Industrial Crops & Products 211 (2024) 118224

Contents lists available at ScienceDirect

Industrial Crops & Products

journal homepage: www.elsevier.com/locate/indcrop

# The opportunities and potential of camelina in marginal land in Europe

Federica Zanetti [a,*], Pietro Peroni [a], Elena Pagani [a], Moritz von Cossel [b], Beatrice Elisabeth Greiner [b], Michał Krzyżaniak [c], Mariusz J. Stolarski [c], Iris Lewandowski [b], Efthymia Alexopoulou [d], Walter Stefanoni [e], Luigi Pari [f], Erika Facciolla [a], Andrea Monti [a,*]

[a] Department of Agricultural and Food Science (DISTAL), Alma Mater Studiorum, Università di Bologna, Viale G. Fanin 44, Bologna 40127, Italy
[b] Biobased Resources in the Bioeconomy (340b), Institute of Crop Science, University of Hohenheim, Stuttgart 70599, Germany
[c] Department of Genetics, Plant Breeding and Bioresource Engineering, Faculty of Agriculture and Forestry, University of Warmia and Mazury in Olsztyn, Plac Łódzki 3, Olsztyn 10-724, Poland
[d] Centre for Renewable Energy Sources and Saving (CRES), 19th km Marathonos Avenue, Pikermi 19009, Greece
[e] Institute of Research on Terrestrial Ecosystems (IRET), National Research Council of Italy (CNR), Monterotondo, Italy
[f] Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA), Centro di Ricerca, Ingegneria e Trasformazioni Agroalimentari, Via della Pascolare 16, Monterotondo 00015, Italy

ARTICLE INFO

*Keywords:*
Biobased industry
Steep slope
Acidic soil
Shallow soil
Sandy soil
Clay soil

ABSTRACT

The European bioeconomy is steadily driving an industrial, economic, and social growth looking for sustainable biobased feedstocks able to replace fossil-based materials. In this scenario, there is an urgent and increasing need to produce locally industrial crops, with multiple applications and broad suitability to different pedo-climates. Furthermore, the actual EU legislation imposes to produce industrial crops not competing with food ones, and one possibility is to grow them on marginal land. Among others, camelina [*Camelina sativa* (L.) Crantz] has been identified as one of the most suitable options for marginal land in Europe, but so far there is a lack of studies conducted in such conditions able to provide reliable production data, on which it will be possible to build plausible business plans. At this scope different field trials have been established in four European countries, i.e., Italy, Greece, Germany, and Poland, in multiple growing seasons from 2018 to 2021, under different types of marginality. In details, in Italy camelina was tested under steep slopes (25% and 15%), in Greece in a soil with low fertility (pH < 5.5) and adverse terrain conditions (steep slope >12%); in Germany in a soil with limitations in rooting, i.e., rooting depth < 30 cm + stoniness > 15%, and in Poland in two sites one with sand > 40%, and the other with clay > 50% of the texture. Camelina was grown with an autumn cycle in Italy and Greece, and with a spring one in Germany and Poland. Camelina production was impacted by the marginal land, seed yield was on average 0.94 Mg DM $ha^{-1}$, ranging from 0.38 Mg DM $ha^{-1}$ for camelina sown in spring in Poland in the sandy soil, up to 1.93 Mg DM $ha^{-1}$ for camelina sown in autumn in Italy on a 15% slope. Camelina completely failed only in one growing season in the clay soil in Poland, in relation to extreme weed pressure, while in all the other situations it was able to produce seed. Seed quality, that was surveyed only in Italy and Poland, was not negatively impacted by marginality, demonstrating its capacity to cope with harsh growing conditions. Growing camelina in southern European marginal land, in autumn sowing, seemed the most conservative and safe strategy to achieve profitable yields. In terms of agronomic management, the most important choices to optimize the crop in marginal land resulted: weed management, N fertilization, and the harvesting phase.

## 1. Introduction

Currently, in Europe, the bioeconomy produces ~ 2 trillion euros of turnover and with more than 18 M employees, which are estimated to further grow by 2030 (European Bioeconomy Strategy, 2022). This is mainly linked to the need of Europe to fulfill several targets for developing new markets aiming at the green economy and the sustainable transition toward it (European Commission, 2022; Krzyżaniak et al., 2020). As a consequence, a significant increase in the demand for feedstocks for the biobased industry is expected, which will directly increase the need for industrial crops, in particular oilseed, carbohydrate, and lignocellulosic crops, able to provide renewable raw materials

* Corresponding authors.
*E-mail addresses:* federica.zanetti5@unibo.it (F. Zanetti), a.monti@unibo.it (A. Monti).

https://doi.org/10.1016/j.indcrop.2024.118224
Received 10 December 2023; Received in revised form 31 January 2024; Accepted 7 February 2024
Available online 16 February 2024

for bioenergy and circular economy sectors, currently dependent on petrol-based chemicals (Alexopoulou, 2018; Panoutsou and Alexopoulou, 2020; Stolarski, 2021). In this scenario, marginal land could represent an opportunity to develop these crops on large areas respecting the limitations imposed by the Revised Renewable Energy Directive (RED, 2023/2413). The definition of marginal land has been widely questioned by several international political and research authorities (e.g., OECD, CGIAR, World Bank, USDA-NRCS, EU member states, Eliasson, 2007; Pulighe et al., 2019;), and it is still controversial from many perspectives. The present study refers to the definition of marginal land made by MAGIC project, that includes six main types of biophysical constraints as identified by the JRC Report (Eliasson, 2007; Rossiter et al., 2014), and subsequently it considers the socio-economic context in which marginal land is located and the specific ecosystem services needed to be preserved (Elbersen et al., 2018). This approach aimed to solve the necessity for detailed mapping of these areas, at least in the EU context, in order to quantify the available land to meet the RED criteria as proposed by Vera et al. (2021), and consequently to develop appropriate incentive policies for local landowners and farmers, as emphasized by Khanna et al. (2021). Remarkably, nearly 29% of the EU agricultural area (EU-28) falls under the category of marginal land (Elbersen et al., 2018; Von Cossel et al., 2019b), with considerable risks of abandonment: from 1% to 10% of the European agricultural land could be also abandoned by 2030 (Elbersen et al., 2017). This process is particularly pronounced in rural communities characterized by a local economic pattern and small farms with limited economic opportunities and low productivity (EEA, 2019). The main consequence of abandonment is the development of natural revegetation processes, with consequent indisputable negative effects on the agro-ecosystem (Halbac-Cotoara-Zamfir et al., 2020). Therefore, in many cases it is preferable to develop diversified and more profitable agricultural systems to prevent abandonment (EEA, 2019). The introduction of industrial crops in new environment should avoid any possible negative impact on native biodiversity (Cervelli et al., 2020; Elbersen et al., 2018; Von Cossel et al., 2019a). In this regard, the approach adopted within the MAGIC project was to use low input agricultural practices for selected industrial crops suitable for marginal land (Von Cossel et al., 2019a; Von Cossel et al., 2019b). Among these crops, camelina, annual oilseed crop native to Europe, is considered particularly interesting thanks to its remarkable agronomic versatility and the large number of potential uses (Zanetti at al., 2021). Camelina is highly suitable to different pedo-climates, and the availability of both winter and spring types further expand its cultivation area to whole Europe. Additionally, the low agricultural input requirement, the very short growing cycle, and the high tolerance to biotic and abiotic stresses have made camelina a good candidate for marginal areas (Zanetti et al., 2021). Several studies across Europe showed a seed yield potential between 1.3 and 3.3 Mg DM $ha^{-1}$ (Zanetti et al., 2021), depending on site, soil, and genotype, while under non-limiting growing conditions, with an improved variety, the range of variation was narrower (2.5–3.2 Mg DM $ha^{-1}$, Righini et al., 2016). Both seed yield and quality were strongly influenced by soil characteristics and environment (Walia et al., 2021; Righini at al., 2016; Zubr, 2003).

In addition to the wide range of obtainable products (Berti et al., 2016; Balanuca et al., 2015; Balanuca et al.; 2017; Keske et al., 2013), the interest in camelina as a crop for marginal areas derives from its drought tolerance. Camelina can in fact be grown rainfed in semi-arid environments (Hunsaker et al., 2011); moreover, thanks to its exceptional cold tolerance of both winter and spring biotypes (Berti et al., 2011, 2016; Von Cossel et al., 2019b; Zanetti et al., 2021) and short growth cycle can be grown in environments characterized by a constrained growing season. Additionally, camelina can be cultivated using common farm machines (Zanetti et al., 2021), and with a limited use of fertilizers. The resistance to common pathogens that usually limit other *Brassicaceae* species, and its positive impact on pollinators, further increase the interest on camelina (Séguin-Swartz et al., 2009; Thom et al., 2018).

