Industrial Crops & Products 250 (2026) 123937

Contents lists available at ScienceDirect

Industrial Crops & Products

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

Long-term study on crambe (*Crambe abyssinica*) grown on marginal land

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ARTICLE INFO

Keywords:
Biobased industry
Steep slope
Seed oil content
Erucic acid
Brassicaceae
Oilseed crop
Compensation effect

ABSTRACT

Sloping land represents one of the major biophysical constraints limiting agricultural productivity in Mediterranean Europe, particularly in Italy. According to European Union (EU) legislation, non-food crops, like crambe (*Crambe abyssinica* Hochst. ex R.E. Fr.), should be cultivated on marginal lands. Crambe emerged as a promising industrial oilseed crop for sloping marginal areas due to its rustic nature, low input requirements, and resilience to several biotic and abiotic stresses. This study provides a six-year evaluation of crambe under favorable conditions (0% slope) and marginal sites with 15% and 25% slopes in northern Italy. The aim was to assess the effects of slope on crop productivity and quality, evaluating the suitability of crambe for marginal land valorization. Cultivation on a 15% slope resulted in a 27% reduction in seed yield. Despite the decline in seed yield, seed oil content increased significantly under marginal conditions, indicating a compensatory response to reduced stand density and productivity. As a result, oil yield was not significantly affected at the 15% slope. This suggests that the increase in oil concentration offset the reduction in seed yield. In contrast, under steep slope condition (25%), this compensatory mechanism was insufficient, and oil yield showed a marked decline (approximately −60%) compared with the flat site. Erucic acid concentration showed minor variations across slope, resulting in a stable parameter. These findings demonstrate that crambe maintains good productivity (~1.5 Mg DM ha^{-1}) and stable oil quality on 15% slope sites, highlighting its potential for the valorization of Italian sloping marginal lands.

1. Introduction

The third update of the European Bioeconomy Strategy, adopted in 2025, constitutes a key set of policy instruments through which the European Union seeks to achieve climate neutrality by 2050 (European Commission, 2025). Together with the Clean Industrial Deal, the EU Climate Law, and the revised Renewable Energy Directive (RED III), it contributes to the broader EU policy framework supporting this transition (Directive EU 2023/2413; European Commission, 2024). Bioeconomy markets are expected to foster the development of increasingly advanced bio-based solutions (e.g. biomaterials, biochemicals, and biofuels). They offer viable alternatives to fossil-based products and accelerate the transition from laboratory-scale solutions to large-scale industrial value chains (BIC, 2025; European Commission, 2025). This process may also promote the cultivation of industrial crops as sustainable feedstock for bio-based industries (Panoutsou and Alexopoulou, 2020; Panoutsou et al., 2022). Currently, the production of crops dedicated to bioenergy and other industrial applications in the EU must follow two principles: (i) sustainable intensification through intermediated crops, intercropping or relay cropping systems with food crops; (ii) the utilization of severely degraded and abandoned land (Delegated Directive (EU) 2024/1405). This second principle builds on evidence from several recent European projects (e.g., SEEMLA, BIOPLAT-EU, MAGIC). These projects have demonstrated that industrial crops can be successfully cultivated on marginal agricultural land across Europe, thereby restoring their productivity. To standardize the classification of these areas, the Joint Research Centre (JRC) established common biophysical criteria applicable across all Member States (Van Orshoven et al., 2012). This process aims to enhance industrial competitiveness while revitalizing marginal areas. Consequently, this approach has emerged as a promising strategy to foster new bioeconomy markets, promote crop diversification, and enhance ecosystem services (Von Cossel et al., 2019; Zanetti et al., 2024).

In a context where 18% of global vegetable oil production is already used for bio-based applications, restrictive environmental policies are limiting the development of traditional feedstocks such as palm oil (FAO, 2025). Consequently, oilseed crops are expected to play an increasingly central role. New oilseed crops such as crambe, *Camelina*

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https://doi.org/10.1016/j.indcrop.2026.123937
Received 3 March 2026; Received in revised form 3 July 2026; Accepted 14 July 2026
Available online 20 July 2026

sativa L. Crantz (camelina), *Ricinus communis* L. (castor bean), and *Carthamus tinctorius* L. (safflower) are therefore poised to move beyond their current "promising" status and become potential feedstocks for evolving bio-based value chains (Von Cossel et al., 2019; Zanetti et al., 2013). Indeed, many minor oilseeds crops are known for the quality of their oils, which in some cases is even higher than that of traditional feedstocks, such as soybean (Costa et al., 2024; Wazilewski et al., 2013). They are also valued for green chemistry applications and the valorization of their protein- and fiber-rich defatted cakes in phytochemical, and pharmaceutical sectors (Alberghini et al., 2022; Costa et al., 2024; da Silva et al., 2024; Grahovac et al., 2025). However, these considerations can only remain theoretical unless the agronomic feasibility of these crops in European farming systems is demonstrated (Costa et al., 2024; Prajapati et al., 2026).

Crambe (*Crambe abyssinica* Hochst ex R.E.Fr.) is an annual crop belonging to the *Brassicaceae* family, characterized by a unique fatty acid composition of its oil. The oil is mainly characterized by a high monounsaturated fatty acid content, particularly erucic acid, of which crambe oil is recognized as the richest source in nature (Mandal et al., 2002). Erucic acid is a fatty acid containing 22 atoms of C and it owns several unique biobased applications, such as the production of bioplastics, biolubricants and cosmetics (Samarappuli et al., 2020). The very high content of erucic acid (>50%) together with the high glucosinolate content in the cake (Lazzeri et al., 1994) makes crambe a typical non-food crop, as both these compounds make it not suitable for food or feed uses. Another unique trait of crambe is the formation of single-seeded siliques, which are harvested as a whole and then used as propagation material (Righini et al., 2016). Crambe owns very interesting agronomic traits. It shows broad environmental adaptability, limited resource requirements, and resilience toward many biotic and abiotic stresses. Crambe growth cycle is typically 100–120 d, from sowing to harvest, corresponding to roughly 1300–1500 GDD (Growing Degree Days), using 5°C base temperature. As a result, it can be successfully grown across different pedoclimates in Europe and North and South America (Berzuini et al., 2021; Eberle et al., 2024; Cajamarca et al., 2018). Consequently, seed yields reported in the literature vary widely, ranging from less than 0.5 Mg ha^{-1}, in Brazil to more than 3.0 Mg ha^{-1}, in UK (Samarappuli et al., 2020). Crambe has limited resistance to temperatures below 0°C, so it is usually grown as spring crop in northern regions, while it can adapt to fall sowing only in southern Mediterranean regions (Zanetti et al., 2016). The mean plant height at harvest is often ~1 m, and shorter plants are usually found when sowing is delayed, and higher temperatures occur early in the season (Berzuini et al., 2021). Recent field trials under marginal conditions (Loew et al., 2024; Reinhardt et al., 2021) and preliminary assessments of tolerance to metal-contaminated soils (Abias et al., 2024; Fernando et al., 2025) have highlighted the potential of crambe to grow under unfavorable conditions. Nevertheless, within Europe crambe remains less frequently considered for such applications compared with other oilseed crops such as castor bean (Costa et al., 2024; Testa et al., 2023) and camelina (Zanetti et al., 2024). According to Von Cossel et al. (2019) crambe is among the most versatile industrial crops and could potentially be adapted to about 86% of marginal areas in Europe. Despite this potential, evidence on crambe's performance under marginal conditions in Italy remains limited. In Italy, the only study comparing its performance on fertile land and on marginal one was conducted by Zanetti et al. (2016), who evaluated its productivity on fertile soils in the Po Valley and semi-arid soils in Sicily. To the best of our knowledge, however, no published studies have specifically addressed the performance of crambe on sloping land, the main biophysical constraint affecting marginal agricultural land in Italy (Elbersen et al., 2018; Fiorese and Guariso, 2010; Sallustio et al., 2018). In accordance with the definitions of marginal land set out in the EU MAGIC project (Elbersen et al., 2018) which are based on the parameters identified by the JRC (Eliasson, 2007; Van Orshoven et al., 2012) land is considered marginal when its slope gradient exceeds 15%. This condition affects over 60% of Italian marginal land.

