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Mechanical Harvesting of Marginal Land and Agroforestry Field: New Insights from Safflower for Bio-Product Production

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Abstract: Considering the increase in market requests for bio-products, it is necessary to study the possibility of cultivating industrial crops in areas still untapped to extend the total cultivation surface, reducing land competition with food crops. With this aim in mind, we studied the harvesting performance and cost, and seed losses of Safflower (*Carthamus tinctorius* L.) cultivation during two growing seasons and in three different locations: (A) an agroforestry field, (B) a marginal field and (C) a dedicated field utilized as a control. The overall efficiency of the cultivation system was higher in location C in respect to the other two fields. The yield was 12–22% and 21–26% higher in location C compared to locations B and A, respectively, while seed losses were 40–33% and 28–50% lower in C compared to locations A and B, as well as the total harvesting costs, which were 45% and 31–35% lower in location C compared to locations A and B, respectively. Despite this, the results highlighted how the reduction in cultivation efficiency given by limiting factors was lower compared to that of other crops, highlighting the possibility of cultivating Safflower for bio-products' production on alternative lands.

Keywords: industrial crops; alternative cultivations lands; European directives; land competition; mechanical harvesting

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1. Introduction

Bio-based products play a crucial function in climate-change mitigation and the reduction in environmental impacts, considering fossil source replacement for producing renewable materials [1]. The United Nations Sustainable Development Goals (SDGs) [2], the Conference of the Parties COP21 and COP26 [3,4], the European Green Deal (EGD) [5], the Circular Economy and the Farm2Fork Strategies [6,7] aim to transform the EU into a resource-efficient and competitive economy with zero net greenhouse gas emissions in 2050, decoupling economic growth from resource use, while halting and reversing loss of biodiversity. In this context, the demand for renewable biomass sources for transforming the fossil economy to a bioeconomy is expected to grow [8,9]. Agriculture has a pivotal role in this context [1]; in fact, the whole sector can contribute by providing feedstock (i.e., crop residues and dedicated crops [10–13]) for bio-products and bioenergy production [14–17].

Regarding annual crops, residues are made by the non-edible parts of the plants that normally are left on the ground and not harvested [18], or collected and used for lower-value applications (i.e., bedding in animal husbandry). Even if the agricultural residues can potentially provide large quantities of biomass to be collected, some bottlenecks still exist and are limiting the value chain development. In fact, the feedstock derives from different crops cultivated in different areas and seasons, and specific machinery is needed for harvesting. Furthermore, in some cases, the biomass per hectare potentially collectable is very low. In recent years, special attention was paid to some untapped biomass, (i.e., chaff and cob) since wheat (*Triticum* ssp. L.) and maize (*Zea mays* L.) were, respectively, cultivated in 60 and 17 million ha in the last 5 years in Europe [19]. Despite this, the low availability of machinery to collect these by-products and the limited processing application of the obtained feedstock limited the diffusion of chaff and cob harvesting [20,21] Otherwise, dedicated crops allow us to increase the biomass potentially collectable, to concentrate the feedstock in time and space and to increase the processing application. In fact, dedicated industrial crops contribution to bioeconomy is not only limited to biofuel, because vegetable oil can be used as feedstock to produce bioplastics, surfactants, plasticizers, emulsifiers, detergents, lubricants, adhesives, cosmetics and other bio-products [22,23]. However, some constraints still exist for the diffusion of the cultivation of industrial crops for bio-products production. The first is related to possible land competition with food crops, considering the increase in the demand for food at a global scale [24]. For that reason, the scientific community has been working on evaluating the possibilities of cultivating such crops in polluted soils [25,26] or in marginal lands [27–29]. The second aspect regards the production costs of bio-products that are generally higher compared to the petroleum-based ones. For instance, biodiesel is 30% more costly than petroleum-based diesel [30].

In this scenario, among herbaceous oil crops, particular interest is given to Safflower (*Carthamus tinctorius* L.), an oilseed plant from the Asteraceae family that originated in Southern Asia. It is an annual herbaceous plant and is cultivated in different climatic conditions, including the Mediterranean area, given its capacity to resist drought [31] and salinity [32]. Safflower seed has been recognized as a promising oil source because of its high oil content between 26 and 45% and the high oleic and linoleic acid composition [33]. Further bioenergy applications include the production of biogas or bioethanol from Safflower straw and the development of biorefinery processes based on the whole Safflower plant [34,35]. In several studies on the mechanical harvesting of herbaceous oil crops [36], it was already identified that Safflower can be harvested properly with a combine harvester [37]. In particular, Pari et al. (2016) [38] analyzed the combine-harvesting performance of Safflower and showed the good efficiency of a typical wheat header. It is interesting because Safflower can be easily harvested with a conventional wheat header by only applying fine adjustments to the combine harvester. In the framework of the MIDAS project [39], Safflower was selected to be cultivated in marginal lands and in agroforestry environments, with the final aim of finding further arable land for bio-products' production, reducing competition with food crops.

