management This site included an experiment with three different chemical applications for crop termination. In the present study, only the treatment including diquat as a chemical terminator was used in order to obtain comparable results with the high-input field where the same product was used. The crop was established with direct drilling on 24 April 2021 at row distance of 0.75 m using 62,300 seeds per ha. In detail, the utilized hybrid was provided by Kaiima (Moshav Sharona, Israel) and it is named C1012. For the control of the natural vegetation, glyphosate was applied 14 April 2021 at a rate of 5.0 l per ha. Mechanical hoeing was also performed in June to control late weeds. Fertilization phase included the addition of 13 kg N and 46 kg P spread with a centrifugal spreader as a basal dressing prior sowing, which was accomplished with the addition of 58.5 kg N per ha during two fertigation applications. No potassium was applied as the soils of east Thessaly are considered generally rich in Potassium [38] and the usual practice is to exclude it from the fertilization schemes. For crop irrigation, a gun sprinkler was used during the first two events, applying a total of 800 m^3 ha^{-1}, while a drip irrigation system with 16 mm pipes was established later on to provide further 4300 m^3 ha^{-1} of water in seven irrigation events. The castor crop was terminated by applying Diquat 27 August 2021 at the dose of 6 l ha^{-1}. Harvesting was performed manually 15 September 2021. The average seed yield was 1241 kg ha^{-1} (fresh weight). Crop residues were collected with a rectangular baler and loaded to a platform with a forklift. The straw yield was 590 kg ha^{-1}.

High-inputs field management. The same hybrid at the same row spacing and population was used. Nonetheless, seedbed preparation was considerably different following a traditional tillage practice with ploughing at a depth of 0.28 m, accompanied by one pass of a heavy cultivator and one pass of a tandem disk harrow. The tillage operations destroyed the natural vegetation, so glyphosate application at the beginning was not needed. A row crop cultivator was still necessary to control later weeds in June. Higher doses of fertilizers were also used. Basal fertilization phase included 36.3 kg N, 49.5 kg P and 49.5 kg K per ha. A further 63.8 kg N per ha were applied through fertigation. Gun sprinkler was used again for the initial irrigation, through which 600 m^3 of water per ha were applied while a drip system was established successively to further provide 6200 m^3 ha^{-1} of water. The same irrigation system was used for both sites. Apart from irrigation, another 284 mm of water were received on both sites through seasonal precipitation. Crop termination and harvesting was similar to the low input site. Seed yield (fresh weight) was 3680 kg ha^{-1} while straw yield was 2060 kg ha^{-1}.

2.2. Life Cycle Assessment: The Steps

The analysis of the environmental impacts related to castor oil production was performed, applying the life cycle assessment methodology (LCA) according to UNI EN ISO 14040 e 14044: 2006 [39,40] and following an attributional approach [25,41].

Goal and scope definition. In the LCA system boundary (Figure 2) all the agricultural phases are considered and the subsequent oil extraction phase at farm level as well; meanwhile the functional unit, which consists of the reference unit used to calculate all inputs and outputs from the boundaries of the system, is set as 1 Mg of castor oil produced by the farm. Moreover, the results of a LCA study can be affected by several uncertainty sources, mainly due to the methodological choices, such as allocation rules [42]. In fact, the allocation rules can change the LCA findings and for this reason it is necessary to apply a sensitivity analysis. In our case, a sensitivity analysis was carried out by changing the functional unit and switching from 1 Mg of product (castor oil) to 1 ha of cultivated surface. Moreover, the used allocation method was the economic one (Table 1) and the allocation percentages were retrieved from the most recent literature [3].