Based on its documented tolerance to biotic and abiotic stresses and low-input requirements, we hypothesized that crambe would exhibit a moderate decline in its productive performance in response to slope. Within this framework, the objective of the present study was to evaluate the agronomic performance of crambe grown on sloping land with 15% and 25% slope, in comparison with conventional flatland conditions. By integrating multi-year field observations, the study sought to establish whether crambe can maintain acceptable productivity and oil quality under marginal Mediterranean environments.

2. Materials and methods

2.1. Experimental layout

The crambe commercial variety, Galactica (provided by Wageningen Research, Netherlands), was tested in 4 experimental fields (Table 1) over 6 years (2019–21, 2023–25). All the experimental fields were located at the experimental farm of the University of Bologna, in Ozzano dell'Emilia, Northern Italy. The fields were identified as follows: OZE−0, OZE−15, OZE−15–2, and OZE−25, Fig. 1.

The OZE−0 site represented a fertile, flat soil, reflecting the average soil conditions of the surrounding area. OZE−15 and OZE−15–2 were considered marginal due to the presence of a 15% slope, while OZE−25 was characterized by an even steeper slope of 25% (Eliasson, 2007). A detailed soil characterization was reported in Table 1. OZE−0 exhibited overall higher soil fertility compared with the other sites, with a good content of organic matter and nitrogen level. The sloping soils, instead, were generally characterized by subalkaline pH and lower levels of organic matter, nitrogen, and available phosphorus. Given the greater operational complexity associated with sloping areas, crambe was cultivated in a single large strip of approximately 1000 m² at each experimental field. This ensured realistic field conditions under farm-scale management. Within each strip, between four and twelve

Table 1
Descriptions of the four experimental sites where crambe was grown during 2019–21 and 2023–25 in Northern Italy.

	Ozzano plane (OZE−0)	Ozzano slope 1 (OZE−15)	Ozzano slope 2 (OZE−15–2)	Ozzano slope 3 (OZE−25)
Coordinates	44° 43' N, 11° 48' E	44° 42' N, 11° 47' E	44° 41' N, 11° 47' E	44° 40' N, 11° 47' E
Altitude (m a.s.l.)	67	115	200	230
Slope	0%	15%	15%	25%
Texture	Silty clay loam	Clay loam	Sandy loam	Loam
pH	6.60	8.02	8.15	8.08
Organic matter (%)	1.70	1.23	1.42	1.21
Total N (‰)	1.39	0.98	0.73	0.73
Available P (ppm)	145	16	20	30
Exchangeable K (ppm)	246	233	226	190

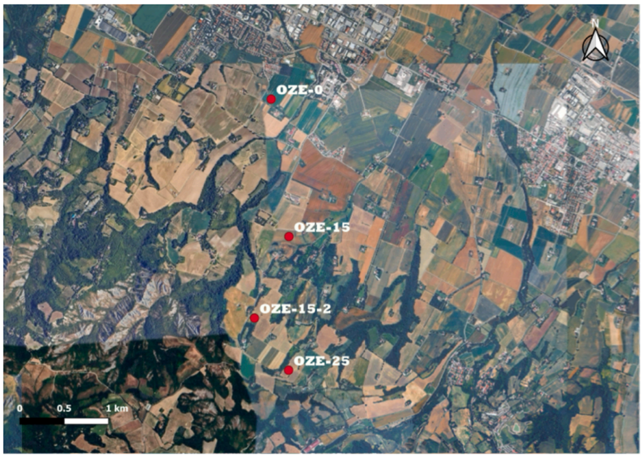

Fig. 1. Location of the four experimental fields (OZE−0, OZE−15, OZE−15–2 and OZE−25) at the University of Bologna experimental farms in Ozzano dell'Emilia (Northern Italy). Red dots indicate the experimental fields. The scale bar is expressed in kilometres (km).

sampling areas of 2 × 1 m (=pseudo-replicates) were randomly harvested to account for within-strip variability. The number of sampling areas are summarised in Table 2.

2.2. Agronomic management

The preceding crops were: in OZE−0 winter wheat (*Triticum aestivum*), in OZE−15–2 and OZE−25 spontaneous grassland, and in OZE−15 alfalfa (*Medicago sativa*). Soil tillage included disk harrowing, to a depth of 0.3 m, followed by two passes with a rotary tillage in order to obtain a fine and firm seedbed. Pre-sowing fertilization was carried out applying an organic fertilizer (GUANITO, NPK 6–15–2) at a dose of 500 kg ha^{-1} at all sites. Crambe was sown by means of a mechanical cereal seeder (DAMAX) at a rate of 18 kg ha^{-1}, with rows spaced 0.15 m apart as suggested by Zanetti et al. (2016). The crop was managed according to organic farming practices under rainfed conditions. Together with the duration of the growing cycle, the sowing and harvest dates are summarised in Table 2.

2.3. Measured parameters

Daily minimum and maximum air temperatures and precipitation were recorded by weather stations at the experimental farm of the University of Bologna in Ozzano dell'Emilia. Growing degree days (GDD) were also calculated with a base temperature (T_{base}) of 5°C for crambe (Meijer and Mathijssen, 1996) accumulated between sowing and harvest dates, using the following equation:

$$GDD = \Sigma\ [\ (T_{max} + T_{min})\ /\ 2 - T_{base}]$$

Where T_{max} and T_{min} are the maximum and minimum air temperatures, respectively.

Crambe was hand-harvested at full maturity. At harvest, final plant density (plants m^{-2}) was determined by counting all plants present within each sampling area. Plant height (m) was measured at plant maturity on three plants per sampling area, from the base of the plant to the top pod on the main branch. All harvested plants from each sampling area were then threshed using a plot combine (Wintersteiger, Austria). Seed and straw were weighed separately. A sub-samples of both fractions were oven dried at 105°C for 24 h until a constant weight was reached to determine the dry matter content. Harvest index (HI) was also calculated as the ratio between seed yield and the total aboveground biomass (seed + straw). The weight of 1000-seeds (TKW) was determined on a representative sample of cleaned seeds using a seed counter (Data Technologies, Israel) at LARAS (seed analysis laboratory at the University of Bologna). The seed production (number of seeds produced per unit of soil surface) was calculated as the ratio between seed yield and TKW.

2.3.1. Seed quality analyses

Qualitative analyses were performed on the harvested seeds to determine total oil content and the fatty acid composition. Seed oil content was determined on approximately 30 g of crambe seeds previously ground using an electric grinder. An aliquot of 1.5 g of ground material was placed in a cellulose thimble (22 × 80 mm; Axiva, Delhi, India) and inserted into a 30 mL Soxhlet glass extractor. Oil extraction was performed in an in-line multi-unit Soxhlet apparatus (mod. R 306 S, Behr Labor-Technik, Düsseldorf, Germany) using 60 mL of n-hexane as solvent for 2 h from the first solvent reflux. Oil yield was calculated as the product of seed yield and oil content.Fatty acid composition was determined by gas chromatography (GC–FID, model 7820 A, Agilent Technologies, Santa Clara, CA, USA) after transesterification according to Christopherson and Glass (1969). The analysis was carried out using a BPX70 capillary column (30 m × 0.25 mm i.d., 0.25 µm film thickness; SGE, Ringwood, Australia). Gas chromatography separation was performed on a BPX70 capillary column (30 m × 0.25 mm i.d., 0.25 µm film thickness; SGE, Ringwood, Australia). Detector temperature was set at 250°C. Fatty acids were identified by comparing retention times with those of standard FAME mixtures, and their relative proportions were calculated from individual peak areas. Erucic acid yield was calculated as the product of seed yield and erucic acid content.