The definition of marginal land has been globally faced by political and research authorities [40–42], and it is still controversial. The same conditions that make an area "marginal" could make the arable land productive in another location [43,44]. Moreover, marginal lands also face a higher risk of abandonment; it has been estimated that from 1% to 10% of the European agricultural land could be abandoned by 2030 [45]. In many situations, it is preferable to adapt the production systems and develop diversified agricultural practices to prevent abandonment [46]. Marginal land can be properly cultivated with industrial crops for bio-products' production, as demonstrated in the MAGIC project [47] and other relevant research [45,48], without competing with food crops.

Further arable land that could be used for bio-based application derives from fields cultivated in agroforestry systems. The term "agroforestry" was first used in 1977 to describe the integration of trees and agriculture [49,50]. The essence of agroforestry is the inclusion of trees and shrubs in conventional agricultural systems. The USDA [51] has defined agroforestry as "*The intentional integration of trees and shrubs into crop and animal farming systems to create environmental, economic, and social benefits*". Trees can be planted inside fields, such as in alley cropping, or at the edges of fields, such as boundary planting [52,53]. The introduction of trees into agricultural landscapes has been shown to result in a strong increase in ecosystem services [54,55].

Considering the obligation to respect the goals identified globally [2–7] and the need to reduce competition with arable land destinated for food production, additional cultivation areas should be found for industrial crops. The present work aims to evaluate whether marginal and agroforestry lands could represent suitable agricultural surfaces, from a mechanical point of view, for the cultivation of Safflower for bio-products. The mechanical-harvesting performance and cost and seed losses were compared with those obtained by the cultivation in a very productive area destinated to food production in two following growing seasons.

2. Materials and Methods

2.1. Experimental Fields

Mechanical harvesting of Safflower was tested in a multi-location trial aimed at identifying the potential of cultivation in different environments. The study was carried out through the comparison of 3 different growing situations during 2 following seasons (2023 and 2024) (Figure 1):

1. Location A: An agroforestry field of 0.54 ha originating from a 12-year-old Poplar plantation harvested in 2022.
2. Location B: A field of 0.5 ha with marginality constraint caused by high waterlogging in the autumn–winter months. This type of field is usually cultivated with waterlogging-tolerant species, such as Poplar.
3. Location C: A dedicated field with optimal cultivation characteristics, generally used for wheat production. The field has a total area of 11.15 ha.