Despite the lack of available studies on camelina in marginal contexts, some specific morphological traits lead scientists to believe that camelina can be suited for many marginal areas across Europe (Hunsaker et al., 2011; Lohaus et al., 2020; Obour et al., 2015). For example, camelina is characterized by a shallower and less expanded root system than similar *Brassicaceae* (Berti et al., 2016; Obour et al., 2015), so it is likely a better crop to areas characterized by limitations in rooting than other common oil crops such as rapeseed (*Brassica napus* var. *oleifera*). It should be recognized that rooting depth has been identified by the MAGIC project as the most widespread biophysical constraint in Europe (Elbersen et al., 2018; Reinhardt et al., 2021). Within the MAGIC project, several field trials were performed on camelina under different marginality conditions across Europe. In the present study we aimed at analyzing the yield potential of camelina under different marginality conditions, namely adverse terrain conditions (steep slope >12%) in Italy; low soil fertility (pH < 5.5) and adverse terrain conditions (steep slope >12%) in Greece; limitations in rooting (rooting depth < 30 cm, stoniness > 15% of the texture) in Germany, and sub-optimal soil texture in Poland (sand > 40% and clay > 50% of the texture) (Elbersen et al., 2019).

## 2. Material and methods

### 2.1. Characterization of the trial sites

The experimental camelina fields were established in four European countries (Italy, Germany, Greece, and Poland) under different marginality conditions for two or three consecutive growing seasons from 2018 to 2021. In particular, in Italy two sites were compared within the same location (Ozzano dell'Emilia) but characterized by two different slopes, namely Ozzano 1 (OZ-1, slope ~25%) and Ozzano 2 (OZ-2, slope~15%), also in Poland the trials were established at two locations, Leginy characterized by clay soil and Fingaty characterized by sandy soil, while in Germany and Greece the trials were established only at one location per country but on two consecutive growing seasons. The full characterization of the trial sites, soils and climates are reported in Table 1 & 2. At each location camelina was grown in large strips of at least 1000 $m^2$ (apart from Germany where camelina was grown on a randomized plot trial), which were run by means of available farm-scale equipment, in order not only to test the feasibility of the crop in such conditions but also how realistic it may be for local farmers to grow camelina. The presented yield data derived from manual harvest in Italy, Greece and Germany, while in Poland harvest was carried out by means of a combine harvester. Additionally, only in Italy an additional study was carried out to evaluate the feasibility and seed losses derived by combine harvesting under steep slope conditions.

### 2.2. Genetic materials

With both winter and spring camelina types available, at each test location the most suitable camelina cultivar was grown, selected for its capability to best fit the planned growing cycle, the environmental conditions, and the previous experience of MAGIC partners. The respective country, camelina genotype, and growing cycle were as follows: in Italy the commercial spring variety, Cypress (by Smart Earth Camelina Inc, Saskatoon, Canada), with autumn and winter cycle; in Poland the spring commercial variety Omega (by Poznan University of Life Sciences, Poznan, Poland) with spring cycle; in Greece the winter commercial variety Luna (by Poznan University of Life Sciences, Poznan, Poland) with autumn cycle; in Germany the spring breeding line WUR (by Wageningen University and Research, Wageningen, The Netherlands) with spring cycle.

**Table 1**
Countries, locations, soil type, marginality conditions, and main historical meteorological data (10-years) in the camelina trials established in Italy, Greece, Poland and Germany from 2018 to 2021.

| Country | Location | Location ID | Coordinates | Soil type | Marginality factor/s | Mean annual temperature (°C) | Mean annual precipitation (mm) |
|---|---|---|---|---|---|---|---|
| Italy | Ozzano dell'Emilia | OZ-1 | 44° 24' N, 11° 28' E | Silt loam | 25% slope | 14.2 | 786 |
| | | OZ-2 | 44° 25' N, 11° 28' E | Silty clay loam | 15% slope | | |
| Germany | Oberer Lindenhof | ENIN | 48° 28' N, 9° 18' E | Clay loam | Rooting depth < 0.3 m + stoniness > 15% | 10.1 | 697 |
| Greece | Keramos | KER | 41° 61' N, 26° 34' E | Clay Loam | Acidic soil (pH < 5.5) + Mild slope (> 10%) | 14.0 | 597 |
| Poland | Leginy | LEG | 53° 59' N, 21° 8' E | Clay | Clay 40–60% | 8.1 | 656 |
| | Fingaty | FIN | 54° 0' N, 21° 12' E | Sand/loamy sand | Sand 85–95% | | |

### 2.3. Experimental lay out

#### 2.3.1. Autumn/winter sown trials

*2.3.1.1. Italy.* Two trials were carried out at the experimental organic farm of University of Bologna in Ozzano dell' Emilia (44°26' N, 11°28' E) in two adjacent marginal fields characterized by 25% (OZ-1) and 15% (OZ-2) slope, respectively. The experiment was laid out in a strip plot for three consecutive growing seasons (2018–2020). At both sites the land was previously managed for green forage production for several years. Before the trial start the soil was disk harrowed and then a couple of passes with a rotary tillage were applied to obtain a fine and firm seedbed for camelina. Sowing took place in autumn in OZ-1 and early winter on OZ-2, mimicking possible alternative management solutions for such marginal conditions, and harvest was carried out in June (Table 3). The seed was drilled with double-disk openers in rows 0.17 m apart, and the sowing depth was very shallow corresponding to ~10 mm. The crop was not irrigated and cultivated according to organic farming practices. During each growing season a commercial organic fertilizer (Guanito, NP 6–15) was applied before sowing (30–75 kg ha$^{-1}$, of N and P, respectively), then before camelina stem elongation additional organic fertilizer (Biouniversal, N 12%) was applied at a rate of 42 kg ha$^{-1}$ of N. Weed control was performed mechanically by means of a harrow. Before harvesting, plants in 10 randomized areas (2 m × 2 m) were manually cut at the soil surface for productivity analysis, to determine the seed yield of camelina, which was then calculated per 1 hectare. Thereafter the remaining part of the trials was harvested by means of a New Holland TC 5080 self-levelling combine. Plant samples were threshed and seed samples were obtained to determine seed yield, 1000-seed weight, seed oil content, and fatty acid composition. Seed oil content was determined on about 5 g of finely grinded camelina seed from each sample. An aliquot of 1.5 g of ground material was included in a cellulose thimble and inserted in a 30 mL glass extractor. Oil extraction was carried out in an in-line Soxhlet extraction unit (mod. R 306) from Behr Labor-Technik (Düsseldorf, Germany), using 60 mL of n-hexane as an organic solvent. Extraction was performed for 2 h. The extracted oil was dried and then, transferred by means in a 10 mL Teflon screw-cap glass tube, and stored at −18°C until FA determination. Fatty acid determination was carried out by means of a gas chromatographer (mod. 7820 A, Agilent Technologies, Santa Clara, CA, USA), equipped with an automatic liquid sampler (mod. G4567A) and a flame ionisation detector (FID). Hexane was used as the carrier gas. Fatty acids were identified by matching peak retention times with those of a FAME standard mixture (GLC-463) from Nu-Check (Elysian, MN, USA).

Additionally, only in Italy, since the presence of very steep slope (>15%) could technically prevent the optimal harvesting of the crop in such condition, an additional study was carried out to evaluate the incidence of seed losses at harvest in such conditions. This assessment was carried out only in OZ-2 (Fig. 1), since the slope in OZ-1 was too steep to assure the security of the operators taking the measures. During combine harvesting, threshed material exiting the combine harvester was randomly collected five times from a tarp carried manually right behind the machinery for 20 m length. Thus, each sampling area measured 120 m$^2$ (6 × 20 m). The collected material was put in sealed bags and brought to the laboratory for seed loss evaluation. Seeds were mechanically separated form straw and chaff via Fritsch vibro sifter mod. Analysette 18 equipped with 10.0, 5.0, 2.5, 1.0, and 0.5-mm sieves. Thus, seeds were collected, dried, and then weighed to estimate seed yield and seed losses.

*2.3.1.2. Greece.* The test location was at Keramos in northern Greece (Table 1). The soil was characterized by low pH and the area was sloped (Table 2). The trials were carried out in two consecutive growing seasons (Table 3) from December 2018 until June 2020. Camelina was sown at a seeding rate of 5 kg ha$^{-1}$ of seeds by means of a mechanical cereal seeder on about half a hectare each year. The trials were rainfed


**Fig. 1.** Combine harvesting carried out in the camelina fields established in Italy under different steep slope conditions: left: OZ-1 (25% slope), right: OZ-2 (15% slope).

**Table 2**
Main soil chemical characteristics in the camelina trials established in Italy, Greece, Poland and Germany.

| Country | Location | pH | Total N (g $kg^{-1}$) | Available P (mg $kg^{-1}$) | Exchangeable K (mg $kg^{-1}$) | Organic C (g $kg^{-1}$) | SOM (%) |
|---|---|---|---|---|---|---|---|
| Italy | OZ-1 | 8.09 | 0.78 | 25 | 161 | 5.91 | 1.02 |
| | OZ-2 | 8.08 | 0.87 | 16 | 213 | 7.70 | 1.33 |
| Germany | ENIN | 7.2 | 2.33 | 46.6 | 15.8 | NA | NA |
| Greece | KER | 5.5 | NA | NA | NA | NA | 2.3 |
| Poland | LEG | 6.6 | 2.79 | 10.6 | 35 | 18.20 | 3.14 |
| | FIN | 5.8 | 0.95 | 16.3 | 11 | 11.30 | 1.95 |

NA= data not available.