2.4. Statistical analysis

Statistical analyses were performed using R software (version 4.3.0). Prior to analysis, the dataset was screened for outliers using the interquartile range (IQR) method. For each variable, observations falling below Q1 − 1.5 × IQR or above Q3 + 1.5 × IQR were considered

Table 2
Sowing and harvest dates, growing cycle duration, total precipitation, mean minimum (T_{min}), and mean maximum (T_{max}) air temperatures, and growing degree days (GDD) and number of sampling areas surveyed during the crambe growing cycle at the different experimental sites (ID) in Ozzano dell'Emilia, Italy, from 2019 to 2025.

GS	ID	Sowing Date	Harvest Date	Cycle	Precipitation (mm)	T_{min} (°C)	T_{max} (°C)	GDD	Sampling areas
2019	OZE−0	05 March	20 June	107	315	9.2	20.1	1057	4
	OZE−25	05 March	20 June	107	315	9.2	20.1	1057	12
2020	OZE−0	26 February	28 June	123	65	9.3	21.0	1295	4
	OZE−15	26 February	28 June	123	65	9.3	21.0	1295	10
	OZE−25	26 February	28 June	123	65	9.3	21.0	1295	10
2021	OZE−0	03 March	29 June	118	157	9.0	20.6	1178	11
	OZE−15	03 March	29 June	118	157	9.0	20.6	1178	8
	OZE−25	03 March	29 June	118	157	9.0	20.6	1178	6
2023	OZE−15–2	09 March	05 July	118	554	10.9	22.4	1368	12
2024	OZE−15–2	25 March	07 July	99	109	12.0	23.8	1292	12
2025	OZE−0	21 March	03 July	104	176	12.6	24.5	1435	12
	OZE−15–2	21 March	03 July	104	176	12.6	24.5	1435	12

outlying observations and removed from the dataset. Given the unbalanced experimental design, a Type III one-way ANOVA was used to determine the effect of the slope considering slope as a fixed factor, and year as a random factor. This was done to identify whether the slope influenced crop performance (both quantitative and qualitative performance). The normality of residuals and homogeneity of variances were assessed. Particular attention was paid to homoscedasticity, as its violation significantly increases the risk of Type I errors (false positives). Therefore, both assumptions were carefully evaluated through graphical inspection and formal tests (Shapiro–Wilk and Levene's tests). When these assumptions were not met, the data were transformed according to the Box–Cox transformation. For parameters where the ANOVA results showed statistically significant differences ($p \leq 0.05$), the Least Significant Difference (LSD) post hoc test was used to separate the means. In addition, three separate Principal Component Analyses (PCA) were performed to investigate how slope affects the relationships between the two most abundant fatty acids (oleic and erucic acids) and the main traits, including seed yield, straw yield, seed production (seed P), plant density, plant height, HI, TKW and oil content. Prior to PCA, the presence of outlier was assessed (as previously described for the ANOVA) and, when detected, outlying observations were removed from the dataset. All variables were scaled and centered. The PCA was performed using the prcomp function in R. The number of principal components (PCs) to retain was determined according to several criteria: the Kaiser–Guttmann criterion (eigenvalues > 1), the cumulative percentage of explained variance, and the scree plot. Variable loadings were then examined to identify those fatty acids contributing most to each selected PC, with particular attention to the highest absolute values.

3. Results

3.1. Meteorological data

The meteorological parameters surveyed at Ozzano dell'Emilia are reported in Table 2. Compared with the long-term means (2008–2018), during the six-year experimental period (2019–2025), temperatures increased progressively. Between 2019 and 2025, minimum temperatures increased by ~3.4°C, average seasonal temperatures increased by ~4°C, and maximum temperatures rose by approximately 4.4°C.

Cumulative precipitation in the long-term reference period averaged 335 mm during the crambe growth cycle. In contrast, precipitation during the experimental period showed high interannual variability. Very dry conditions were recorded in 2020, with cumulative precipitation of 65 mm, whereas in 2023 total precipitation exceeded 550 mm, with heavy and exceptional rains, mainly concentrated in May. In the remaining years (2021, 2024, and 2025), cumulative precipitation ranged between 150 and 175 mm, remaining well below the long-term average.

3.2. Crambe productive performances

Plant height varied slightly depending on slope, ranging from 0.96 m under the steepest conditions to 1.16 m under flatland conditions (Table 3). Notably, plant height exhibited lower variability across slope conditions compared with other measured traits, with a coefficient of variation (CV) of approximately 10% (Table 4). Plant density at harvest was also significantly affected by slope (Table 3). The highest density was recorded under flat conditions (130 plants m^{-2}), while 103 and 90 plants m^{-2} were recorded at 15% and 25% slopes, respectively. Plant density variability increased with slope from a CV of 23% under flat conditions to 33% under 25% slope, respectively (Table 4). Slope significantly ($P \leq 0.05$) affected crambe productivity (Fig. 2 A). Under flat conditions, crambe achieved the highest seed yield (1.83 Mg DM ha^{-1}), while at 15% and 25% slope, it significantly decreased by 27% and

Table 4
Coefficient of variation (CV, %) of seed yield, straw yield, harvest index, final plant density, plant height at harvest, and thousand seed weight (TKW) surveyed in crambe grown under different slopes: 0 = 0% slope site, 15 = 15% slope sites, 25 = 25% slope site.

Parameter	CV (%)		
	0	15	25
Seed yield	28	39	82
Straw yield	30	40	97
Harvest Index	24	28	29
Plant density	23	29	33
Plant height	10	11	12
TKW	8	8	8

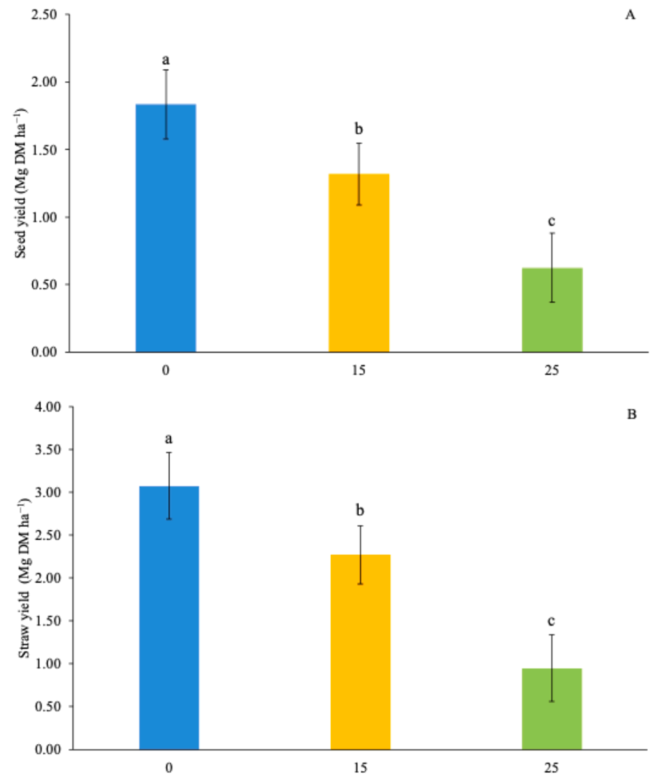

Fig. 2. A) Crambe Seed yield (Mg DM ha^{-1}) and B) Straw yield (Mg DM ha^{-1}) obtained under different slopes: 0 = 0% slope site, 15 = 15% slope sites, 25 = 25% slope site. Vertical bars: standard errors. Different letters: statistically different means for $P \leq 0.05$, LSD test.