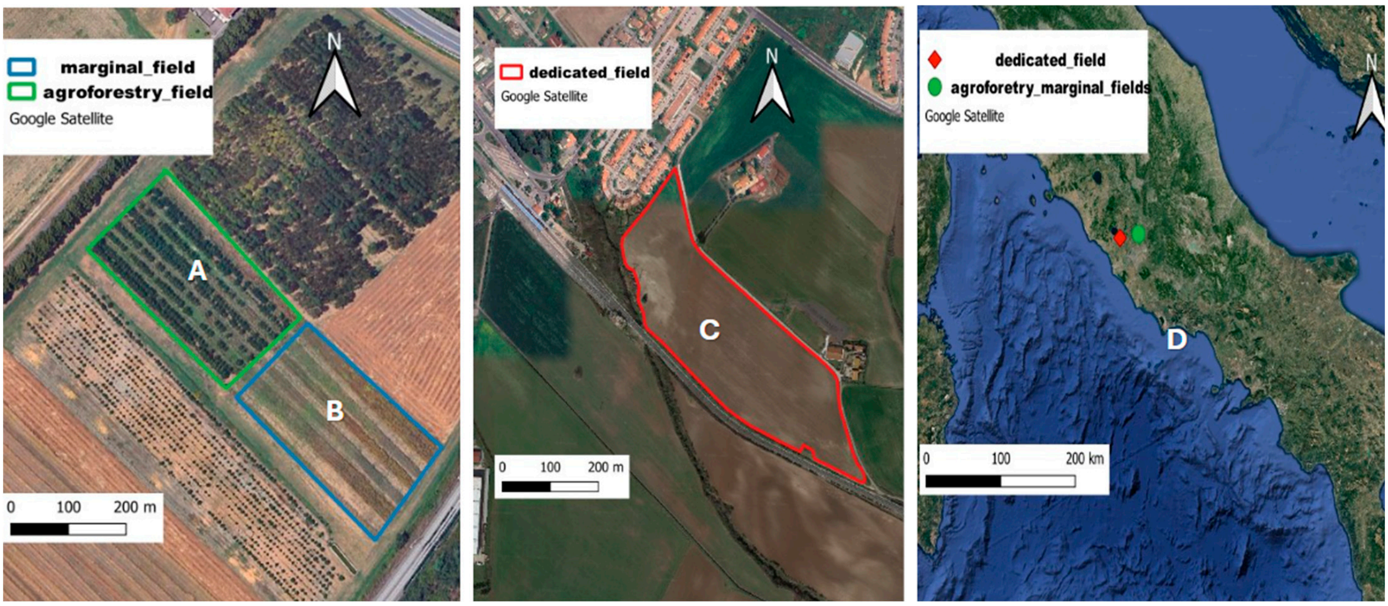


Figure 1. Satellite view of the different fields: (**A**) agroforestry field, (**B**) marginal field, and (**C**) dedicated field. (**D**) Territorial framework of the fields.

Locations A and B are located at the CREA-IT farm in Monterotondo. The agroforestry field (location A) was obtained through the conversion of a 12-year-old Poplar plantation for biomass production at the second harvest cycle. The layout before the conversion in the agroforestry field was 3 m between the tree lines and 1 m among the plants, but by removing, alternatively, one of the rows, now there are eight tree lines, each measuring 1.5 m wide, with an inter-row of 6 m, for a total of 5400 m^2. The last utilization was carried out in 2022.

Location B differs from location A in its stationary situation taking characteristics of "Marginal land", as reported by [41,56,57]. The definition of marginal land was derived from MAGIC project [46] that includes six main types of biophysical constraints as identified by the JRC Report. The soil chemical and physical characteristics of the three locations, studied before starting the test, are classified according to the GEPPA soil-texture triangle diagram and were prepared with superficial tillage before seeding in Table 1.

Table 1. Soil chemical and physical characteristics of the three locations.

Parameters	Agroforestry (A)	Marginal (B)	Dedicated (C)
Clay (%)	58	48	31
Sand (%)	22	16	48
Silt (%)	20	36	21
Organic matter (%)	2.1	1.7	1.8
N (%)	0.13	0.09	0.11
pH (water)	6.1	7.9	6.7
P_2O_5 Olsen (mg kg^{-1})	7	6	21
K_2O (mg kg^{-1})	317	304	992

Meteorological data were acquired during the two growing seasons (2023 and 2024) of the Safflower from 10 March to 10 September of each year. The three locations fell in the same climatic area and can be defined as hot-summer Mediterranean (Table 2), corresponding to the "Csa" in the Köppen climate classification [58,59], characterized by relatively mild winters and warm, sunny summers.