**Table 3**
Sowing and harvest date, cumulative precipitation, mean temperature, mean maximum, and minimum temperature, growing degree days (GDD), and cycle length from sowing to harvest in all the camelina field trials considered in the study.

| Country | Site ID | Years | Sowing Date | Harvest Date | Precipitation (mm) | T mean (°C) | T max (°C) | T min (°C) | GDD | Cycle length (d) |
|---|---|---|---|---|---|---|---|---|---|---|
| Italy | *OZ-1* | 2018–2021 | 16 Nov 2018 | 14 Jun 2019 | 360 | 9.4 | 15.0 | 4.8 | 1057 | 210 |
| | | | 10 Nov 2019 | 05 Jun 2020 | 283 | 10.2 | 15.9 | 5.5 | 1129 | 208 |
| | | | 23 Oct 2020 | 25 May 2021 | 221 | 8.2 | 14.3 | 4.0 | 933 | 214 |
| | *OZ-2* | 2019–2021 | 07 Jan 2020 | 05 Jun 2020 | 104 | 11.4 | 17.4 | 6.2 | 987 | 150 |
| | | | 20 Jan 2021 | 03Jun 2021 | 100 | 10.7 | 16.8 | 5.5 | 814 | 131 |
| Germany | *ENIN* | 2018–2020 | 15 May 2019 | 30 Aug 2019 | 330 | 18.1 | 23.3 | 12.4 | 1413 | 107 |
| | | | 15 May 2020 | 15 Sept 2020 | 352 | 17.1 | 22.3 | 11.4 | 1502 | 123 |
| Greece | *KER* | 2018–2020 | 03 Dec 2018 | 06 Jun 2019 | 293 | 8.4 | 14.2 | 3.6 | 873 | 185 |
| | | | 29 Nov 2019 | 09 Jun 2020 | 293 | 9.0 | 15.2 | 3.9 | 944 | 193 |
| Poland | *LEG* | 2018–2020 | 14 Apr 2018 | 30 Aug 2018 | 327 | 17.0 | 21.8 | 11.7 | 1669 | 138 |
| | | | 11 Apr 2019* | 28 Aug 2019 | 182 | 18.4 | 23.2 | 10.2 | 1196 | 88 |
| | | | 17 Apr 2020 | 07 Aug 2020 | 316 | 14.4 | 19.0 | 9.1 | 1062 | 112 |
| | *FIN* | | 21 Apr 2018 | 30 Aug 2018 | 317 | 17.3 | 22.1 | 12.0 | 1622 | 131 |
| | | | 11 Apr 2019* | 28 Aug 2019 | 182 | 18.4 | 23.2 | 10.2 | 1196 | 88 |
| | | | 17 Apr 2020 | 07 Apr 2020 | 316 | 14.4 | 19.0 | 9.1 | 1062 | 112 |

* In 2019, due to extreme drought after sowing, the trials were re-sown on 1st June.

and before camelina sowing a basic fertilization with 45, 15, and 35 kg $ha^{-1}$ of N-P-K was applied. Before sowing Stomp Aqua (pendimethalin) was applied in a dose of 2 L $ha^{-1}$, thereafter no additional chemicals were applied. When camelina reached full maturity, five representative areas of 2 m x 2 m were manually cut at soil level and then threshed separately to determine potential seed and straw yield of camelina, camelina final plant height was also surveyed in those areas. The residual part of the field was mechanically harvested by means of a combine small-scale harvester (WinterSteiger, Austria), locally available, to obtain the real camelina seed yield attainable by means of farm scale equipment.

### 2.3.2. Spring sown trials

*2.3.2.1. Germany.* The camelina field trial was established in southwest Germany in Eningen commune (Table 1 & 2) on a site characterized by shallow soil (< 0.30 m depth), high stone content (15 vol%) and high clay content (> 40 wt%). The silt and sand contents amounted for 44.1 and 12.2%, respectively. The field trial was run in two consecutive growing seasons from 2019 to 2020. No herbicides or other pesticides were used. Instead, the site was cultivated via shallow ploughing and tilled with cultivating unit in spring before sowing. Each year, camelina was sown on 15th May in single rows with a row distance of 135 mm and a drill at rate of 7.5 kg seeds $ha^{-1}$. This was achieved with the help of disc coulters (Fig. 1), which make the process easier than drag coulters due to the stony and flat soil conditions at the site. The latter would come into continuous contact with the stones and be damaged as a result. The net area of the plots was 36 $m^2$ (6 m width, 6 m length). In addition to soil mineral N (which was estimated of about 60 kg N $ha^{-1}$), N fertilization (N= 26%) was applied as ammonium nitrate in two rates of 40 and 120 kg $ha^{-1}$ before stem elongation. During the vegetation periods, the occurrence of diseases such as downy mildew (*Hyaloperonospora camelinae*) was observed (Fig. 2). The harvests were conducted by hand within a representative sampling area of 0.5 $m^2$ on 30th August 2019 and 15th September 2020, respectively. The parameters measured at harvest were (i) fresh matter weight of stems and seeds, (ii) average height of the plant stand, and (iii) number of plants. Based on this data, the seed and straw yield per hectare, the harvest index (HI) as well as the plant density were calculated.

**Fig. 2.** Disc coulters used for sowing in Germany.

*2.3.2.2. Poland.* Camelina field trials were established in northeast Poland in Reszel commune at two locations: Leginy and Fingaty, which are about 5 km away from each other (Table 1). The trial was run in three consecutive growing seasons from 2018 to 2020. In the first year in spring, before sowing, the site was sprayed with Roundup 360 SL (glyphosate) in dose of 5 L $ha^{-1}$, then the soil was ploughed and tilled with a cultivating unit. In subsequent years, the soil was only prepared with a cultivation unit. Camelina was sown with a drill at a rate of 6 kg seeds $ha^{-1}$. Plants were sown in single rows; the distance between rows was 0.13 m, and the strip covered an area of 2200 $m^2$. Nitrogen fertilization at a rate of 100 kg $ha^{-1}$ N was applied as ammonium nitrate before stem elongation. No pesticides were used. In 2018 camelina seeds were sown on 21st April and on Fingaty site and on 14th April on Leginy site. In 2019 seeds were sown on 11th April on both sites however, due to drought and emergence failure, the trials were re-sown on 1st June. In 2020 the trials were established on 17th April on both sites. Harvest dates were: 30th August 2018, 28th August 2019 and 7th August 2020 (Table 3). During the camelina cycle, observations of the growth and development of plants as well as the occurrence of diseases and pests were monitored. At plant maturity, just before their harvest, final plant height was measured. Subsequently, camelina seeds were harvested by combine harvester. The collected seeds were weighed and on this basis the seed yield was calculated per 1 hectare. In the laboratory the purity of the seeds was determined and, on this basis, the yield of pure seeds was calculated from the area of 1 hectare. In 2019, an analysis of the properties of seeds from both sites was also performed. The 1000-seed weight was assessed, and also seed oil content and the composition of fatty acids was analyzed. Seed oil content was determined by means of a Soxhlet extraction method on the BUCHI Extraction System B-811. Dried and homogenized samples was placed into extraction thimbles and extracted with 150 mL of petroleum ether. Fatty acid (FA) composition was determined by gas chromatography GC-FID of FA methyl esters (FAMEs) according to PN-EN ISO 12966–4:2015–07 standard. Fatty acid derivatives were prepared by the transesterification method using BF3 or trimethylsulfonium hydroxide (TMSH) according to PN-EN ISO 12966–2:2017–05 and PN-EN ISO 12966–3:2016–07 standards. The chromatographic analysis was performed using a Shimadzu GC-2014 chromatograph equipped with 60 m x 0.25 mm×0.2 µm fused silica cyanopropyl-polysiloxane column with as a stationary phase connected to a flame ionization detector (FID). A Supelco standard solution composed of a mixture of 37 FAMEs was used for the identification of peaks. Additionally, the identification of FA was confirmed by the gas chromatography mass spectrometry (GC-MS) method using the Shimadzu GCMS-QP2020 NX system.

### 2.4. Statistical analysis

Given the marginality conditions, the management practices, and the camelina genotype different at each study site, each trial was statically analyzed separately. In Italy a one-way ANOVA was conducted to determine the effect of the slope, while the growing season was considered as a random effect. In Greece a one-way ANOVA was conducted to determine the effect of the growing season. In Germany, a one-way ANOVA was conducted to determine the effect of the N fertilization, while the growing season was considered as a random effect. In Poland where yield was assessed mechanically on the entire field, and a one-way ANOVA was conducted on seed quality parameters surveyed only in 2019 comparing the effect of the two locations. When significant differences were observed Fisher's LSD test was used to separate the means at $P \leq 0.05$ significance level.