Table 3
Plant height at harvest (m), final plant density (plant m^{-2}), seed production (seed m^{-2}) and thousand seed weight (TKW, g) of crambe obtained under different slopes: 0 = 0% slope site, 15 = 15% slope sites, 25 = 25% slope site. Different letters: statistically different means for $P \leq 0.05$, LSD test.

SLOPE (%)	Plant height (m)	Plant density (plant m^{-2})	Seed production (seed m^{-2})	TKW(g)
0	1.16 a	130 a	33904 a	5.41 a
15	1.08 b	103 b	24392 b	5.46 a
25	0.96 b	90 b	12099c	5.43 a

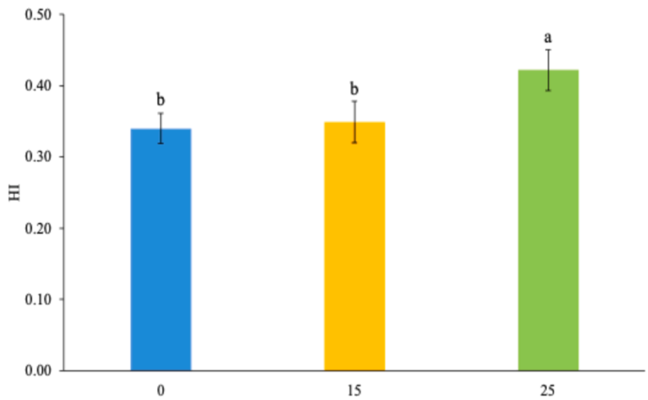

Fig. 3. Crambe Harvest index (HI) surveyed under different slopes: 0 = 0% slope site, 15 = 15% slope sites, 25 = 25% slope site. Vertical bars: standard errors. Different letters: statistically different means for $P \leq 0.05$, LSD test.

66%, respectively. Yield stability progressively decreased with steepness, in fact the CV ranged from 28% to 82% in flatland and at 25% slope, respectively (Table 4).Increasing slope also negatively affected straw yield (Fig. 2 B). The highest straw yield was recorded in the flat conditions (3.08 Mg DM ha^{-1}), whereas under 15% and 25% slope, straw yield was respectively 26% and 69% lower. As observed for seed yield, straw yield variability increased with slope steepness (Table 4). This result was further confirmed by the analysis of the HI. HI was significantly higher under the steepest slope condition (0.42) compared with both the favourable (0.34) and the 15% (0.35) slope (Fig. 3). Under 25% slope, the reduction in straw biomass was proportionally greater than

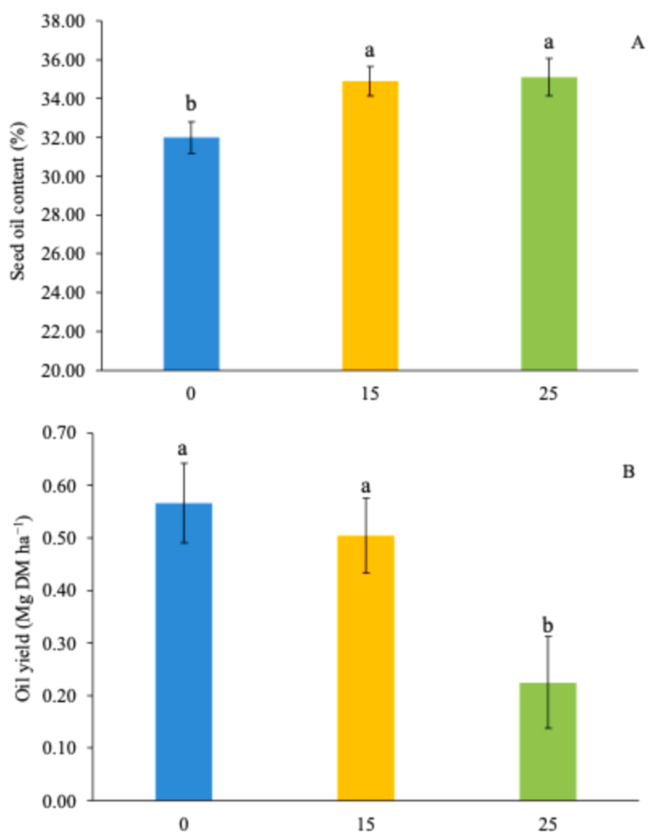

Fig. 4. A) Crambe Seed oil content (%) DM and B) Oil yield (Mg DM ha^{-1}) surveyed under different slopes: 0 = 0% slope site, 15 = 15% slope sites, 25 = 25% slope site. Vertical bars: standard errors. Different letters: statistically different means for $P \leq 0.05$, LSD test.

Table 5
Main fatty acid composition (oleic, linoleic, linolenic and erucic acid) of crambe seed oil obtained under different slopes: 0 = 0% slope site, 15 = 15% slope sites, 25 = 25% slope site. Different letters: statistically different means for $P \leq 0.05$, LSD test and coefficient of variation (CV, %).

Slope	Oleicacid	Linoleic acid	Linolenic acid	Erucic acid
0	17.20 b	8.44 a	4.69 a	54.90 a
15	17.60 a	8.07 a	4.68 a	53.90 b
25	17.40 ab	8.76 a	5.02 a	55.10 a
CV (%)	6.0	8.3	9.8	3.9

the reduction in seed yield, resulting in an increase in HI of ~25%. Seed production (seeds m^{-2}) was significantly affected by slope ($P \leq 0.05$; Table 4). TKW was not affected by slopes reporting a mean value of 5.43 (± 0.72) g (Table 3). The highest seed production was recorded under flat conditions, followed by the 15% slope conditions, while the lowest value was observed under the 25% slope condition (Table 3).

3.3. Crambe seed quality

Seed oil content (% DM) was affected by slope. The highest seed oil content was recorded under 25% slope, while the lowest content was observed in flatland (Fig. 4 A). Oil yield (Mg DM ha^{-1}) showed an opposite trend than seed oil content (Fig. 4 B). Under 25% slope, oil yield was less than half of than that measured under 15% slope and flat conditions. Slope also affected the fatty acid composition of crambe oil: oleic and erucic acid contents significantly changed with slope. Linoleic, and linolenic acids were not affected by slope (Table 5). Erucic acid was the most stable fatty acid ranging from 53.9% to 55.1%. It showed, the lowest coefficient of variation among fatty acids (Table 5). Due to the markedly lower oil production under 25% slope, erucic acid yield was significantly lower at 25% slope compared to the other two conditions (Fig. 5).

3.4. Multivariate analysis

To investigate how slope influenced the relationships between the main parameters surveyed, principal component analyses (PCA) were performed separately for each condition (0%, 15%, and 25% slope) (Fig. 6 A-C). The analysis included the main parameters surveyed: seed yield, seed production, straw yield, plant density, plant height, TKW, HI, seed oil content, and the two most abundant fatty acids (oleic and erucic acid). In the PCA for 0% slope (Fig. 6 A), the first two principal components explained 61.6% of the total variance. PC1 was positively associated with seed yield, erucic acid, oil content, plant height, seed

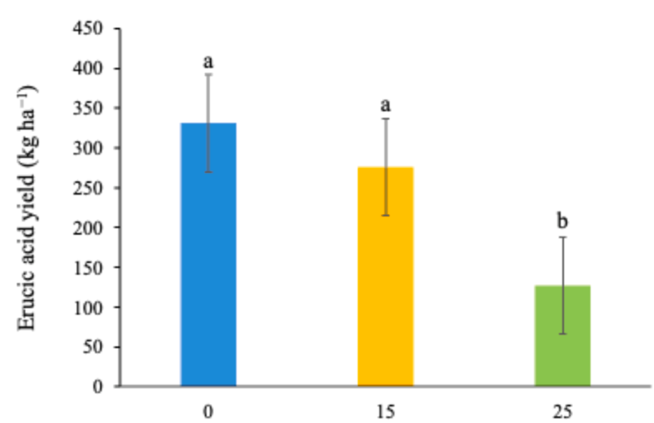

Fig. 5. Crambe Erucic acid yield (kg ha^{-1}) obtained under different slopes: 0 = 0% slope site, 15 = 15% slope sites, 25 = 25% slope site. Vertical bars: standard errors. Different letters: statistically different means for $P \leq 0.05$, LSD test.