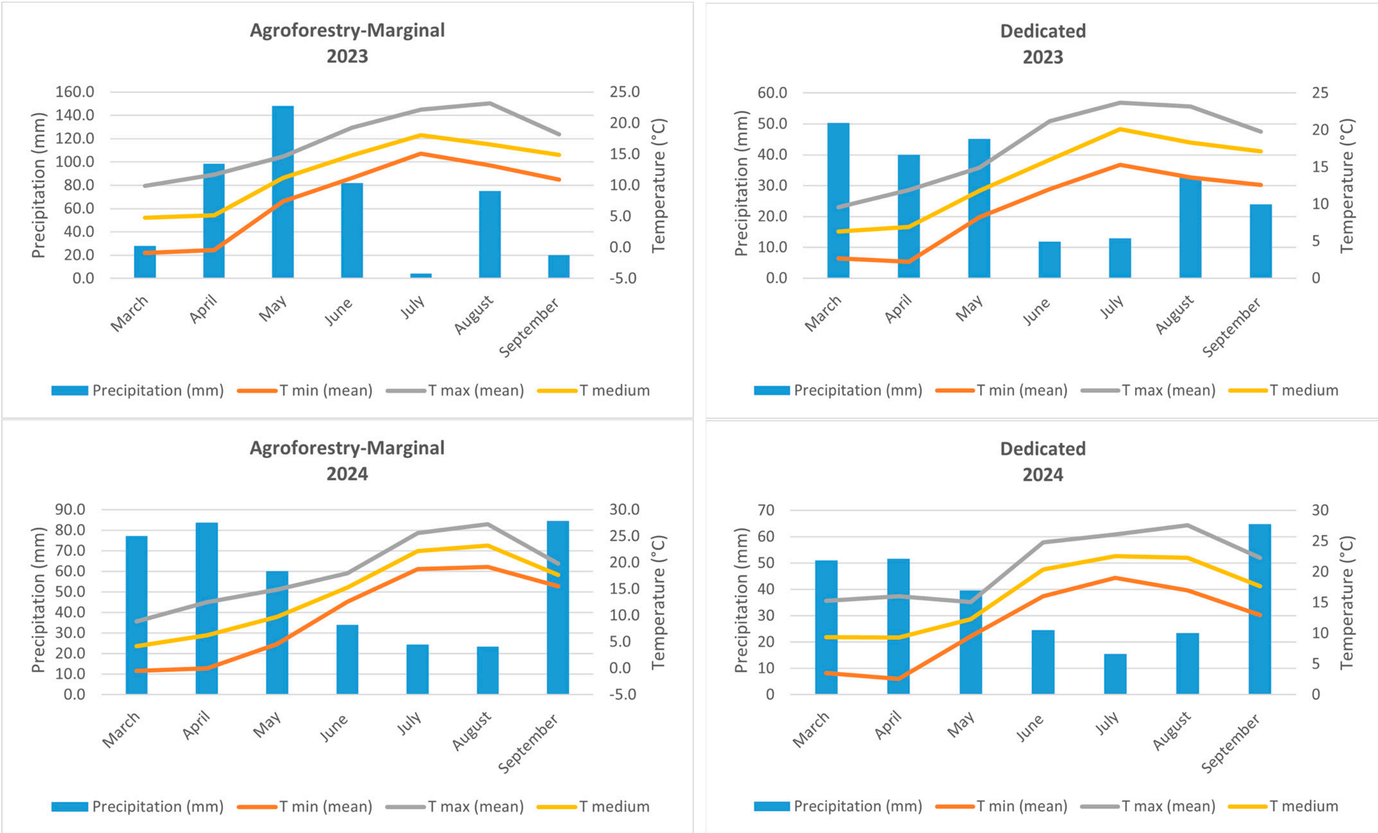
Table 2. Description of the different fields under study.

Type	Location	Region	Latitude/ Longitude	Years	Climate Type [1]	PrS [2] 2023 (mm)	PrS [2] 2024 (mm)
Agroforestry (A)	Monterotondo (RM)	Lazio	42°06′09″ N 12°37′43″ E	2023–24	Csa	456.2	387.6
Marginal (B)	Monterotondo (RM)	Lazio	42°06′09″ N 12°37′43″ E	2023–24	Csa	456.2	387.6
Dedicated (C)	Cesano (RM)	Lazio	42°05′06″ N 12°33′04″ E	2023–24	Csa	217.0	271.0

[1] Csa = hot-summer Mediterranean climate; [2] PrS = total precipitation during the growing season (March–September).

Detailed weather data concerning the growing periods of Safflower in the different areas of the study are depicted in Figure 2.

The crop management was the same for all three locations. Soil preparation was carried out in the autumn, with deep tillage, using a ripper, and superficial chisel tillage before seeding. A fertilization was performed before sowing, using diammonium phosphate (18% N, 46% P_2O_5) and urea fertilizers (46% N). The crop was cultivated under rainfed conditions, with no irrigation application, in each location and growing season. The sowings were performed during the last week of March in the A and B locations, while in location C, the sowings were performed in mid-February. The seeding rate was 25–30 kg ha^{-1}, with a final layout of 3 cm on the row and 14 cm between the rows. Before the first growing season, the soil was not cultivated in locations A and B, while in location C, it was cultivated with barley (*Hordeum vulgare* L.). Between the two following crop seasons, the field was not cultivated in all the locations.



(**a**) (**b**)

Figure 2. Thermo-pluviometric diagram during the two growing periods: (**a**) agroforestry–marginal field and (**b**) dedicated field. Accumulated monthly precipitation (mm, blue bars), mean monthly minimum temperature (T min, °C, orange line), mean monthly maximum temperature (T max, °C, gray line) and average temperature (°C, yellow line).