## 3. Results and discussion

### 3.1. Meteorological data

The main meteorological data for each study site and growing season were collected from meteorological data stations present within the trial farms, a part from Greece where this infrastructure was not available locally, and so data were retrieved from the NASA meteorological website (https://power.larc.nasa.gov/data-access-viewer/). In particular, for each location and growing season the key dates and main meteorological data considered (Table 3), from camelina sowing to harvest, were: the air maximum and minimum daily temperature and the daily precipitation. Then, camelina cycle, from sowing to harvest, expressed in days (d,) and the cumulative growing degree days (GDD) were also calculated. In particular, for GDD calculation a base temperature of 4°C was used, as suggested by Gesch and Cermak (2011), in the following formula: GDD=Σ [(Tmax+ Tmin)/2 – Tbase]. Camelina confirmed to be a very plastic crop being able to fit all the growing conditions and completing its cycle in an average ~190 d, when sown in autumn/winter, i.e., Italy and Greece, and in ~112 d, when sown in spring, i.e., Poland and Germany. When analyzing the GDD accumulation from sowing to harvest, for the autumn/winter sown trials camelina completed its cycle accumulating ~1000 GDD on average. Otherwise spring sown trials, established in Poland and Germany, showed about 35% higher GDD sum, needing 1340 GDD for reaching harvest maturity. Those data are in line with literature (Berti et al., 2016; Zanetti et al., 2021), demonstrating that cycle length in terms of days and GDD accumulation are two parameters not affected by marginality conditions, but more by locations and sowing date. It is worth keeping in mind that growing cycles with increased GDD and shorter cycle length, like in Poland and Germany in the present study, are often resulting in lower seed yields (Zanetti et al., 2020). Despite being the test sites characterized by different long-term meteorological conditions (Table 1), the growing conditions during camelina cycle were not so different in terms of temperatures, when comparing similar sowing dates, so for autumn sown camelina the mean Tmax was 15.5°C and the mean Tmin was 4.8°C, while for spring sown camelina the mean Tmax was 21.7°C and the mean Tmin was 10.8°C, and this explains the significantly higher GDD needed to reach maturity. Nevertheless, when considering cumulative precipitation, the range of variation across sites and growing seasons appeared quite impressive, with camelina sown in winter in Italy (OZ-2) being able to complete the cycle with only ~100 mm of rain, while for autumn sown camelina in the same location the cumulative precipitation was nearly triple that (288 mm), and very similar to that occurring in Greece (293 mm). Interestingly, spring sown camelina in Poland and Germany received often more than 300 mm of precipitation, with the largest amount in Germany in 2020. Presumably this can be one of the reasons behind the presence of downy mildew in the camelina stand in Germany. Downy mildew was the only impacting disease on camelina production (Fig. 3), and cultivation on too wet

**Fig. 3.** Observation of downy mildew infection on camelina grown in south-west Germany, 2020.

regions should be carefully evaluated, since yield losses can be conspicuous, as recently reported by Leclere et al. (2021). Camelina irrespective of genotype, growing cycle and marginality conditions confirmed its wide adaptability to European pedoclimates, as previously reported (Zanetti et al., 2017; 2021), and thus also corroborated the suitability map created within the MAGIC project (Von Cossel et al., 2019b), in which camelina was identified as one of the industrial crops with the broadest suitability for European marginal land.

### 3.2. Camelina productive performances under marginal land

The possibility to grow camelina on marginal land across the whole of Europe is one of the main driving forces underpinning the interest and the diffusion of this minor oilseed crop. Nevertheless, since camelina is a multi-use crop suitable for different biobased applications it is compulsory to set up reliable business plans basing on consolidated yield data from field trials, while so far, most of the available information derives from modelling approaches (Schillaci et al., 2023). To date, there is not any extensive study, including real field data on camelina productivity under marginal land, as defined by the JRC (Eliasson, 2007) in different European pedo-climates. In fact, much of the attention devoted to this crop is linked to its intrinsic tolerance to heat and drought, which often characterize marginal land, but as described before biophysical constraints leading to marginal land definition are much more complex. The present study includes real field data in replicated trials in several growing seasons, established in four different European countries, thus for the first time proving and demonstrating the suitability/unsuitability to camelina to marginal land, and finally providing operational data for setting up business plans in real case studies.

Spring camelina, sown in autumn/winter, in Mediterranean countries (i.e., Italy and Greece, in the present study) has previously been identified as the best option to obtain adequate seed yields (Masella et al., 2014; Righini et al., 2019; Zanetti et al., 2021). In Italy, camelina was grown in two different slopes (25% and 15%), its seed yield was significantly reduced under the steepest slope (OZ-1, Fig. 4) reaching on average only 0.43 Mg DM ha$^{-1}$, compared with 1.93 Mg DM ha$^{-1}$, achieved in OZ-2. This latter value is in line or in some cases even higher than typical seed yield of spring camelina sown in autumn in the Mediterranean and Balkan area under non-marginal conditions (Angelini et al., 2020; Marjanović Jeromela et al., 2021; Masella et al., 2014; Matteo et al., 2020; Royo-Esnal and Valencia-Gredilla, 2018). Camelina demonstrated to adapt well to sloped marginal land up to 15%, without any significant losses in terms of seed yield, while when slope increased up to 25% seed yield was reduced by almost 80%. Furthermore, from a morphological point of view camelina grown under very steep slope produced shorter plants compared with those grown under milder slope (0.54 vs. 0.93 m OZ-1 vs. OZ-2, respectively, data not shown). Under steep slope all the agronomic practices to manage camelina, such as sowing and harvesting were more complicated, and a satisfactory soil coverage was never achieved thus leading to stronger weed pressure, mainly by grass species (i.e., *Avena fatua*). According to the results obtained during seed loss assessment in OZ-2 trial, a self-leveling combine harvester allowed camelina harvesting with very little loss of seeds: about 8 kg DM ha$^{-1}$ on average, corresponding to 0.53% (w/w) of expected seed yield. In fact, similar studies performed on flat fields reported seed loss averaging between 5% and 11% (Sintim et al., 2016; Stefanoni et al., 2020, 2021). On the other hand, the same studies reported a working speed of the combine harvester ranging between 5 and 7 km h$^{-1}$, whilst in OZ-2 the working speed of machinery was halved due to slope. In Italy camelina seed quality was also surveyed determining: 1000-seed weight, seed oil content (Fig. 5A), and fatty acid profile. Interestingly, seed quality was improved with the increase of slope, and 1000-seed weight and seed oil content were both significantly improved in the OZ-1 conditions, compared with OZ-2. Despite being the camelina variety grown in Italy (Cypress, former 787–08, Zanetti et al., 2017), characterized by increased seed size, the results achieved in OZ-1 are remarkable since 1000-seed weight was steadily above 1.72 g, a value reached before only in very few cases in northern Italy (Alberghini et al., 2022; Zanetti et al., 2017, 2021). Presumably such response behavior of camelina under marginal condition was related to a compensation effect (Gesch et al., 2017) for low seed yield and low plant density, and from a technological point of view the post-harvest processing of larger seeds is often easier. The same trend has been surveyed for seed oil content (Fig. 5B), in fact it was increased under steeper slope (OZ-1), and the mean value was 39.9% in comparison with 37.5% under milder slope (OZ-2). Also, the seed oil composition of camelina was affected by marginality conditions (Table 4), and this aspect should be

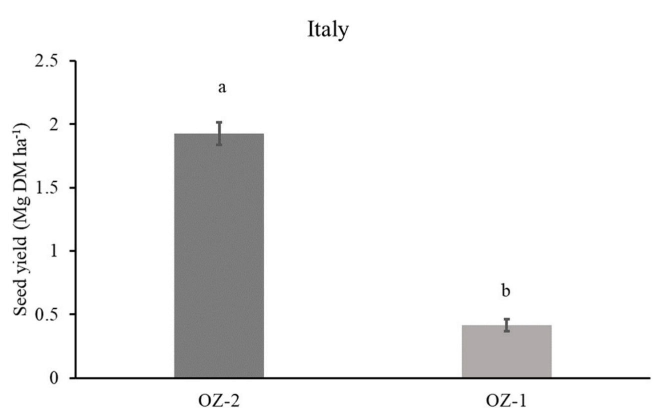


**Fig. 4.** Camelina seed yield (Mg DM ha$^{-1}$) in Italy obtained in two sites characterized by different slopes: OZ-2 = 15% slope, OZ-1= 25% slope. Vertical bars: standard errors. Different letters: statistically different means for $P \leq 0.05$, LSD test.