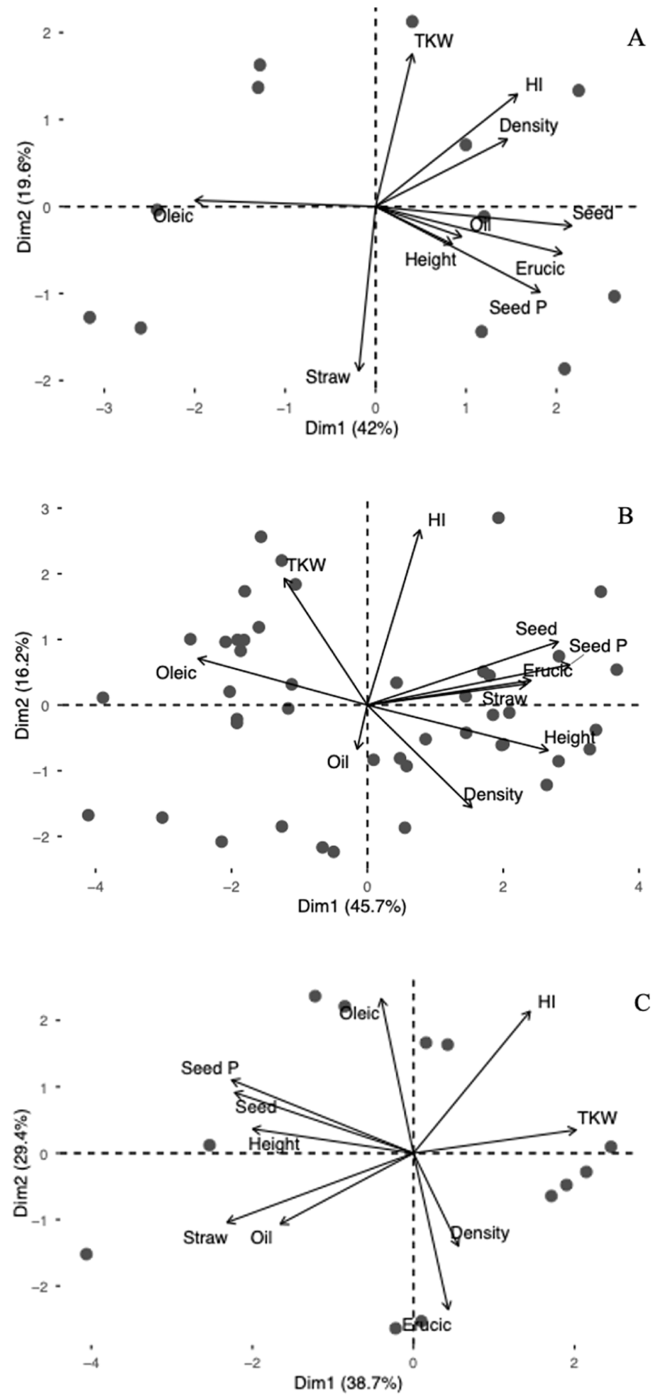

Fig. 6. PCA biplots for the first two principal components (PC1 and PC2), showing the multivariate relationships among crambe seed oil content, oleic and erucic acid and key yield-related traits (Seed, Straw, Density, Height, TKW and Seed production (Seed P)). Panels represent the three slope conditions: (A) 0% slope, (B) 15% slope, and (C) 25% slope. Points correspond to individual samples in each different condition.

production, plant density, TKW and HI. PC1 was negatively associated with oleic acid and straw yield. PC2 was positively associated with TKW, HI and plant density. Negative associations were observed between PC2 and straw yield, seed production, erucic acid, plant height, seed yield and oil content. In the PCA for 15% slope (Fig. 6 B) the first two principal components explained 61.8% of the total variance. PC1 was positively associated with seed yield, seed production, straw yield, erucic acid, plant height, and plant density, and HI. PC1 was negatively associated with oleic acid, TKW and oil content. PC2 was positively associated with seed yield, seed production, straw yield, erucic acid, TKW, HI and oleic acid. Negative associations were observed between PC2 and oil content, plant height, and plant density. In the PCA for 25% slope (Fig. 6 C) the first two principal components explained 68.1% of the total variance. PC1 was positively associated with erucic acid, plant density, TKW and HI, and negatively associated with seed yield, plant height, straw yield, seed production, oleic acid, and oil content. PC2 was positively associated with TKW, oleic acid, seed yield, seed production, plant height and HI. PC2 was negatively associated with erucic acid, plant density, straw yield and oil content. The multivariate analysis indicated that slope affected not only individual parameters, as previously shown, but also the relationships among variables. Several associations remained stable across all slope conditions. For example, seed yield and seed production were consistently associated in all PCA biplots. Plant height, seed production and seed yield were always strongly associated under all slope conditions. In addition, oleic and erucic acids consistently displayed a strong negative relationship. In contrast, the relationships involving HI and straw yield varied with increasing slope. Under flat conditions, HI and straw were almost perpendicular, whereas at 25% slope HI was almost opposite to the straw yield vector (Fig. 6 C). Furthermore, the relationship between HI and plant height varied with increasing slope: under flat conditions HI and plant height were correlated. Under slope conditions, this relationship progressively weakened and became almost opposite at 25% slope, as observed for HI and straw. Under flat conditions (Fig. 6 A), plant density, plant height, seed production and seed yield were closely aligned. However, with increasing slope (Fig. 6 B–C), the plant density vector progressively diverged from the vectors of plant height, seed production and seed yield.

4. Discussion

Climate change effects are not only impacting agricultural production in the Mediterranean basin, but they are further exacerbating crop growth limitation under marginal soils. This has recently led to huge land abandonment in southern EU countries, such as Italy. Growing resilient crops under marginal conditions might represent an opportunity for farmers to bring abandoned land back into cultivation. In the present long-term study, crambe confirmed its suitability to marginal land with moderate slope (15%). Even under the 25% slope condition, although seed yield was markedly reduced, the crop completed its cycle and never failed. Thermal accumulation was mainly driven by interannual temperature differences rather than slope. On average, crambe required 1239 (± 128) GDD from sowing to harvest across all slope conditions, a value well aligned with literature (Falasca et al., 2010; Righini et al., 2016; Zanetti et al., 2013). As expected, slope negatively affected crambe productivity (Fig. 2 A-B), as under flat conditions crambe achieved the highest performance, with an average seed yield of 1.83 Mg DM ha^{-1}. This value falls within the range for Italy, reported by Samarappuli et al. (2020) under conventional farming practices. The reported range in this study varies between 1.35 and 2.67 Mg ha^{-1}. Similar results were reported by Berzuini et al. (2021), who evaluated crambe across multiple conventional flatland sites in Europe (Italy, Greece, and Poland), who identified Italy as the most suitable site with an average seed yield of 2.11 Mg DM ha^{-1}. Therefore, the yield obtained in the present study under non-marginal conditions aligns with the typical productive potential of crambe in Italy. This is particularly relevant in the context of rising temperatures and the growing occurrence of drought and extreme weather events (Table 2) affecting the Mediterranean region (Lazoglou et al., 2024).