2.2. Pre-Harvesting Sampling

Before harvesting, 6 square-shaped sample plots of 1 m^2 each were randomly established in the three locations to assess the whole amount of the epigeous biomass (stem, flower heads and seeds). All plants from each plot were harvested, closed in sealed bags and transferred to the laboratory of Research Centre for Engineering and Agro-Food Processing (CREA-IT, Monterotondo, Rome, Italy) for further investigations. In particular, the number of plants for each sample, potential seed yield (PSY), dry weight (DW) and moisture content were evaluated. Dry weight and moisture content were estimated according to EN ISO 18134-2:2017 [60], while PSY was measured using a stationary thresher (PLOT 2375 Thresher, Cicoria Company, San Gervasio, Italy). The pre-harvest tests were performed in order to study the development of the Safflower before mechanical harvesting.

2.3. Crop Yield, Harvesting Performances and Cost Analysis

Seed harvesting was performed at complete maturity by using the same combine harvester machine for the two growing seasons. For locations A and B, we used a 250 kw combine harvester equipped with a 5 m width cereal header for the agroforestry field and with 6 m width cereal header for the marginal field (Figure 3).

For location C, we used a 225 kw combine harvester equipped with 6 m width cereal header (Figure 4).

(**a**) (**b**)

Figure 3. (**a**) Combine harvester at work in agroforestry field (location A) and (**b**) combine harvester at work in marginal field (location B).

Figure 4. Combine harvester at work in dedicated field (location C).

The harvesting in locations A and B was carried out on 9 October 2023 and on 9 February 2024 in the first and in the second growing seasons, respectively. For location C, the harvesting was performed on 8 August 2023 and on 8 February 2024 in the first and in the second growing seasons, respectively. This delay of approximately one month between the locations was due to the different degrees of maturation of crops. As depicted in the thermo-pluviometric diagram (Figure 2), locations A and B are characterized by more rainfall and lower average temperatures compared to location C. The combination of these factors, together with the marginal factor (A) and the presence of trees (B), determined this difference in the crop maturation. In each field, the crop yield was quantified by discharging the seed collected by the combine harvester on the scale at the farm level. The work performances during harvesting were measured using the methodology developed by Reith et al. (2017) [61]. The parameters taken into account were the working speed (km h^{-1}), Theoretical Field Capacity (TFC, ha h^{-1}, calculated using the working speed and the width of the header) and Effective Field Capacity (EFC, ha h^{-1}, calculated considering accessory times). The percentage ratio between EFC and TFC is termed the field efficiency (FE). The whole cost for the harvesting operation in each location was calculated by using the CRPA (Research Centre on Animal Productions) methodology to retrieve the standard values for the calculation [62], whilst standard ASAE D497.4 was used to calculate lubricant consumption [63]. The price of the machinery was lower than the price in 2023, according to Banca d'Italia Institute landing rate, by 3.9% [64]. The work performances and cost analysis for Safflower harvesting were assessed by using the above-mentioned parameters and following the methodology suggested by Pari et al. (2024) for Camelina (*Camelina sativa* (L.) *Crantz*) [65].

2.4. Seed-Loss Assessment and Reduction in Cultivable Areas

Seed losses were evaluated by using two different methods after the passage of combine harvester machines in each location, according to the methodology proposed by Pari et al. (2024) and Stefanoni (2020) [65–67].

Following the first method, we used a tarpaulin in the rear part of the combine harvester machine to collect the seeds lost by the sieves and straw walkers. The entire amount of biomass expelled by the machine in 10 m of advancement was thus collected by the tarpaulin. The biomass was weighed and sieved to assess the number of seeds lost by the combine harvester. The procedure was repeated three times in each location. The weight of the seeds was referred to as the surface given by the width of the combine header multiplied by the length of the advancement of the combine (10 m):

- 50 m^2 for the combine harvester of field A;
- 60 m^2 for the combine harvester of field Cs and B.

To determine seed losses using the second method, the difference between the potential seed yield assessed in the pre-harvest and the harvested seed yield from the combine was calculated.

The reduction in cultivable areas was determined in each location directly through measurements of the cultivated surface where the crop was not present during the germination phase. The values obtained for the various locations were expressed as a percentage of the total area by comparing the measured surfaces with the total ones. The procedure was repeated for each growing season.

2.5. Statistical Analysis

The analysis of variance (ANOVA) was performed using the software R version 3.6.1 to separate statistically different means among the groups; when a significant effect was found, the means of the treatments were compared by the Tukey test ($p \leq 0.05$). Previously, all data were tested for normality and homoscedasticity [68].

3. Results

3.1. Pre-Harvesting, Moisture Content, Crop Yield and Seed Losses

The main results obtained in the two growing seasons regarding pre-harvesting operation, crop yield and seed losses are reported in Table 3. Table 4 shows the values of the moisture content.