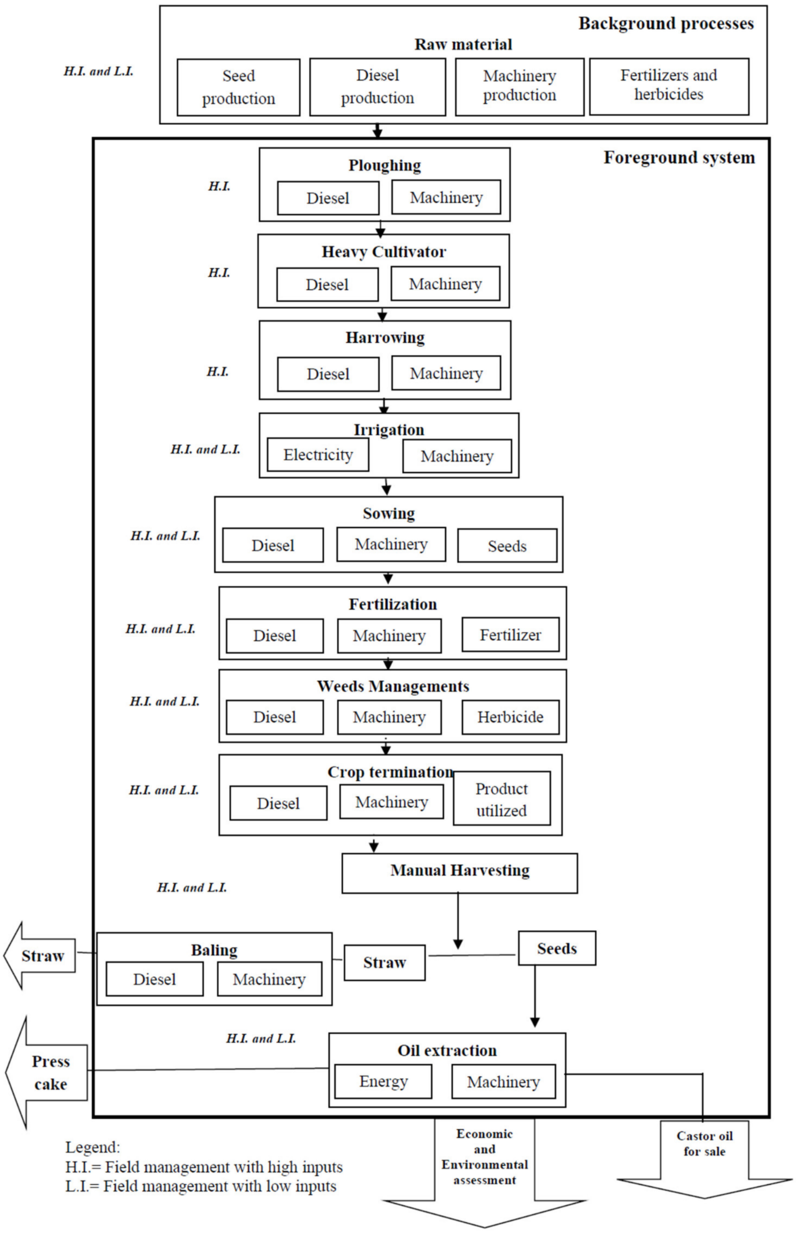

Figure 2. System boundary of the two different field management methods.

Table 1. Allocation percentages for each phase.

Phases	Product and By-Products	Allocation
Agricultural phases	Husks with seed Straw	95.84% 4.16%
Total		**100.00%**
Oil extraction phase	Castor oil Castor mill	99.93% 0.07%
Total		**100.00%**

Source: extracted by Pari et al. 2020 [3].

Life Cycle Inventory. The necessary data for the assessment—for instance, the technical features of tractors and agricultural equipment, fuel consumption, kind and dose of herbicides and fertilizers applied—were derived from the survey (Tables 2 and 3). The secondary data (i.e., data referring to the emission related to the machineries during different agricultural phases and from fertilizers and herbicides used) were derived from the Simapro code database 8.0.2 (Prè Consultants, Amersfoort, The Netherlands) as reported in similar studies in the current literature (e.g., [3,25])

Table 2. The life cycle inventory analysis for low inputs field management.