To the best of our knowledge, no field studies have explicitly tested crambe on marginal land with slope constraints. Previous studies emphasized the ability of crambe to grow under different marginal conditions. Reinhardt et al. (2021) reported two studies conducted in Brazil carried out under unfavourable soil types, characterized by high clay content, reporting seed yield ranging between 0.49 and 1.70 Mg

ha^{-1} . Similarly, a study conducted on shallow and stony soils of the Swabian Alb in Germany reported yield levels of approximately 1.2–1.5 Mg DM ha^{-1} (Schlecht et al., 2025; Loew et al., 2024). These findings confirmed the good crambe suitability to grow under diverse and marginal pedoclimatic constraints. Although slope had a negative effect on crambe yield, the reduction was not as pronounced as reported in other comparable situations involving different oilseed crops. For instance, camelina exhibited an 80% seed yield reduction at 25% slope under the same slope conditions examined in the same study area (Zanetti et al., 2024). Under the steepest slope conditions, straw production decreased more than proportionally compared to seed yield leading to an increase of HI (Fig. 3). The highest plant density was recorded under flat conditions compared to sloping ones (Table 3). Under slope, agronomic operations, such as sowing, were more difficult to perform with precision and uniformity, than under flat condition. Comparable management constraints under 25% slope condition were previously documented in camelina by Zanetti et al. (2024), where the crop never reached satisfactory soil coverage. Therefore, it cannot be excluded that under the conditions investigated here sowing efficiency decreased, leading to reduced plant density. In contrast, seed weight (TKW) was not affected by slope and remained a stable parameter, with a mean of 5.4 (± 0.72) g. This value is in line with those typically reported for crambe under favourable conditions, ranging between 6 and 10 g (Falasca et al., 2010; Reinhardt et al., 2021; Righini et al., 2016). It is also fully consistent with values reported for the same crambe variety cultivated in the same area of Emilia–Romagna (Berzuini et al., 2021). Given this stability of crambe seed weight across conditions, the reduction in seed yield observed under slope cannot be attributed to limitations during the seed filling phase, but rather to other processes.

The PCA biplots provide further insight into these observations. Under flat conditions (Fig. 6 A) plant density, plant height, seed production and seed yield are closely aligned, indicating that higher yields were associated with both higher plant density and taller plants. However, slope altered the structure of these relationships. With increasing slope (Fig. 6 B–C), the plant density vector progressively diverged from those of seed production, seed yield and plant height. This indicates that under sloping conditions, seed yield variability becomes less controlled by plant density and increasingly dependent on the ability of individual plants to maintain vegetative vigour and reproductive development. This ability of individual plants to compensate across different plant densities is a known phenomenon in other *Brassicaceae* crops, such as oilseed rape (*Brassica napus* L. var. oleifera) and *Brassica carinata* (Seepaul et al., 2021; Roques and Berry, 2016). In contrast to plant density, the plant height vector remained consistently associated with seed production and seed yield across all slope conditions (Fig. 6 B–C). Therefore, the decrease in plant height observed under slope conditions (Table 4) was directly associated with reduced seed production and seed yield. This interpretation is consistent with previous findings, i.e., Zoz et al. (2018) reported that taller plants produced a greater number of branches and, consequently, more grains per plant resulting in a higher seed yield. Since crambe is characterized by single seeded siliques, with stem nodes forming for each single seeded siliques, reduced seed production might reflect a limited capacity of the crop to develop secondary branches and reproductive structures under slope conditions (Meijer et al., 1999; Zanetti et al., 2016). Seed oil content, under sloping conditions increased compared with flat conditions by 9% (Fig. 4 A). This trend could be explained by a compensatory effect, where reducing seed yield and plant density are associated with an increase in seed oil concentration (De Marins et al., 2024). Similar results have been reported for other *Brassicaceae* species such as camelina, where a decline in seed yield under marginal conditions was accompanied by an increase in oil content (Reinhardt et al., 2022; Zanetti et al., 2024). However, when considering oil yield significant differences among slope conditions emerged (Fig. 4 B). Despite the lower seed yield under the 15% slope conditions, oil yield did not differ significantly from that of the flat conditions. This indicated that the increase in seed oil concentration compensated the reduction in seed yield, resulting in a comparable oil yield under 15% slope conditions. In contrast, oil yield was significantly reduced under steep slope, despite the increase in oil content. Slope negatively affected not only the main productivity parameters but also crop stability. The analysis of the CV revealed a clear gradient of increasing interannual variability with slope steepness across the six growing seasons (Table 4). The increase in variability differed markedly between the two slope conditions. The CV observed under the 15% slope condition compared with flat conditions indicated that even moderate slope constraints negatively affected crop stability. However, the effect became much more pronounced under 25% slope, particularly for seed yield (CV = 82%) and straw yield (CV = 97%). This was further confirmed by the multivariate analysis. Fig. 6 A-C shows a progressive increase in sample dispersion from 0% to 25% slope conditions, indicating increasing crop heterogeneity with slope severity. These findings suggested that the impact of slope on the stability of productive traits intensified progressively with increasing slope steepness. In contrast, across the different slope conditions and growing seasons, crambe seed quality showed marked stability in oil composition. Among all fatty acids, erucic acid was the most stable, exhibiting the lowest coefficient of variation. Similar findings were reported by Vollmann and Ruckenbauer (1993) and later confirmed by Laghetti et al. (1995). Previous studies conducted in Italy reported comparable erucic acid concentrations within the range observed in the present study (53.9–55.1%) (Bondioli et al., 1998; Berzuini et al., 2021; Zanetti et al., 2016). Despite oil compositional stability, erucic acid yield was strongly affected by the 25% slope, following the decreasing trend of seed yield (Fig. 5). Overall, these findings indicate that crambe preserved high stability in its key qualitative characteristics, including oil composition and seed weight. Even though increasing slope severity significantly reduced productivity and increased variability in plant traits, these characteristics remained stable.

More than half of the Emilia-Romagna region is classified as hilly or mountainous (ISTAT, 2014). In these areas agricultural production is frequently constrained by slope. The results of the present study indicate that crambe maintained oil yield and oil quality under the 15% slope condition at levels comparable to those observed on flat land. These findings suggest that crambe may represent a suitable crop for sloping agricultural areas in Emilia-Romagna with 15% slope, providing a valuable option for diversifying crop rotations thereby supporting the productive use of sloping land, where land abandonment is widespread.

5. Conclusions

This study provided the first long-term study on crambe cultivated under marginal sloping conditions. These conditions represented a major constraint affecting large areas of the Italian agricultural landscape and had so far received limited attention. Across six growing seasons, slope negatively affected crambe growth and yield stability, primarily through reductions in plant height, final plant density and seed production. Crambe exhibited a limited capacity to compensate for plant density reduction, leading to lower seed yield under sloping conditions, although acceptable productivity was maintained under the 15% slope conditions. This reduction in seed yield, was accompanied by improvement in seed quality. In particular, oil concentration increased with increasing slope, resulting in comparable oil yields between the flat and the 15% slope conditions. Moreover, the stability of fatty acid composition over the six-year experimental period represented a relevant agronomic advantage. This ensured a consistent and standardized raw material suitable for industrial applications even under marginal conditions. Taken together, these findings indicated that slopes up to approximately 15% provided a reasonable compromise between productivity and seed quality. From an agronomic management perspective, adjusting seeding rates in sloping areas may help compensate for lower seedling establishment. However, increases in plant density should be carefully calibrated to avoid excessive intra-specific competition and reduced yield potential at the individual plant level.

CRediT authorship contribution statement

Andrea Parenti: Data curation. **Federica Zanetti:** Writing – review & editing, Writing – original draft. **Andrea Monti:** Writing – review & editing, Funding acquisition. **Pietro Peroni:** Writing – review & editing, Writing – original draft. **Alexandro Ferreira:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation.