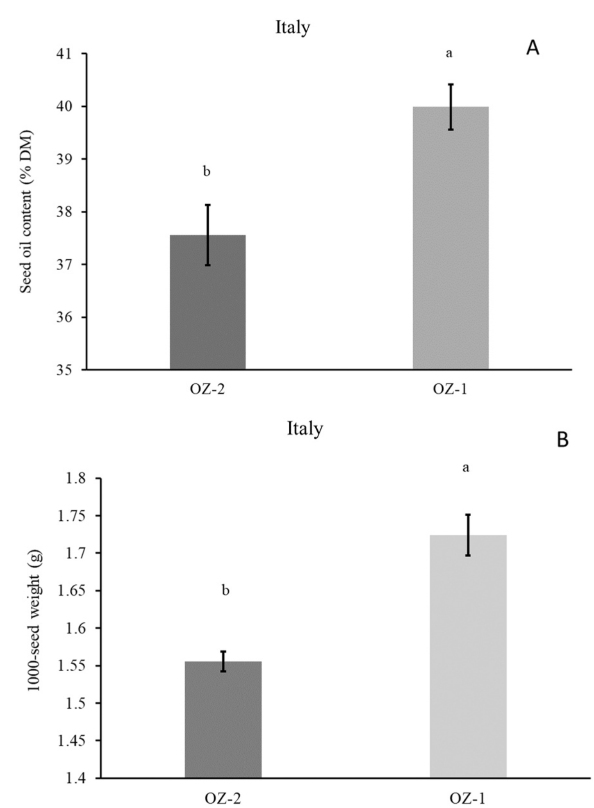


**Fig. 5.** A) Camelina seed oil content (% DM); B) Camelina 1000-seed weight obtained in Italy in two sites characterized by different slopes: OZ-2 = 15% slope, OZ-1= 25% slope. Vertical bars: standard errors. Different letters: statistically different means for $P \leq 0.05$, LSD test.

**Table 4**
Main fatty acid composition (oleic, linoleic, linolenic, and eicosenoic acid) of camelina grown in Italy in response to different marginality conditions. Mean value ± standard error. Different letters = significant different means for $P \leq 0.05$ (LSD's Test).

| Location | Slope | Oleic acid (%) | Linoleic acid (%) | Linolenic acid (%) | Eicosenoic acid (%) |
|---|---|---|---|---|---|
| OZ-1 | 25% | 12.9 b | 17.1 b | 36.1 a | 14.5 |
| OZ-2 | 15% | 13.5 a | 19.2 a | 33.5 b | 14.4 |

also carefully considered in view of the different end-uses. Camelina oil in OZ-1 resulted significantly higher in linolenic acid, while in OZ-2 oleic and linoleic acid were promoted (Table 4). Eicosenoic acid was not affected by growing conditions. In general, linolenic acid content is promoted under colder temperatures (Walia et al., 2021) and this would have been the case also of the present study (Table 3) since OZ-1 was characterized by lower temperatures during camelina growing season than OZ-2.

In Greece camelina seed yield was affected by the growing season, in particular the second one (2020) obtained significantly higher seed yield (Fig. 6), while for straw yield the results were the opposite, higher production was in 2019 than in 2020. The two seasons were quite similar from a meteorological point of view, but the second was slightly milder in terms of temperatures and one week longer and this might have caused the better productive performance of the crop. When analyzing the differences between seed yield obtained by manual harvest and those derived from mechanical harvest of the entire field (data not presented), the values were coherent with those of the manual harvest, but seed losses appeared remarkable, always higher than 15% w/w, particularly in the second growing season reaching 18% w/w. Presumably in relation to the fact that in this latter season camelina plants were significantly taller than in the previous (0.82 vs. 0.72 m, in 2020 vs. 2019, respectively, Fig. 7), and this might have led to increased seed losses, when using a small-scale combine, as the one present locally. These results should be carefully considered together with those obtained in Italy under different marginality conditions, but they both indicated that to prevent remarkable camelina seed losses the combine harvester should be carefully adjusted and in particular great attention should be taken for the working speed which negatively impacted seed losses together with the small size of the cutting bar. Nevertheless, it is worth remarking that the average camelina yield in such marginal conditions was 1.61 Mg DM ha$^{-1}$, a value quite in line with previous studies conducted in Greece for autumn sown camelina (Walia et al., 2021), and higher than those obtained under non-marginal conditions in spring sowing (Angelopoulou et al., 2020) corroborating the fact that autumn/winter sowing represent the optimal strategy for camelina in Greece. Furthermore, the choice of the correct sowing date represents a key strategy to mitigate the penalizing effects of marginal land, and confirming the great suitability of camelina to such conditions.

In Germany under very shallow marginal soil, camelina was sown in spring, and the mean seed yield across growing seasons and fertilization rate was 0.84 Mg DM ha$^{-1}$. Despite camelina being a crop highly suitable to continental climates, so far there is not much published agronomic research for Germany, even for non-marginal conditions (Zanetti et al., 2021), thus for comparison purposes the authors referred to data obtained in similar pedo-climates like Austria (Zubr, 2003) or Poland (Kurasiak-Popowska et al., 2018), where values on average 30 to 50% higher than those obtained in the present study are reported. Interestingly, none of the surveyed parameters at harvest (plant height, seed and straw yield, and plant density) a part from the HI (Fig. 8) was significantly influenced by fertilization. In details, camelina HI was significantly higher when a lower fertilization rate was applied (40 N), mainly in relation to an almost stable seed production, irrespectively of the fertilization rate, and an increased straw yield under 120 N. This is a remarkable result, since camelina did not respond to increased N availability by producing more seeds but just more vegetative biomass, which might have promoted the mildew infestation (Fig. 3). There was no clear benefit in term of overall productivity, and consequently drawbacks on sustainability issues, since fertilization is highly impacting both on production and also environmental costs. Camelina thus confirmed to be only poorly responding to N fertilization (Wysocki et al., 2013), and presumably in relation to the adequate soil N availability of

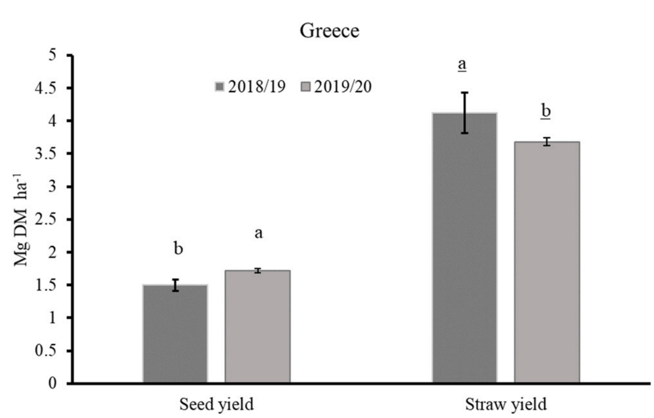


**Fig. 6.** Camelina seed and straw yield (Mg DM ha$^{-1}$) obtained in Greece under marginal land in two consecutive growing seasons. Vertical bars: standard errors. Different letters: statistically different means for seed yield ($P \leq 0.05$, LSD test). Different underlined letters: statistically different means for straw yield ($P \leq 0.05$, LSD test).

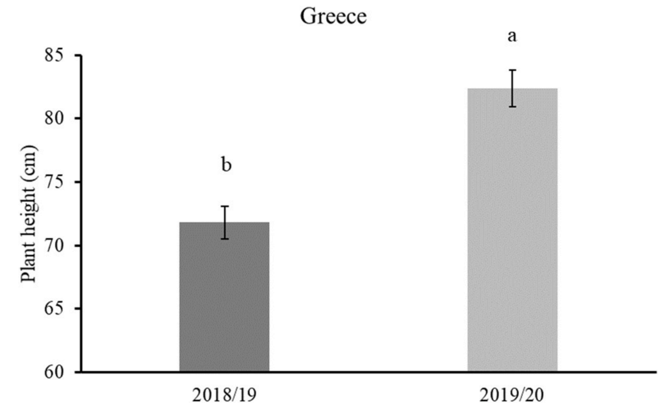


**Fig. 7.** Camelina final plant height (cm) surveyed in Greece under marginal land in two consecutive growing seasons. Vertical bars: standard errors. Different letters: statistically different means ($P \leq 0.05$, LSD test).

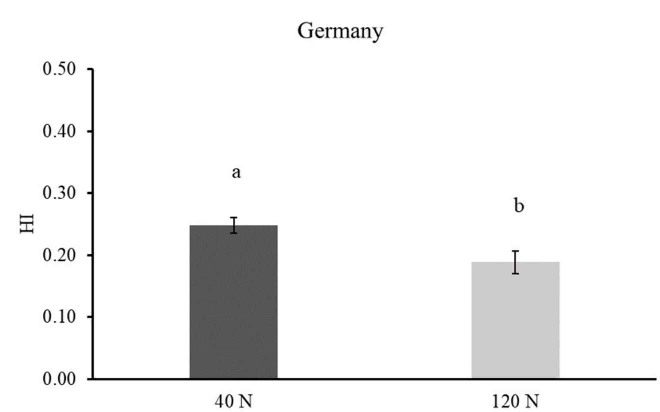


**Fig. 8.** Camelina harvest index (HI) in Germany under shallow soil in response to different fertilization rates (40 and 120 kg N ha$^{-1}$). Vertical bars: standard errors. Different letters: statistically different means ($P \leq 0.05$, LSD test).

the test soil (Table 2), able to completely fulfil to camelina needs for N (Mohammed et al., 2017).

