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Research Article – Dossier

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New perspectives of European oleochemistry
Les nouvelles perspectives de l'oléochimie européenne

Dossier

The bio-based economy can serve as the springboard for camelina and crambe to quit the limbo

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Abstract – Social, economic and environmental importance of bio-based economy is rapidly growing and vegetable oils play an important role. About 75% of global production of vegetable oils derives from commodity oilseeds (*i.e.*, soybean, oil palm, rapeseed), while the remaining 25% is produced from minor oilseeds characterized by unusual fatty acid composition. The present review aims at analyzing the potentialities of two alternative oilseed crops for Europe, camelina (*Camelina sativa*) and crambe (*Crambe abyssinica*), identified as major candidates for the future European bio-based economy as testified by the recently funded EU Project (Horizon 2020) COSMOS (Camelina and crambe Oil crops as Sources of Medium-chain Oils for Specialty oleochemicals). The interest on camelina and crambe is mainly due to their unique fatty acid profile, low input management and wide environmental adaptability. We attempted to analyze pros and cons of development of camelina and crambe in Europe in the light of biorefinery concept (*i.e.*, using oil and whole produced biomass) as undertaken by COSMOS project.

Keywords: Bioeconomy / oil crops / *Brassicaceae* / PUFA / eicosenoic acid / erucic acid

Résumé – La bioéconomie, tremplin de développement pour la cameline et le crambe. L'importance sociale, économique et environnementale de l'économie reposant sur le bio, est en pleine expansion et les huiles végétales y jouent un rôle important. De l'ordre de 75 % de la production mondiale d'huiles végétales provient de graines oléagineuses (à savoir le soja, le palmier à huile et le colza), tandis que les 25 % restants sont produits à partir de graines oléagineuses mineures caractérisées par une composition inhabituelle en acides gras. Le présent article vise à analyser le potentiel pour l'Europe de deux cultures oléagineuses alternatives, la caméline (*Camelina sativa*) et le crambe (*Crambe abyssinica*), identifiées comme les principaux candidats à la future bio-économie européenne comme en témoigne le projet de recherche dit COSMOS (acronyme de : *Camelina and crambe Oil crops as Sources of Medium-chain Oils for Specialty oleochemicals*, ou Les cultures de cameline et de crambe comme sources d'huiles à chaîne moyenne pour les produits oléochimiques de spécialité) financé dans le cadre du programme Horizon 2020 de la Communauté européenne. L'intérêt porté à la caméline et au crambe est principalement lié à leur profil unique d'acides gras, à leur faible demande d'intrants et à leur large capacité d'adaptation environnementale. Nous avons tenté d'analyser les avantages et les inconvénients du développement de la caméline et du crambe en Europe à la lumière du concept de bioraffinerie (à savoir, en utilisant l'huile et toute la biomasse produite) comme dans le cadre du projet COSMOS.

Mots clés : Bioéconomie / cultures oléagineuses / *Brassicaceae* / AGPI / acide eicosénoïque / acide érucique

1 Introduction

The European policy has set the course for a resource-efficient and low-emissions bioeconomy, including bio-based economy, reconciling agriculture, biodiversity, environmental safety, while promoting the displacement of fossil-based products with bio-based surrogates. The bio-based economy is expected to grow rapidly creating new markets and jobs. The traditional petrol-based chemical industry is the one suffering more from its dependence on depleting resources thus pushing the search for innovative applicable renewable alternatives (Monteiro de Espinosa and Meier, 2011). Apart from their renewability, vegetable oils offer many advantages such

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Table 1. Major commodity oils at global and European level (FAOSTAT 2013). Oil composition is reported only for the principal fatty acids (source: CHEMPRO).