Funding

This research was carried out partially in the framework of the MAGIC project which has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 727698. The remaining part of the research was carried out in the framework of the MIDAS project which has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement No. 101082070.

Declaration of Competing Interest

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

Acknowledgments

Authors want to acknowledge the technical help in conducting the trials provided by Marco Acciai, Lorenzo Samuil Mordos and Angela Vecchi. Authors specially thank Prof. Jed Eberly (MSU) and Giorgia Davi for helping to review and edit the manuscript.

Data availability

Research Link Provided.

References

Abias, M., Costa, J., Fernando, A.L., 2024. Opportunities and risks associated with the production of crambe oil when cultivated in soils contaminated with heavy metals. Conference Proceedings (peer-reviewed contribution). Universidade NOVA de Lisboa, Departamento de Química, MEtRICS – Centro de Engenharia Mecânica e Sustentabilidade de Recursos (Available at: https://novaresearch.unl.pt/en/publications/opportunities-and-risks-associated-with-the-production-of-crambe-/).

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, 114944. https://doi.org/10.1016/j.indcrop.2022.114944.

Berzuini, S., Zanetti, F., Christou, M., Alexopoulou, E., Krzyżaniak, M., Stolarski, M.J., Ferioli, F., Monti, A., 2021. Optimization of agricultural practices for crambe in Europe. Ind. Crops Prod. 171, 113880. https://doi.org/10.1016/j.indcrop.2021.113880.

BIC. Policy paper for the new EU Bioeconomy Strategy 2025).Brussels:Bio-based Industries Consortium.https://biconsortium.eu/sites/biconsortium.eu/files/publications/Bioeconomy%20Strategy%202025_0.pdf.

Bondioli, P., Folegatti, L., Lazzeri, L., Palmieri, S., 1998. Native Crambe abyssinica oil and its derivatives as renewable lubricants: An approach to improve its quality by chemical and biotechnological processes. Ind. Crops Prod. 7 (2), 231–238. https://doi.org/10.1016/S0926-6690(97)00053-8.

Cajamarca, F.A., Lancheros, A.F., Araújo, P.M., Mizubuti, I.Y., Simonelli, S.M., Ida, E.I., Guedes, C.L.B., Guimarães, M.F., 2018. Evaluation of various species of winter oleaginous plants for the production of biodiesel in the State of Parana, Brazil. Ind. Crops Prod. 126, 113–118. https://doi.org/10.1016/j.indcrop.2018.10.003.

Christopherson, S.W., Glass, R.L., 1969. Preparation of milk fat methyl esters by alcoholysis in an essentially nonalcoholic solution. J. Dairy. Sci. 52 (8), 1289–1290. https://doi.org/10.3168/jds.S0022-0302(69)86739-1.

Costa, E., Valdrez, I., Almeida, M.F., Alvim-Ferraz, M.C., Dias, J.M., 2024. Nonedible crops as alternative raw materials for biodiesel production: An overview. Agroenergy. Elsevier, pp. 41–91. https://doi.org/10.1016/B978-0-443-21430-1.00017-X.

da Silva, C., Schmitz, J.A., Raspe, D.T., Stevanato, N., Hoscheid, J., Gimenes, M.L., Bolanho Barros, B.C., Cardozo-Filho, L., 2024. Application of the biorefinery concept in the processing of Crambe abyssinica seed defatted meal in a pressurized medium. Plants 14 (3), 326. https://doi.org/10.3390/plants14030326.

De Marins, A.C., Secco, D., Ruffato, G.G., Bassegio, D., Tiruneh, G.A., Reichert, J.M., 2024. Soil chemical properties affecting grain yield and oil content of crambe biofuel crop. Soil. Sci. Soc. Am. J. 88 (5), 1891–1908. https://doi.org/10.1002/saj2.20741.

Eberle, C., Scott, D.A., Forcella, F., Gesch, R.W., Weyers, S., Johnson, J.M.F., Schneider, S., 2024. Planting date impact on flowering, pollinator visitation and yield of mass flowering oilseed crops in the Northern Corn Belt. Agr. For. Entomol. 26, 534–545. https://doi.org/10.1111/afe.12644Digital.

Elbersen, B.S., van Eupen, M., Boogaard, H.L., Mantel, S., Verzandvoort, S.J.E., Mücher, C.A., Ceccarelli, T., Elbersen, H.W., Bai, Z., Iqbal, Y., von Cossel, M., McCallum, I., Carrasco, J., Ramos, C., Monti, C.D., Scordia, D., Eleftheriadis, I., 2018. *Methodological approaches to identify and map marginal land suitable for industrial crops in Europe* (Deliverable 2.6, MAGIC Project). & Research / ISRIC - World Soil Information. Wageningen University. https://magic-h2020.eu/reports-deliverables/.

Eliasson, Å., 2007. Review of land evaluation methods for quantifying natural constraints to agriculture (Joint Research Centre. Institute for Environment and Sustainability). Publications Office. https://data.europa.eu/doi/10.2788/17545.

European Commission, 2024. The Clean Industrial Deal: A joint roadmap for competitiveness and decarbonisation. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52025DC0085.

European Commission, 2025. Communication on a new EU Bioeconomy strategy: Towards a Circular, Regenerative and Competitive Bioeconomy, 2025. Publications Office of the EU. EUR-Lex - Ares. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=intcom%3AAres%282025%292559560, 2559560 - EN - EUR-Lex.

Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 on the promotion of the use of energy from renewable sources (recast) 2023 Official Journal of the European Union, L. 2023/2413 https://eur-lex.europa.eu/eli/dir/2023/2413/oj.

Falasca, S.L., Flores, N., Lamas, M.C., Carballo, S.M., Anschau, A., 2010. Crambe abyssinica: An almost unknown crop with a promissory future to produce biodiesel in Argentina. Int. J. Hydrog. Energy 35 (11), 5808–5812. https://doi.org/10.1016/j.ijhydene.2010.02.095.

FAO, 2025. OECD-FAO Agricultural Outlook 2025-2034. OECD Publishing / FAO. https://doi.org/10.1787/601276cd-en.

Fernando, A.L., Abias, M., Gomes, L.A., Costa, J., 2025. Improving the sustainability of the production of crambe oil when cultivated in soils contaminated with heavy metals. In. Proceedings of the 33rd European Biomass Conference and Exhibition (EUBCE 2025), 9–13 June 2025. Poster Area B, Session 1DV.4 Sustainable Integrated Agricultural Management Practices, Lisbon, Portugal.

Fiorese, G., Guariso, G., 2010. A GIS-based approach to evaluate biomass potential from energy crops at regional scale. Environ. Model. & Softw. 25 (5), 702–711. https://doi.org/10.1016/j.envsoft.2009.11.008.

Grahovac, N., Aleksić, M., Trajkovska, B., Marjanović Jeromela, A., Nakov, G., 2025. Extraction and valorization of oilseed cakes for value-added food components-A review for a sustainable foodstuff production in a case process approach. Foods 14 (13), 2244. https://doi.org/10.3390/foods14132244.

Laghetti, G., Piergiovanni, A.R., Perrino, P., 1995. Yield and oil quality in selected lines of Crambe abyssinica Hochst. Ex RE Fries and C. hispanica L. grown in Italy. Ind. Crops Prod. 4 (3), 203–212. https://doi.org/10.1016/0926-6690(95)00033-9.

Lazoglou, G., Papadopoulos-Zachos, A., Georgiades, P., Zittis, G., Velikou, K., Manios, E. M., Anagnostopoulou, C., 2024. Identification of climate change hotspots in the Mediterranean. Sci. Rep. 14, 29817. https://doi.org/10.1038/s41598-024-80139-1.