The pre-harvest tests were performed in order to study the development of the Safflower before mechanical harvesting, evaluate the differences among treatments and acquire data for further seed losses evaluation. According to the results reported in Table 3, a very similar trend was found in the two following cropping seasons. In fact, in location C, higher values of potential seed yield (PSY) and total biomass (TB) were found in comparison to the other two locations. Location A recorded the lowest values of PSY and TB, while location B highlighted an intermediate value compared to locations A and C. Consistently with the PSY, the harvested seed yield (HSY) was higher in location C in respect to locations A and B. The differences among values of PSY and TB of location C were statistically significant compared to locations A and B for each year. Considering plant density (PD), the value of location C was lower compared to that of locations A and B, even if no statistically significant differences were found in the two seasons. In 2024, each value described above was higher compared to that in 2023, with an average increase in the three locations of 7.84% for the PSY, 6.44% for the TB, 9.74% of HSY and 4.85% of PD. Seed losses estimated as difference between PSY and HSY in 2023 amounted to 2% for location C and 6% and

7% for locations A and B, respectively. Contrary to biomass value, in 2024, the values of seed losses for locations A and B were lower compared to those in 2023 (i.e., 5% and 4%, respectively), while no variation was recorded for location C. The results of seed losses evaluated with the tarpaulin method showed the same trend as that described above, but they were, on average, 30.86% and 37.73% for 2023 and 2024, respectively, higher than the estimated seed losses, as a simple difference between the PSY and HSY. This result is consistent with other experiences with seed-loss assessments [65].

Table 3. Plant characteristics as a result of pre-harvesting, crop yield and seeds losses during combine harvesting (mean ± SD).

2023			
Parameter	**Agroforestry (A)**	**Marginal (B)**	**Dedicated (C)**
Potential seed yield (DM Mg ha^{-1})	1.06 ± 0.3 a	1.15 ± 0.2 a	1.29 ± 0.1 b
Total biomass (DM Mg ha^{-1})	6.32 ± 2.7 a	6.78 ± 0.6 a	8.47 ± 3.2 b
Harvested seed yield (DM Mg ha^{-1})	1.0 *	1.07 *	1.27 *
Plant density (n m^{-2})	52.60 ± 5.5 a	56.01 ± 6.1 a	46.27 ± 8.7 a
Seed losses tarpaulin (%)	8.51 ± 0.001 a	9.13 ± 0.004 a	3.32 ± 0.002 b
Seed losses (%)	6 *	7 *	2 *
Reduction in cultivated area (%)	14.85	11.64	/
2024			
Parameter	**Agroforestry (A)**	**Marginal (B)**	**Dedicated (C)**
Potential Seed Yield (DM Mg ha^{-1})	1.14 ± 0.5 a	1.2 ± 0.3 a	1.44 ± 0.1 b
Total biomass (DM Mg ha^{-1})	6.73 ± 2.2 a	7.09 ± 0.6 a	9.17 ± 2.8 b
Harvested seed yield (DM Mg ha^{-1})	1.09 *	1.16 *	1.42 *
Plant density (n m^{-2})	55.30 ± 5.4 a	57.05 ± 6.4 a	49.77 ± 9.1 a
Seed losses tarpaulin (%)	7.7 ± 0.004 a	8.1 ± 0.006 a	2.76 ± 0.005 b
Seed losses (%)	5 *	4 *	2 *
Reduction in cultivated area (%)	13.22	10.84	/

Note: DM = dry matter; (*) this value was not replicated since all seeds were collected within one trailer and weighed only once at the end of the harvesting. Values within rows followed by different letters are statistically different at the level of $p \leq 0.05$, according to Tuckey's HSD test.

Table 4. Values of the moisture content and dry-matter weight of the biomass collected during pre-harvesting study. Value of dry-matter weight refers to a sample of 5 plants randomly collected from each treatment.

2023						
	Dry Matter (g)			**Moisture Content (%)**		
	Agroforestry (A)	**Marginal (B)**	**Dedicated (C)**	**Agroforestry (A)**	**Marginal (B)**	**Dedicated (C)**
Straw	152.08 ± 4.53 a	157.12 ± 3.65 a	170.34 ± 3.34 b	33.20 ± 0.09 a	22.17 ± 0.96 a	19.23 ± 0.08 b
Seeds	72.16 ± 3.87 a	78.97 ± 4.63 a	86.77 ± 1.89 b	25.19 ± 0.47 a	19.49 ± 0.05 a	9.33 ± 0.05 b
2024						
	Dry Matter (g)			**Moisture Content (%)**		
	Agroforestry (A)	**Marginal (B)**	**Dedicated (C)**	**Agroforestry (A)**	**Marginal (B)**	**Dedicated (C)**
Straw	161.81 ± 5.53 a	190.89 ± 2.52 a	208.91 ± 4.22 b	34.09 ± 0.32 a	16.16 ± 0.06 a	13.78 ± 0.02 b
Seeds	81.13 ± 4.30 a	99.12 ± 3.25 a	114.41 ± 3.11 b	26.85 ± 0.01 a	19.77 0.02 a	11.65 ± 0.03 b

Values within rows followed by different letters are statistically different at the level of $p \leq 0.05$, according to Tuckey's HSD test.