Results from Poland did not permit the statistical analysis of the productive data, since the entire field was managed by means of farm-scale equipment without proper replicates. Camelina seed yield obtained at the two marginal sites is reported in Table 5. Seed yield was on average of the three growing seasons 0.38 Mg DM ha$^{-1}$ under marginal sandy soil (Fingaty), while double was achieved in the clay soil (Leginy). Nevertheless, it is worth mentioning that in the latter site in the last growing season (2020) camelina was not harvested since weed pressure was so high it caused complete failure of the stand. Very interestingly in the growing season when camelina was resown due to emergence failure (2019), the production was the highest at both locations, corroborating the extreme environmental plasticity of this crop (Großkinsky et al., 2023). Consistently across study growing seasons camelina established better in the sandy soil (Fingaty), while the emergence in the clay soil was slower (Leginy), and this is probably the reason behind the higher weed pressure in such conditions. Thus, if clay marginal soil provided higher seed yields than the sandy one, the present results are ranging from half to one third of those currently reported for Poland in spring sowing under non-marginal conditions (Krzyżaniak et al., 2019), also when comparing to data obtained from farm-scale trials with comparable management adopted (Stolarski et al., 2018). Given that weed control is a key management factor for the future implementation of camelina at a wider scale in all of Europe, it is important to keep in mind that the establishment phase of the crop is the one more susceptible and so it is important to adapt the sowing time and technique accordingly to promote a quick and even emergence. This is particularly important for late spring sown camelina since the crop cycle is shorter and the ability to produce a broad rosette of leaves, which will directly compete for space with weeds, could be limited. In Poland, only for 2019 trials, camelina seed quality in terms of 1000-seed weight, seed oil and protein content fatty were statistically analyzed on replicated samples derived from the experimental fields (Table 6). It is interesting to note that seed quality was affected by the location, but in general the reported data are quite in line with available literature, corroborating the results obtained in Italy, where camelina productive capacity was impaired by the marginality of the site, but seed quality was maintained or even improved compared with previous research for Poland (Krzyżaniak et al., 2019; Stolarski et al., 2018), presumably in relation to camelina intrinsic compensation capacity to cope with marginal soils promoting the quality of its seeds. In details, 1000-seed weight was not statistically influenced by the type of marginal soil, otherwise seed oil and protein content was significantly affected (Table 6), with significantly higher amounts of both components in the clay soil (Leginy), presumably resulting in “a less limiting condition” than the sandy soil (Fingaty).

### 3.3. Lesson learnt from camelina under marginal land in Europe

Schillaci et al. (2023) used a modeling approach to estimate camelina’s seed production under marginal land and quantified as a range from 0.7 to 1.4 Mg DM ha$^{-1}$, but the present field real-data showed a much lower potential yield, particularly in very limiting environments (i.e., steep slope, very sandy soil). Obviously, the present multi-year multi-location study has been conducted across highly different pedo-climates and in “real” marginal land affected by severe biophysical constraints, as defined by the JRC (Rossiter et al., 2014). Otherwise, the majority of published studies referred to “generic” marginal land, only basing on low, but again not defined, organic matter content. So, from a political point of view in Europe there is the urgent need of a unequivocal definition of marginal land, with specific limits, and on the other hand camelina confirmed its suitability to be grown under marginal conditions, with only one experimental field that completely failed in one specific growing season (i.e., very clay soil in Poland, in 2020). Interestingly, when comparing seed yields across all the marginal MAGIC sites (Fig. 9), camelina production was on average 0.94 Mg DM ha$^{-1}$, ranging from 0.38 Mg DM ha$^{-1}$ for camelina sown in spring in Poland in a very sandy soil, up to 1.93 Mg DM ha$^{-1}$ for camelina sown in autumn in Italy on a 15% slope. Interestingly, when analyzing the coefficient of variation (CV), it was the highest (0.99) in Poland in the clay soil, since in one year the harvest completely failed due to weed pressure, followed by the steepest slope (OZ-1) in Italy (0.81), while the lowest values were calculated for Greece with only 0.11, followed by Italy under milder slope (OZ-2) and Germany reporting a similar value (0.28). From an agronomic point of view, camelina production should be targeted to fields with low weed pressure, since there are no herbicide options against dicots for camelina, while usually grass-killers could be safely in-stand applied. Furthermore, since there is the availability of both spring and winter types, for a future spread of this crop it will be strategic to identify the most suitable biotype for each specific pedo-climate. In southern marginal land the choice of autumn/winter sowing seemed to be able to assure getting seed yields in any conditions. Camelina confirmed to respond only slightly to N fertilization, and in general the choice of performing soil characterization before the establishment of the field would permit saving useless extra fertilizations, with consequent environmental and economic cost savings. Harvesting might represent a key point in the agronomic management of camelina, but available combine for cereals are all suitable, even if with the careful set up of available equipment, i.e. reducing working speed and ventilation, permitted to have negligible seed losses, even lower

**Table 5**
Camelina seed yield (Mg DM ha$^{-1}$) in the two locations in Poland characterized by different soil type, i.e., Fingaty: sandy soil, Leginy: clay soil.

| Site/year | Seed yield (Mg DM ha$^{-1}$) | | | |
|---|---|---|---|---|
| | 2018 | 2019 | 2020 | Site Mean |
| Fingaty | 0.42 | 0.53 | 0.18 | 0.38 |
| Leginy | 0.50 | 0.99 | 0.00* | 0.75 |

* Camelina plantation failure due to complete field domination by *Polygonum persicaria*

**Table 6**
Camelina seed quality traits (1000-seed weight, oil and protein content) surveyed in Poland during 2019 at the two trial locations; i.e., Fingaty: sandy soil, Leginy: clay soil. Mean value ± standard error. Different letters: significant different means for $P \leq 0.05$, LSD test.

| Location | 1000-seed weight (g) | Seed oil content (% DM) | Seed protein content |
|---|---|---|---|
| Fingaty | 0.99±0.02 | 40.70±0.14b | 23.91±0.12b |
| Leginy | 1.04±0.03 | 41.85±0.10a | 26.87±0.02a |
| Grand mean | 1.01±0.03 | 41.27±0.19 | 25.39±0.94 |

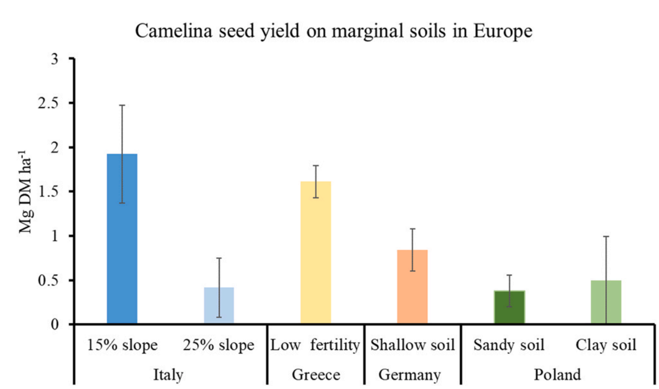


**Fig. 9.** Camelina seed yield on marginal soils in Europe obtained in the multi-year multi-location trials carried in the MAGIC project. Marginal soils were: steep slope, 15% and 25% in Italy, low fertility soil in Greece, shallow soil in Germany, and sandy and clay soils in Poland. Mean value ± standard deviation.

than other small-seeded oilseed crops, e.g. oilseed rape. All these aspects should be carefully evaluated from an economic perspective since the average seed yield obtained in marginal land (0.94 Mg DM $ha^{-1}$) is not that far from the break-even yield (1–1.4 Mg DM $ha^{-1}$) defined by Panoutsou and Alexopoulou (2020) as profitable, but from the present study it appeared evident that it cannot be reached steadily in all the European marginal conditions, so some economic support, from the political sector, willing to fight land abandonment, or from the biobased industries, interested in using certified low iLUC feedstocks, are needed for the future scale-up of camelina. Finally, since from the quality point of view camelina seemed less or even not impacted by marginal conditions, it would be important to economically reward farmers also considering this aspect, and not only basing on seed production levels.

## 4. Conclusion

Camelina is a highly resilient crop characterized by remarkable cold and drought tolerance. It requires low input techniques and can be grown both as spring and winter crop in almost all European environments. Therefore, the development potential of camelina on European marginal land seems considerable; however, there are still some doubts about the possibility of achieving sustainable yields in unfavorable environments. Our study generally confirmed that camelina may have interesting potentials of being developed in some marginal areas; however, seed yield was generally limited and lower than expected by modeling studies. Growing camelina in southern European marginal land, where the crop can be sown in autumn, seems the most conservative and safe strategy to achieve profitable yields. In terms of agronomic management, the most important choice to optimize the crop in marginal land regards: i) weed presence in the field, which should be carefully evaluated, ii) N fertilization which should be tailored to soil N availability in order to reduce costs, and iii) the harvesting phase, which needs a thorough setting up in order not to lose product.