Agricultural Operation	Plough.	Heavy Cultivator	Harr.	Irrigation	Sow.	Fert.	Weeds Manag	Crop Termination	Manual Harv.	Baling	Oil Extrac.
Tractor power (kW)	-	-	-	23	56.4	56.4	56.4	56.4	-	82.1	3.00
Tractor weight (kg)	-	-	-	120	3100	3100	3100	3100	-	4500	1900
Fuel or electricity consumption (l ha^{-1})	-	-	-	4366 kWh	1.32	1.32	9.46	1.18	-	3.5	-
Lubricant consumption (l ha^{-1})	-	-	-	-	0.05	0.06	0.04	0.04	-	0.07	-
Lifetime (h ha^{-1})	-	-	-	12,000	12,000	12,000	12,000	12,000	-	16,000	-
Machineries used (type)	-	-	-	-	Monosem NX2 (4 rows)	Centrifugal spread 12 m	Boom type sprayer (10 m)	Boom type sprayer (10 m)	-	Forklift and Platform 2 ton	-
Machineries power (kW)	-	-	-	-	30.4	12.4	10.2	10.2	-	-	-
Weight Machineries (kg)	-	-	-	-	1350	165	130	130	-	1550	-
Lifetime (h)	-	-	-	-	2000	1200	1500	1500	-	3000	-
Product utilized (type)	-	-	-	Water	Seeds	13-46-0 (N-P-K)	Glyphosate 36EC	Diquat	-	-	-
Quantity (kg ha^{-1})	-	-	-	5,100,000	19.3	270	5.00	5.00	-	-	-

Source: Our elaboration on survey data and oil extraction phase comes from Pari et al. [3].

Life Cycle Impact Assessment. Following our previous work [3], the environmental impacts of 1 Mg of castor oil production was based on the related GHG emissions. In particular, the carbon footprint was defined as the overall amount of all GHGs emitted during agricultural phases within the considered system boundary and expressed in CO_2 eq. applying the IPCC 2007 methodology (GWP−100 year life span−V1.02) [3]. Following the current literature [3,24,27,43], the carbon footprint was calculated with a "cradle-to-gate" approach which includes the full life cycle of a product (i.e., from cradle to farm gate). It is important to underline that the carbon footprint was calculated using the Simapro code 8.0.2 (Prè Consultants, Amersfoort, The Netherlands). Moreover, an economic evaluation was carried out in parallel with LCA also using a life cycle approach that considers all the activities in the supply chain at farm level. The economic assessment is obviously a critical issue because in the assessment of different alternatives for management, the focus of farmers is not only on environmental impacts, but also (and mainly) on economic ones.

Table 3. The life cycle inventory analysis for high-inputs field management.

Agricultural Operation	Plough.	Heavy Cultivator	Harr.	Irrigation	Sow.	Fert.	Weeds Manag	Crop Termination	Manual Harv.	Baling	Oil Extrac
Tractor power (kW)	82.1	82.1	82.1	23	56.4	56.4	56.4	56.4	-	82.1	3.00
Tractor weight (kg)	4500	4500	4500	120	3100	3100	3100	3100	-	4500	1900
Fuel or electricity consumption (l ha^{-1})	49.2	49.2	49.2	4366 kWh	1.32	1.32	9.46	1.18	-	3.5	-
Lubricant consumption (l ha^{-1})	0.05	0.05	0.05	-	0.05	0.06	0.04	0.04	-	0.07	-
Lifetime (h ha^{-1})	16,000	16,000	16,000	12,000	12,000	12,000	12,000	12,000	-	16,000	-
Machineries used (type)	Moaldboard plough	Tine cultivator (heavy type)	Tandem disk harrow	-	Gasperdo (4 rows)	Centrifugal spread 12 m	Boom type sprayer (10 m)	Boom type sprayer (10 m)	-	Forkift and Platform 2 ton	-
Machineries power (kW)	59.9	59.1	46.0	-	14.1	12.4	10.2	10.2	-	-	-
Weight machineries (kg)	850	450	1050	-	740	165	130	130	-	5500	-
Lifetime (h)	2000	2000	2000	-	2000	1200	1500	1500	-	3000	-
Product utilized (type)	-	-	-	Water	Seeds	11-15-15 (N-P-K)	Glyphosate 36EC	Diquat	-	-	-
Quantity (kg ha^{-1})	-	-	-	6,800,000	19.3	515	5.00	5.00	-	-	-

Source: Our elaboration on survey data and oil extraction phase comes from Pari et al. [3].