It must be noted that, even if the values of seed yield for location A are expressed in Mg ha^{-1}, considering the surface designated for Poplar and not for Safflower, a total area of 1.37 ha will be needed to cultivate 1 ha of Safflower. For the reduction in cultivated area, in location A, the affected surface was 800 m^2 in 2023 and 713 m^2 in 2024, corresponding to

14.85% and 13.22% of the total area given mainly by the shade of the Poplar on the crop and by the presence of weeds. In location B, the marginality factor of the field caused waterlogging in a spotted area of 580 m^2 in 2023 and 540 m^2 in 2024, that is, 11.64% and 10.84% of the total field with the consequent reduction in Safflower development.

The results shown in Table 4 highlight how the moisture content value was lower in location C in respect to locations A and B, with statistically significant differences for straw and seeds. Location A shows the highest values, and location B shows intermediate values, with no statistically significant differences between them. The same trend was registered in each growing season, with a slight increase in 2024 compared to 2023 for location A and for the seed value of locations B and C.

The results for the dry matter highlighted how the values were higher in location C compared to locations A and B, with statistically significant differences for both straw and seeds. Location A showed the lowest values, and location B showed intermediate values, with no statistically significant differences between them. The same trend was registered in each growing season, with an increase in 2024 compared to 2023 in each location.

3.2. Work Performances and Cost Analysis

The results of the working performance of the machines used for the harvesting operation and cost analysis are depicted in Table 5.

Table 5. Evaluation of the working performance and associated costs of the machinery involved in Safflower-seed harvesting. Calculations were performed by relying on average working times per treatment; therefore, statistical analysis was not applied.

	2023		
Parameter	**Agroforestry (A)**	**Marginal (B)**	**Dedicated (C)**
Theoretical Field Capacity (TFC ha h^{-1})	1.21	1.41	2.35
Effective Field Capacity (EFC ha h^{-1})	0.95	1.12	1.98
Field efficiency (FE%)	78	79	84
Total cost (EUR ha^{-1})	205.80	174.56	114.59
	2024		
Parameter	**Agroforestry (A)**	**Marginal (B)**	**Dedicated (C)**
Theoretical Field Capacity (TFC ha h^{-1})	1.20	1.41	2.32
Effective Field Capacity (EFC ha h^{-1})	0.93	1.15	1.93
Field efficiency (FE%)	77	82	83
Total cost (EUR ha^{-1})	210.23	169.62	117.55

The results of working performance depicted in Table 5 highlight similar trends in the two growing seasons. Values of TFC, EFC and FE recorded in the dedicated field (location C) were higher compared to those of the other treatments. The agroforestry field (A) showed the lowest values, while location B had intermediate values compared to the other treatments. The values of 2024 were slightly lower than those of 2023 for the agroforestry (0.82% TFC, 2.10% EFC, and 1.28% FE) and for the dedicated field (1.27% TFC, 2.52% EFC, and 1.19% FE), while in location B, the EFC and FE increased by 3 and 4%, respectively.

Considering the total cost of the harvesting operation, the lowest values were calculated for location C, intermediate values for location B and highest values for location A for each growing season. The total cost of location C was 45% and 35% lower than the cost for locations A and B in 2023 and 45% and 31% lower than the cost for locations A and B in 2024.

4. Discussion

Seed yields were lower in the marginal and in the agroforestry fields than in the dedicated field for each growing season. The different results of seed yield can be explained by the reduction in the effective cultivated areas in locations A and B. In fact, in location

A, the shadow of Poplar affected Safflower development after seeding, creating an area in which weeds, which are more tolerant to shade, have prevailed. In location B, the areas with waterlogging negatively affected the crop's growth. Moreover, the results of seed losses can be ascribed to the presence of weeds in locations A and B, mainly in the low-development areas, that caused improper functioning of the combine machine during harvesting, increasing the seed losses in respect to location C, which showed the lowest values.