## CRediT authorship contribution statement

**Stolarski Mariusz J.:** Writing – review & editing, Data curation. **Krzyżaniak Michał:** Writing – review & editing, Data curation. **Alexopoulou Efthymia:** Writing – review & editing, Funding acquisition, Data curation. **Lewandowski Iris:** Writing – review & editing, Supervision. **Pagani Elena:** Formal analysis, Data curation. **Monti Andrea:** Writing – review & editing, Supervision, Funding acquisition. **Peroni Pietro:** Writing – original draft. **Greiner Beatrice Elisabeth:** Data curation. **von Cossel Moritz:** Writing – review & editing, Data curation. **Stefanoni Walter:** Data curation. **Facciolla Erika:** Writing – review & editing, Project administration. **Zanetti Federica:** Writing – original draft, Conceptualization. **Pari Luigi:** Writing – review & editing, Data curation.

## Declaration of Competing Interest

If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

Data will be made available on request.

## Acknowledgements

This research was supported by the MAGIC project, which has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement no. 727698.

## References

Alberghini, B., Zanetti, F., Corso, M., Boutet, S., Lepiniec, L., Vecchi, A., Monti, A., 2022. Camelina [*Camelina sativa* (L.) Crantz] seeds as a multi-purpose feedstock for bio-based applications. Ind. Crops Prod. *182* https://doi.org/10.1016/j.indcrop.2022.114944.

Alexopoulou, E., 2018. List with the selected most promising industrial crops for marginal lands (Versione V1). Zenodo D1.3. https://doi.org/10.5281/zenodo.3539151.

Angelini, L.G., Abou Chehade, L., Foschi, L., Tavarini, S., 2020. Performance and potentiality of camelina (*Camelina sativa* L. Crantz) genotypes in response to sowing date under Mediterranean environment. Agronomy *10* (12). https://doi.org/10.3390/agronomy10121929.

Angelopoulou, F., Tsiplakou, E., Bilalis, D., 2020. Tillage intensity and compost application effects on organically grown camelina productivity, seed and oil quality. Not. Bot. Horti Agrobot. Cluj. -Napoca *48* (4), 2153–2166. https://doi.org/10.15835/nbha48412056.

Balanuca, B., Stan, R., Hanganu, A., Lungu, A., Iovu, H., 2015. Design of new camelina oil-based hydrophilic monomers for novel polymeric materials. J. Am. Oil Chem. ' Soc. *92* https://doi.org/10.1007/s11746-015-2654-z.

Balanuca, B., Stan, R., Lungu, A., Vasile, E., Iovu, H., 2017. Hybrid networks based on epoxidized camelina oil. Des. Monomers Polym. *20* (1) https://doi.org/10.1080/15685551.2016.1231031.

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

Berti, M., Wilckens, R., Fischer, S., Solis, A., Johnson, B., 2011. Seeding date influence on camelina seed yield, yield components, and oil content in Chile. Ind. Crops Prod. *34* (2) https://doi.org/10.1016/j.indcrop.2010.12.008.

Cervelli, E., Scotto di Perta, E., Pindozzi, S., 2020. Energy crops in marginal areas: Scenario-based assessment through ecosystem services, as support to sustainable development. Ecol. Indic. 113, 106180 https://doi.org/10.1016/j.ecolind.2020.106180.

EEA, 2019. The sustainability transition in Europe in an age of demographic and technological change. doi:10.2800/571570.

Elbersen, B., van Eupen, E., Mantel, S., Verzandvoort, S., Boogaard, H., Mucher, S., Cicarreli, T., Elbersen, W., Bai, Z., Iqbal, Y., von Cossel, M., McCallum, I., Carrasco, J., Ciria Ramos, C., Monti, A., Scordia, D., Eleftheriadis, I., 2017. D2.1. Definition and classification of marginal lands suitable for industrial crops in Europe (Versione V1). Zenodo. https://doi.org/10.5281/zenodo.3539229.

Elbersen, B., Eupen, van E., Mantel, S., Verzandvoort, S., Boogaard, H., Mucher, S., Cicarreli, T., Elbersen, W., Bai, Z., Iqbal, Y., Cossel, M., MCallum, I., Carrasco, J., Ciria Ramos, C., Monti, A., Scordia, D., (2018) D2.6. Methodological approaches to identify and map marginal land suitable for industrial crops in Europe (https://magic-h2020.eu/wp-content/uploads/2022/04/MAGIC_D2.6-Methodological-approaches.pdf).

Eliasson, Å., 2007. Review of land evaluation methods for quantifying natural constraints to agriculture. The Institute for Environment and Sustainability. Joint Research Centre, Ispra, Italy. EUR, p. 22923.

European Bioeconomy Strategy (2022). eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022DC0283.

European Commission, Directorate-General for Research and Innovation, European bioeconomy policy – Stocktaking and future developments – Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2777/997651.

Gesch, R.W., Cermak, S.C., 2011. Sowing date and tillage effects on fall-seeded camelina in the northern corn belt. Agron. J. *103* (4) https://doi.org/10.2134/agronj2010.0485.

Gesch, R.W., Dose, H.L., Forcella, F., 2017. Camelina growth and yield response to sowing depth and rate in the northern Corn Belt USA. Ind. Crops Prod. *95* https://doi.org/10.1016/j.indcrop.2016.10.051.

Großkinsky, D.K., Faure, J.-D., Gibon, Y., Haslam, R.P., Usadel, B., Zanetti, F., Jonak, C., 2023. The potential of integrative phenomics to harness underutilized crops for improving stress resilience. Front. Plant Sci. 14, 1216337 https://doi.org/10.3389/fpls.2023.1216337.

Halbac-Cotoara-Zamfir, R., Smiraglia, D., Quaranta, G., Salvia, R., Salvati, L., Giménez-Morera, A., 2020. Land degradation and mitigation policies in the Mediterranean region: a brief commentary. Sustainability *12* (20). https://doi.org/10.3390/su12208313.

Hunsaker, D.J., French, A.N., Clarke, T.R., El-Shikha, D.M., 2011. Water use, crop coefficients, and irrigation management criteria for camelina production in arid regions. Irrig. Sci. *29* https://doi.org/10.1007/s00271-010-0213-9.

Keske, C.M., Hoag, D.L., Brandess, A., Johnson, J.J., 2013. Is it economically feasible for farmers to grow their own fuel? A study of *Camelina sativa* produced in the western United States as an on-farm biofuel. Biomass Bioenergy 54. https://doi.org/10.1016/j.biombioe.2013.03.015.

Khanna, M., Chen, L., Basso, B., Cai, X., Field, J.L., Guan, K., Zipp, K.Y., 2021. Redefining marginal land for bioenergy crop production. GCB Bioenergy *13* (10). https://doi.org/10.1111/gcbb.12877.

Krzyżaniak, M., Stolarski, M.J., Tworkowski, J., Puttick, D., Eynck, C., Załuski, D., Kwiatkowski, J., 2019. Yield and seed composition of 10 spring camelina genotypes cultivated in the temperate climate of Central Europe. Ind. Crops Prod. *138* https://doi.org/10.1016/j.indcrop.2019.06.006.

Krzyżaniak, M., Stolarski, M.J., Graban, Ł., Lajszner, W., Kuriata, T., 2020. Camelina and crambe oil crops for bioeconomy—straw utilization for energy. Energies *13* (6). https://doi.org/10.3390/en13061503.

Kurasiak-Popowska, D., Tomkowiak, A., Człopińska, M., Bocianowski, J., Weigt, D., Nawracała, J., 2018. Analysis of yield and genetic similarity of Polish and Ukrainian *Camelina sativa* genotypes. Ind. Crops Prod. 123 https://doi.org/10.1016/j.indcrop.2018.07.001.

Leclère, M., Lorent, A.R., Jeuffroy, M.H., Butier, A., Chatain, C., Loyce, C., 2021. Diagnosis of camelina seed yield and quality across an on-farm experimental network. Eur. J. Agron. *122* https://doi.org/10.1016/j.eja.2020.126190.

Lohaus, R.H., Neupane, D., Mengistu, M.A., Solomon, J.K., Cushman, J.C., 2020. Five-year field trial of eight *Camelina sativa* cultivars for biomass to be used in biofuel under irrigated conditions in a semi-arid climate. Agronomy 10 (4). https://doi.org/10.3390/agronomy10040562.

Marjanović Jeromela, A., Cvejić, S., Mladenov, V., Kuzmanović, B., Adamović, B., Stojanović, D., Vollmann, J., 2021. Technological quality traits phenotyping of camelina across multienvironment trials. Acta Agric. Scand., Sect. B—Soil Plant Sci. 71 (8) https://doi.org/10.1080/09064710.2021.1933162.