2.3. Life Cycle Costing

The LCC applied in the current study relied on LCA steps as reported in the following standards [39,40]. LCC is used to assess the costs along the whole life cycle of a given product, process or service [3], focusing on costs of each step [44]. A conventional cradle-to-gate LCC was used, including the evaluation of all costs associated with the life cycle of the crop cultivation specific to each field management (i.e., field management with high inputs versus field management with low inputs). In particular, following a study by Pari et al. [3], the LCC assessment was centered on the internal costs (value of goods and services consumed, including raw materials, services, other operating expenses and labor costs). Finally, to evaluate the gross margin of the farm, the revenues for each field management (multiplying castor oil price and quantity of product) were assessed. It is important to underline that the selling prices of energy crop analyzed in this study were linked to the cultivation contracts, as happens in many studies (see e.g., [25,27,45]). For this reason, in the economic evaluation, the market castor oil price was EUR 591.88 per Mg [46]. Finally for each field management, the gross margin (that refers to the difference between revenues and the variable costs due to the agricultural phases [3]) was calculated. All data (Table 4) come from the experimental fields studied.

Table 4. Economic data expressed in EUR/ha for each field management.

	Fields Management	
Costs (EUR/Year)	**Low Inputs**	**High Inputs**
Ploughing	-	70.00
Heavy Cultivator	-	60.00
Harrowing	-	40.00
Irrigation	200.00	200.00
Sowing	30.00	30.00
Fertilization	20.00	20.00
Weeds Management	40.00	30.00
Crop termination	35.00	20.00
Manual harvesting	150.00	150.00
Baling	90.00	90.00
Oil extraction	100.00	100.00
Revenues (EUR/year)		
Castor oil for sales	782.46	2178.00

Source: Our elaboration on both survey data and data comes from the literature [3,45,46].

3. Results and Discussions

3.1. LCA

The impact analysis allowed identification of the processes that implied the highest level of impact on the environment. The analysis revealed that fertilization was the agricultural phase with the highest impact, as it occurs frequently in many studies on environmental impacts [3,25,27,47–51]. In the present study, for both scenarios, the environmental impacts of fertilization operation were related to emissions of methane (CH_4), dinitrogen monoxide (N_2O) and carbon dioxide (CO_2) as a consequence of incorporation into the soil. Indeed, fertilization accounted for 74 to 89% of the GHG of the overall castor oil production [3]. According to Malça et al. [52], the cultivation phase of rapeseed for biodiesel production impacted from 66 to 79% of total impacts and fertilization was the main cause of GHG emissions. According to Pari et al. (2020) [3], higher GHG emissions were mainly due to the characteristics of the fertilizer applied (namely manure or chemical fertilizer), and both direct and indirect emissions were generated by fertilizer itself. Despite the higher GHG emissions orienting from the use of fertilizers in the high input field, the case study proved more sustainable due to its significant higher yield. (Figure 3). In fact, according to the current literature [25], the environmental impacts are associated with the yield per hectare. In our case, the castor oil production in the high-inputs regime was higher than in the low-inputs one. Therefore, the environmental impacts of the high-input management were lower if the per Mg functional unit was considered. It is apparent that from a managerial point of view, crop management schemes should rely on potential productivity. In high-productive fields characterized by high yield potentials, high-input crop management and large use of fertilizers, water and other resources, may use the available inputs more effectively. On the other hand, in fields with low yield potentials, the inputs should be reduced (or finely adjusted to chemical properties of the soil) in order to avoid the loss of nutrients, such as that which occurs through nitrogen leaching, which is dangerous for environment and economically unsustainable [25,27].

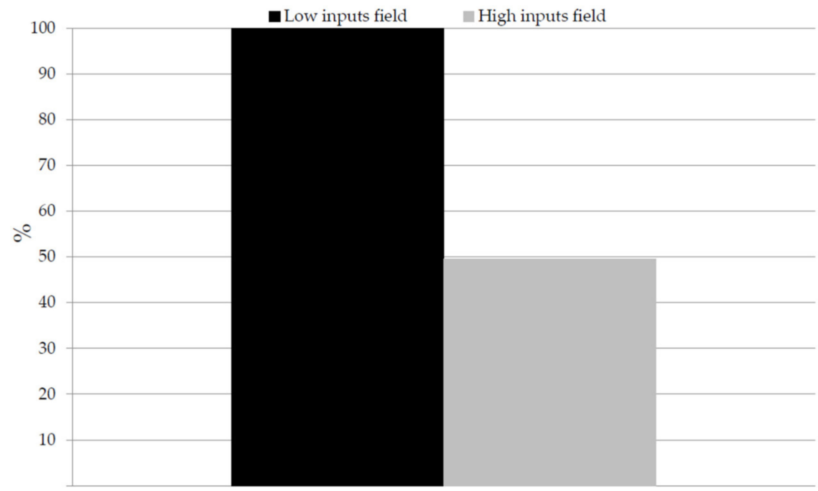

Figure 3. The carbon footprint of the two different fields management (FU = 1 Mg of castor oil). The values are expressed as percentages in relation to the field management with the highest environmental impact, which is expressed as 100%.