The differences in terms of PSY and TB in location C were statistically significant compared to those in locations A and B, even if no statistically significant differences were found concerning plant density. This result highlights how, in locations A and B, the plants were less developed due to interaction with Poplar (A) and marginality factor (B), with a consequent reduction in terms of seed yield.

The values of dry-matter weight were consistent with the values of PSY and TB, confirming how the limiting factors (i.e., marginality and crop interaction with trees) reduced the plant development in locations A and B compared to location C. Furthermore, the above-cited limiting factors also influenced the moisture content of the biomass and of the seed, as it was higher in locations A and B compared to location C, with a consequent effect on harvesting timing and efficiency.

The harvesting performance and the referring cost in location A were influenced by the use of a combine machine with a header of 5 m, due to the distance between Poplar lines, with consequent reduced values for TFC and EFC and a higher value for total cost in respect to location C. Instead, in location B, the combine machine, due to the high presence of weeds, reduced the forward speed, affecting TFC and EFC and, consequently, the total cost. Even if the overall results in locations A and B were lower than expected in the two growing seasons, they shed light on the possibility of finding alternative cultivation strategy for industrial crops with the aim of reducing land competition with food crops.

It must be considered that today's demographic expansion and the need for sustainable food sources are extremely sensitive issues, so, in the future, the cultivation of no-food crops will be limited to land not destinated for food production [69,70]. At the same time, the request for further sources for bio-products, such as florets for biodegradable colorants' production [71–73], is stimulating the identification of additional cultivation areas for industrial crops. At this aim, marginal lands and surfaces not traditionally used for food production, such as a former tree plantation in an agroforestry system, can represent an excellent environment for Safflower cultivation, considering its high adaptability to extreme environmental conditions [69,70,74]. In fact, Safflower is a crop with rustic characteristics, well adapted to arid and semi-arid regions, and thanks to its deep root system and presence of xerophytic spines, it has demonstrated excellent yields even in limited environment conditions and no problems with wildlife [69,75]. These characteristics make it particularly suitable for reducing the effects of increasingly arid climatic conditions on agricultural production, mostly when the supply of irrigation water is limited and wildlife is a problem.

The opportunity to cultivate Safflower under not-favorable conditions is confirmed by the results of recent studies showing that the potential yield of others oil seed crops is more affected by marginality or limiting factors. Schillaci et al. (2023) [76] used a modeling approach to estimate camelina's seed yield under marginal land and quantified it as ranging from 0.7 to 1.4 Mg DM ha^{-1} in respect to a potential seed yield between 1.3 and 3.3 Mg DM ha^{-1} under non-limiting conditions [77], describing a yield reduction of 42–47%. The seed yield of the Castor bean has been reported to be 0.35–0.7 Mg DM ha $^{-1}$ under adverse environmental conditions, and a maximum of 1.25 Mg DM ha^{-1} of seed yield has been registered under favorable conditions [78], with a yield reduction of 44–72%. Concerning the Sunflower, even if its seed oil content is 15% higher than that kf Safflower, a relevant study [79] showed a higher reduction in seed yield (16.3%) and seed oil content (22.5%) compared to Safflower (9.4% and 10.2%, respectively) when subjected to water deficit. In our study, the limiting factors given by marginality and by the interaction with trees in the agroforestry system caused a yield reduction of only 12–26% compared to favorable growing conditions [80,81].

5. Conclusions

Safflower is a broadleaf oilseed crop cultivated as feedstock for bio-products to replace petroleum-based sources. It requires low input techniques; it can be adapted to different growing conditions and can be grown in most of European environments. The literature lacks information on the possibility of properly growing Safflower on alternative lands as a strategy to increase the cultivation area and reduce competition with food crops.

In the present work, we studied Safflower cultivation in marginal lands (location B) and in an agroforestry system (location A) compared with a very productive area (location C) destinated to food production in two following growing seasons. The overall cultivation efficiency, in terms of seed yield, total harvesting cost and performance, and seed losses, was higher in location C compared to in locations A and B in the two growing seasons. Despite these results, the yield reduction observed in locations A and B was lower compared to what was observed in other industrial crops [75–77]. Therefore, these results offer new opportunities for growing Safflower in marginal lands and agroforestry fields, also considering the reduced water requirements, the beneficial effect in breaking disease and weed cycles during crop rotations and its phytoextraction potential [80,81]. Future research will be performed to study a 4-year crops rotation in the three locations and to set up a comparative study between them, investigating the environmental impact a through life-cycle analysis (LCA) and life cycle costing (LCC) methodology.

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