Lazzeri, L., Leoni, O., Conte, L., Palmieri, S., 1994. Some technological characteristics and potential uses of Crambe abyssinica products. Ind. Crops Prod. 3 (1-2), 103–112. https://doi.org/10.1016/0926-6690(94)90083-3.

Loew, L.S., Fiedelak, L.-M., Duff, M.C., Uetsuki, Y., Schlecht, V., Lewandowski, I., Zanetti, F., Alexopoulou, E., von Cossel, M., 2024. Prospects of crambe for the bioeconomy of the Swabian Alb in southwest Germany. J. Clean. Prod. 460, 142376. https://doi.org/10.1016/j.jclepro.2024.142376.

Mandal, S., Yadav, S., Singh, R., et al., 2002. Correlation studies on oil content and fatty acid profile of some Cruciferous species. Genet. Resour. Crop. Evol. 49, 551–556. https://doi.org/10.1023/A:1021210800414.

Meijer, W.J.M., Mathijssen, E.W.J.M., 1996. Analysis of crop performance in research on inulin, fibre and oilseed crops. Ind. Crops Prod. 5 (4), 253–264. https://doi.org/10.1016/S0926-6690(97)82785-9.

Meijer, W.J.M., Mathijssen, E.W.J.M., Kreuzer, A.D., 1999. Low pod numbers and inefficient use of radiation are major constraints to high productivity in Crambe crops. Ind. Crops Prod. 19, 221–233. https://doi.org/10.1016/S0926-6690(98)00028-0.

Panoutsou, C., Alexopoulou, E., 2020. Costs and Profitability of Crops for Bioeconomy in the EU. Energies 13 (5), 1222. https://doi.org/10.3390/en13051222.

Panoutsou, C., von Cossel, M., Ciria, P., Ciria, C.S., Baraniecki, P., Monti, A., Zanetti, F., 2022. Social considerations for the cultivation of industrial crops on marginal agricultural land as feedstock for bioeconomy. Biofuels Bioprod. Bioref. 16 (6), 1319–1341. https://doi.org/10.1002/bbb.2376.

Prajapati, A.K., Mahajan, A., Jadhav, S.M., Kumar, K., 2026. Fourth-generation (4G) biodiesel: Paving the way for a greener and sustainable energy future in emerging economies. Renew. Sustain. Energy Rev. 225, 116103. https://doi.org/10.1016/j.rser.2025.116103.

Reinhardt, J., Hilgert, P., Von Cossel, M., 2021. A Review of Industrial Crop Yield Performances on Unfavorable Soil Types. Agronomy 11 (12), 2382. https://doi.org/10.3390/agronomy11122382.

Reinhardt, J., Hilgert, P., Von Cossel, M., 2022. Yield performance of dedicated industrial crops on low-temperature characterized marginal agricultural land in Europe – a

review. Biofuels Bioprod. Bioref. 16 (2), 609–622. https://doi.org/10.1002/bbb.2314.
Righini, D., Zanetti, F., Monti, A., 2016. The bio-based economy can serve as the springboard for camelina and crambe to quit the limbo. D504–D513 OCL-Ol. CORPS GRAS LIPIDES 23 (5). https://doi.org/10.1051/ocl/2016021.
Roques, S.E., Berry, P.M., 2016. The yield response of oilseed rape to plant population density. J. Agric. Sci. 154 (2), 305–320. https://doi.org/10.1017/S0021859614001373.
Sallustio, L., Pettenella, D., Merlini, P., Romano, R., Salvati, L., Marchetti, M., Corona, P., 2018. Assessing the economic marginality of agricultural lands in Italy to support land use planning. Land. Use Policy 76, 526–534. https://doi.org/10.1016/j.landusepol.2018.02.033.
Samarappuli, D., Zanetti, F., Berzuini, S., Berti, M.T., 2020. Crambe (Crambe abyssinica Hochst): A non-food oilseed crop with great potential – A review. Agronomy 10 (9), 1380. https://doi.org/10.3390/agronomy10091380.
Schlecht, V., Vargas-Carpintero, R., von Cossel, M., Lewandowski, I., 2025. Developing Marginal-Land-Based Bioeconomy Systems—A Design and Development Approach for Bio-Based Value Chains and Webs. GCB Bioenergy 17 (5), e70034. https://doi.org/10.1111/gcbb.70034.
Seepaul, R., Kumar, S., Iboyi, J.E., Bashyal, M., Stansly, T.L., Bennett, R., Boote, K.J., Mulvaney, M.J., Small, I.M., George, S., Wright, D.L., 2021. Brassica carinata: Biology and agronomy as a biofuel crop. GCB Bioenergy 13 (4), 582–599. https://doi.org/10.1111/gcbb.12804.
Testa, G., Corinzia, S.A., Calcagno, S., Cosentino, S.L., Piccitto, A., 2023. A biorefinery model for the production of oil and biomethane using castor plants. GCB Bioenergy 15 (11), 1339–1354. https://doi.org/10.1111/gcbb.13096.
Istituto Nazionale di Statistica, 2014. Principali dimensioni geostatistiche e grado di urbanizzazione del Paese. https://www.istat.it/non-categorizzato/principali-dimensioni-geostatistiche-e-grado-di-urbanizzazione-del-paese/.
Van Orshoven, J., Terres, J.M., Tóth, G., 2012. Updated common bio-physical criteria to define natural constraints for agriculture in Europe. Definition and scientific justification for the common criteria. JRC Scientific and Policy Reports. European Commission. https://hal.inrae.fr/hal-02807751. Joint Research Centre. HAL Id: hal-02807751.
Vollmann, J., Ruckenbauer, P., 1993. Agronomie performance and oil quality ofcrambe as affected by genotype and environment. Bodenkultur.
Von Cossel, M., Lewandowski, I., Elbersen, B., Staritsky, I., Van Eupen, M., Iqbal, Y., Mantel, S., Scordia, D., Testa, G., Cosentino, S.L., Alexopoulou, E., 2019. Marginal Agricultural Land Low-Input Systems for Biomass Production. Energies 12 (16), 3123. https://doi.org/10.3390/en12163123.
Wazilewski, W.T., Bariccatti, R.A., Martins, G.I., Secco, D., de, Souza, S.N.M., Rosa, H.A., Chaves, L.I., 2013. Study of the methyl crambe (Crambe abyssinica Hochst) and soybean biodiesel oxidative stability. Ind. Crops Prod. 43, 207–212. https://doi.org/10.1016/j.indcrop.2012.07.046.
Zanetti, F., Monti, A., Berti, M.T., 2013. Challenges and opportunities for new industrial oilseed crops in EU-27: A review. Ind. Crops Prod. 50, 580–595. https://doi.org/10.1016/j.indcrop.2013.08.030.
Zanetti, F., Scordia, D., Vamerali, T., Copani, V., Dal Cortivo, C., Mosca, G., 2016. Crambe abyssinica a non-food crop with potential for the Mediterranean climate: Insights on productive performances and root growth. Ind. Crops Prod. 90, 152–160. https://doi.org/10.1016/j.indcrop.2016.06.023.
Zanetti, F., Peroni, P., Pagani, E., von Cossel, M., Greiner, B.E., Krzyżaniak, M., Stolarski, M.J., Lewandowski, I., Alexopoulou, E., Stefanoni, W., Pari, L., Facciolla, E., Monti, A., 2024. The opportunities and potential of camelina in marginal land in Europe. Ind. Crops Prod. 211, 118224. https://doi.org/10.1016/j.indcrop.2024.118224.
Zoz, T., Steiner, F., Zoz, A., Castagnara, D.D., Witt, T.W., Zanotto, M.D., Auld, D.L., 2018. Effect of row spacing and plant density on grain yield and yield components of Crambe abyssinica Hochst. Semin. Ciências Agr. árias 39 (1), 393. https://doi.org/10.5433/1679-0359.2018v39n1p393.