When a sensitivity analysis is performed by switching the functional unit from 1 Mg of oil to 1 hectare, the findings change. In fact, comparing GHG emissions deriving from high-input and low-input management systems, the latter exhibits 27% lower emissions (Figure 4). These results are consistent with the current literature [25,27] where the switching of the functional units capsizes the findings. The findings, as expected, were due to different agricultural phases considered for each scenario (see Figure 1). In fact, in a low-inputs system the emission was 878 kg CO_2 eq.; under high-inputs management, it reached 1210 kg CO_2 eq.

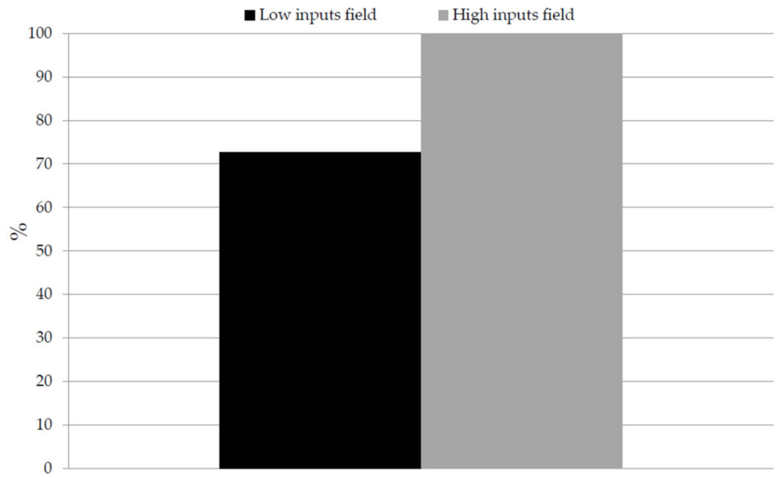

Figure 4. The carbon footprint of the two different fields management (FU = 1 ha^{-1}). The values are expressed as percentages in relation to the field management with the greatest environmental impact, which is expressed as 100%.

3.2. Economic Assessment

The gross margin of both management systems (which refers to the difference between revenues and the variable costs due to the agricultural phases [3]) was calculated taking into account oil yield and the relative costs. Concerning the oil yield in castor crop, the productivity recorded in high-input systems was higher and, consequently, the cost of production per Mg of products was lower (Table 5). By shifting though the field management from a low- to high-input management system, the gross margin increased accordingly by approximately 73%.

Table 5. Economic gross margin for each field management (EUR/Mg of castor oil).

	Fields Management	
Costs (EUR/Year)	**Low Inputs**	**High Inputs**
Ploughing	-	19.02
Heavy Cultivator	-	16.30
Harrowing	-	10.87
Irrigation	151.28	54.35
Sowing	22.69	8.15
Fertilization	15.03	5.43
Weeds Management	15.12	8.15
Crop termination	26.47	5.43
Manual harvesting	113.46	40.76
Baling	68.07	24.46
Oil extraction	80.58	27.17
Total costs (EUR/Mg)	**492.70**	**220.09**
Revenues (EUR/Mg)		
Castor oil for sales (EUR/Mg)	591.88	591.88
Total revenues (EUR/Mg)	**591.88**	**591.88**
Gross margin (EUR/Mg)	**99.18**	**371.79**

Source: Our elaboration on both survey data and data comes from the literature [3,45,46].

Table 6 showed that high inputs scenario had higher gross margin than other scenario and it had the lowest environmental impacts.

Table 6. Gross margin and carbon footprint for each field management.