Masella, P., Martinelli, T., Galasso, I., 2014. Agronomic evaluation and phenotypic plasticity of *Camelina sativa* growing in Lombardia, Italy. Crop Pasture Sci. *65* (5) https://doi.org/10.1071/CP14025.

Matteo, R., D'Avino, L., Ramirez-Cando, L.J., Pagnotta, E., Angelini, L.G., Spugnoli, P., Tavarini, S., Ugolini, L., Foschi, L., Lazzeri, L., 2020. Camelina (*Camelina sativa* L. Crantz) under low-input management systems in northern Italy: Yields, chemical characterization and environmental sustainability. Ital. J. Agron. 15, 1519. https://doi.org/10.4081/ija.2020.1519.

Mohammed, Y.A., Chen, C., Afshar, R.K., 2017. Nutrient requirements of camelina for biodiesel feedstock in central Montana. Agron. J. *109* (1) https://doi.org/10.2134/agronj2016.03.0163.

Obour, A.K., Sintim, H.Y., Obeng, E., Jeliazkov, D.V., 2015. Oilseed camelina (*Camelina sativa* L Crantz): Production systems, prospects and challenges in the USA Great Plains. Adv. Plants Agric. Res 2 (2), 68–76. https://doi.org/10.15406/apar.2015.02.00043.

Panoutsou, C., Alexopoulou, E., 2020. Costs and Profitability of Crops for Bioeconomy in the EU. Energies *13* (5). https://doi.org/10.3390/en13051222.

Pulighe, G., Bonati, G., Colangeli, M., Morese, M.M., Traverso, L., Lupia, F., Fava, F., 2019. Ongoing and emerging issues for sustainable bioenergy production on marginal lands in the Mediterranean regions. Renew. Sustain. Energy Rev. *103* https://doi.org/10.1016/j.rser.2018.12.043.

Reinhardt, J., Hilgert, P., von Cossel, M., 2021. Biomass yield of selected herbaceous and woody industrial crops across marginal agricultural sites with shallow soil. Agronomy *11* (7). https://doi.org/10.3390/agronomy11071296.

Righini, D., Zanetti, F., Martínez-Force, E., Mandrioli, M., Toschi, T.G., Monti, A., 2019. Shifting sowing of camelina from spring to autumn enhances the oil quality for bio-based applications in response to temperature and seed carbon stock. Ind. Crops Prod. *137* https://doi.org/10.1016/j.indcrop.2019.05.009.

Righini, D., Zanetti, F., Monti, A., 2016. The bio-based economy can serve as the springboard for camelina and crambe to quit the limbo. OCL *23* (5). https://doi.org/10.1051/ocl/2016021.

Rossiter, D., Schulte, R., van Velthuizen, H., Le-Bas, C., Nachtergaele, F., Jones, R., van Orshoven, J., 2014. Updated common bio-physical criteria to define natural constraints for agriculture in Europe. In: Terres, J., Toth, T., Van Orshoven, J. (Eds.), EUR, Scientific and technical research series. Publications Office, Luxembourg. ISBN 92-79-38190-3J.TerresT.TothJ.Van Orshoven.

Royo-Esnal, A., Valencia-Gredilla, F., 2018. Camelina as a rotation crop for weed control in organic farming in a semiarid Mediterranean climate. Agriculture *8* (10). https://doi.org/10.3390/agriculture8100156.

Schillaci, C., Perego, A., Acutis, M., Botta, M., Tadiello, T., Gabbrielli, M., Barsali, T., Tozzi, F., Chiaramonti, D., Jones, A., 2023. Assessing marginality of camelina (*C. sativa* L. Crantz) in rotation with barley production in Southern Europe: A modelling approach. Agric., Ecosyst. Environ. 357, 108677 https://doi.org/10.1016/j.agee.2023.108677.

Séguin-Swartz, G., Eynck, C., Gugel, R.K., Strelkov, S.E., Olivier, C.Y., Li, J.L., Klein-Gebbinck, H., Borhan, H., Caldwell, C.D., Falk, K.C., 2009. Diseases of *Camelina sativa* (false flax). Can. J. Plant Pathol. 31 (4), 375–386. https://doi.org/10.1080/07060660909507612.

Sintim, H.Y., Zheljazkov, V.D., Obour, A.K., Garcia y Garcia, A., 2016. Managing harvest time to control pod shattering in oilseed camelina. Agron. J. *108* (2) https://doi.org/10.2134/agronj2015.0300.

Stefanoni, W., Latterini, F., Ruiz, J.P., Bergonzoli, S., Attolico, C., Pari, L., 2020. Mechanical harvesting of camelina: Work productivity, costs and seed loss evaluation. Energies *13* (20). https://doi.org/10.3390/en13205329.

Stefanoni, W., Latterini, F., Ruiz, J.P., Bergonzoli, S., Palmieri, N., Pari, L., 2021. Assessing the camelina (*Camelina sativa* (L.) Crantz) seed harvesting using a combine harvester: A case-study on the assessment of work performance and seed loss. Sustainability 13 (1). https://doi.org/10.3390/su13010195.

Stolarski, M.J., 2021. Industrial and bioenergy crops for bioeconomy development. Agriculture 11, 852. https://doi.org/10.3390/agriculture11090852.

Stolarski, M.J., Krzyżaniak, M., Kwiatkowski, J., Tworkowski, J., Szczukowski, S., 2018. Energy and economic efficiency of camelina and crambe biomass production on a large-scale farm in North-Eastern Poland. Energy *150*. https://doi.org/10.1016/j.energy.2018.03.021.

Thom, M.D., Eberle, C.A., Forcella, F., Gesch, R., Weyers, S., 2018. Specialty oilseed crops provide an abundant source of pollen for pollinators and beneficial insects. J. Appl. Entomol. *142* (1-2) https://doi.org/10.1111/jen.12401.

Vera, I., Hoefnagels, R., Junginger, M., van der Hilst, F., 2021. Supply potential of lignocellulosic energy crops grown on marginal land and greenhouse gas footprint of advanced biofuels—a spatially explicit assessment under the sustainability criteria of the renewable energy directive recast. GCB Bioenergy *13* (9). https://doi.org/10.1111/gcbb.12867.

Von Cossel, M., Wagner, M., Lask, J., Magenau, E., Bauerle, A., Von Cossel, V., Warrach-Sagi, K., Elbersen, B., Staritsky, I., Van Eupen, M., Iqbal, Y., Jablonowski, N.D., Happe, S., Fernando, A.L., Scordia, D., Cosentino, S.L., Volker Wulfmeyer, V., Lewandowski, I., Winkler, B., 2019. Prospects of bioenergy cropping systems for a more social-ecologically sound bioeconomy. Agronomy *9*, 605. https://doi.org/10.3390/agronomy9100605.

Von Cossel, M., Iqbal, Y., Scordia, D., Cosentino, S.L., Elbersen, B., Staritsky, I., van Eupen, M., Mantel, S., Prysiazhniuk, O., Mailiarenko, O., Lewandowski, I., 2019. D4.1 Low-input agricultural practices for industrial crops on marginal land (Versione V1). Zenodo. https://doi.org/10.5281/zenodo.3539369.

Walia, M.K., Zanetti, F., Gesch, R.W., Krzyżaniak, M., Eynck, C., Puttick, D., Monti, A., 2021. Winter camelina seed quality in different growing environments across Northern America and Europe. Ind. Crops Prod. *169* https://doi.org/10.1016/j.indcrop.2021.113639.

Wysocki, D.J., Chastain, T.G., Schillinger, W.F., Guy, S.O., Karow, R.S., 2013. Camelina: seed yield response to applied nitrogen and sulfur. Field Crops Res. *145* https://doi.org/10.1016/j.fcr.2013.02.009.

Zanetti, F., Eynck, C., Christou, M., Krzyżaniak, M., Righini, D., Alexopoulou, E., Stolarski, M.J., Van Loo, E.N., Puttick, D., Monti, A., 2017. Agronomic performance and seed quality attributes of camelina (*Camelina sativa* L. crantz) in multi-environment trials across Europe and Canada. Ind. Crops Prod. 107, 602–608. https://doi.org/10.1016/j.indcrop.2017.06.022.

Zanetti, F., Gesch, R.W., Walia, M.K., Johnson, J.M., Monti, A., 2020. Winter camelina root characteristics and yield performance under contrasting environmental conditions. Field Crops Res. *252* https://doi.org/10.1016/j.fcr.2020.107794.

Zanetti, F., Alberghini, B., Marjanović Jeromela, A., Grahovac, N., Rajković, D., Kiprovski, B., Monti, A., 2021. Camelina, an ancient oilseed crop actively contributing to the rural renaissance in Europe. A review. Agron. Sustain. Dev. *41* https://doi.org/10.1007/s13593-020-00663-y.

Zubr, J., 2003. Qualitative variation of *Camelina sativa* seed from different locations. Ind. Crops Prod. *17* (3) https://doi.org/10.1016/S0926-6690(02)00091-2.