	Units	Low Inputs	High Inputs
Gross Margin GWP	(EUR/FU) (kg CO_2 eq/1Mg)	99.18 667	371.79 326
Total eco-efficiency	**(EUR/kg CO_2eq)**	**0.14**	**1.14**
Sensitivity analysis			
Gross Margin GWP	(EUR/FU) (kg CO_2 eq/1Ha)	99.18 878	371.79 1210
Gross Margin/GWP ratio per 1 Ha	**(EUR/kg CO_2 eq)**	**0.11**	**0.30**

Source: our elaboration on both the survey data and the environmental findings.

Consequently, the ratio between gross margin and GWP emissions was used to assess the economic performance (gross margin) per unit of environmental impact (Table 6). It is important to underline that the higher the ratio value, the higher the economic performance per unit of GWP emitted. Findings showed that high-inputs scenario had the best ratio between economic performance and GHG emitted to the atmosphere (EUR 1.14 per kg CO_2 eq); while the low input scenario showed the unfavorable ratio between economic and environmental performances (EUR 0.14 per kg CO_2 eq) confirming the environmental results. These obtained results were affected by the differences in yields. Similar findings were reached with sensitivity analysis (by switching the functional unit from 1 Mg of oil to 1 hectare) where again the high-input scenario had a better ratio between economic performance and GHG emitted into the atmosphere (EUR 0.30 per kg CO_2 eq).

The above findings provide important insights into castor crop production in Europe, which is little studied in the current literature although castor is a good candidate for industrial vegetable oil production [3]. Moreover, the present study is the second one about the ecoefficiency ratio of castor crop (the pioneer study was by Pari et al. [3]) and is the first on a Greek case study. It revealed that the environmental and economic performance was better under the high-input scenario when the functional unit was accounted for 1 Mg of oil. This was due to an almost threefold higher yield achieved in the high input case compared to the other. Nevertheless, it is important to highlight that the present findings refer to a seed yield obtained via manual harvesting, that, at least in Europe, is economically sustainable only in case of small field cropping and not in extensive cultivation. Contrary to mechanical harvesting, the seed loss encountered in manual harvesting is negligible. Therefore, the quantity of effectively collected seeds is very close to potential seed yield. In fact, especially in castor beans, the mechanical harvesting is responsible for high seed loss [15], and is often even impossible to practice [15]. The main problems encountered in mechanical harvesting of castor beans are associated with the high quantity of fresh aerial biomass produced and the heterogeneous ripening of the capsules [15] However, many efforts have been paid during the last few decades to improve the suitability of castor beans for mechanization and in future, we could likely set a more straightforward study encompassing all the above mentioned practical implications of the mechanical harvesting. Thus far, the present study helps to fill that gap in the literature regarding the environmental and economic aspects related to castor beans cultivation in the Mediterranean climate.

4. Conclusions

In this study, the environmental impact assessment and economic feasibility of the production of castor oil from two fields were evaluated, comparing two different management scenarios (low-inputs field management versus high-inputs ones). To the best of our knowledge, this is the first study that focuses on the economic and environmental sustainability of castor in Greece. The high-inputs cultivation resulted in more economic/environmentally sustainable production per 1 Mg of castor oil due to its considerably higher yield in comparison with the low-input management system. On the other hand, switching the functional unit from 1 Mg of castor oil to 1 hectare, the field management with low inputs showed GHG emissions that were 27% lower than those emitted from the field management with high inputs. From an economic point of view, a difference in Gross Margin (EUR/Mg) between the two different scenarios was evident. In fact, by switching the field management from low inputs to high ones, the Gross Margin increased by about 73%. In addition, the high-inputs scenario had the best ratio between economic performance and GHG emitted into the atmosphere.

Despite the limitations of the present findings, due to the case study approach, the results are quite interesting, revealing that field management is the most crucial aspect in the pursuit of sustainable agriculture. The study revealed that a "good management" practice does not always implies the reduction of agronomic inputs. High-inputs field management may sometimes lead to an increased Gross Margin followed by a reduction of environmental impacts. In the case of castor crop grown in Greece, we found a stunning high yield potential capable of justifying, both economically and environmentally, the intensive use of inputs. In future work, we plan to extend this study to a more diverse climate and soil conditions, including different castor hybrids, in order to prove that castor is a good alternative crop that generates fewer negative externalities in agriculture, making it sustainable in economic, social and environmental terms.

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