Commodity crops	Production share (%)		Average yield (Mg ha^{-1})		Average oil content	Principal fatty acids (%)						
	Global	EU	Global	EU	(%)	C16:0	C18:0	C18:1	C18:2	C18:3	C20:1	C22:1
Oil palm	27	/	15.7	/	40–42	32–45	2–7	38–52	5–11	Tr	Tr	Tr
Soybean	28	7.5	2.5	1.9	18–22	7–11	2–6	22–34	43–56	5–11	Tr	Tr
Rapeseed	7.5	32.5	2.0	2.7	38–45	4–5	1–2	60–63	18–20	8–10	1–2	<1
Sunflower	4.5	40	1.7	1.9	40–45	3–6	1–3	14–35	44–75	Tr	Tr	Tr
Cottonseed	7	0.7	1.9	3.2	18–26	20–22	2	16–35	42–56	Tr	Tr	Tr

Tr = traces.

as: world-wide availability, similarity to petrol derivates and prices that, even if much higher than petrol counterparts, are considered adequate (Monteiro de Espinosa and Meier, 2011).

Diverse chemistry could be easily applied on vegetable oils, leading to a large variety of monomers and polymers, highly requested by diverse bio-based industries, such those producing: surfactants, cosmetic products, lubricants, polymers, etc. For long it has been considered that oil and fat consumption was shared among food, feed, and industrial use in the ratio 80:6:14, but with the increasing production of biofuels (*i.e.*, biodiesel) this is probably now close to 74:6:20 (Metzger, 2009). The current global production of vegetable fats is covered for 75% by commodity oilseeds (Tab. 1), such as soybean, oil palm, cottonseed, rapeseed and sunflower, while the remaining 25% is derived from minor oilseeds generally characterized by infrequent fatty acids (FA) in terms of carbon chain length, double bound position, and functional groups.

Although the demand by industry for unusual FAs has been always high and variegate, widely grown oilseeds (Tab. 1) mainly contain only five major FAs in their oil: palmitic (C16:0), stearic (C18:0), oleic (C18:1), linoleic (C18:2) and α-linolenic acids (C18:3) (Carlsson *et al.,* 2011). Looking at the EU situation (Tab. 1), only mono and poly unsaturated FAs (MUFA and PUFA) are obtained by domestic grown oilseeds in spite of a considerable number of potential oilcrops, with variegate FA profiles, suitable to European environments, some of which (*e.g. Brassica carinata*, *B. juncea*, *Crambe abyssinica and Camelina sativa*) being also at a mature stage technically speaking (Zanetti *et al.,* 2013) (Tab. 1).

Camelina (*Camelina sativa* (L.) Crantz) and crambe (*Crambe abyssinica* Hochst. ex R.E. Fries) have a unique FA profile, good agronomic performances and wide environmental adaptability, and they are also native to Mediterranean basin (Leppik and White, 1975). The unusual composition of crambe oil, containing up to 65% of erucic acid (C22:1), makes it particularly suitable to several bio-based productions such as lubricants and plasticizers. The potentiality of crambe as a source for bio-based applications has been extensively studied in Europe, USA and more recently also in Brazil, but the commercial viability has never been reached mostly due to its low productivity (Lessman, 1990; Meijer *et al.,* 1999), high investment and energy costs for oil transformation (Bondioli *et al.,* 1998).

Camelina was a fundamental part of human diet since the Iron Age (Zubr, 1997), thereafter it progressively declined its importance as food crop (Knorzer, 1978) with only sporadic cultivations in eastern Europe. Recently, the industrial interest on camelina has rapidly grown (Putnam *et al.,* 1993) due to its unique FA composition and sound attractive applications such as drying oil with environmentally safe painting and coating applications similarly to linseed oil (Luehs and Friedt, 1993; Russo and Reggiani, 2012). Moreover, unlike the majority of wild-type *Brassicaceae*, camelina shows a rather low glucosinolate content (Lange *et al.,* 1995), which makes the possible utilization of meal much easier.

An overview of the potentialities of camelina and crambe as new oilseed crops for European environments is presented in the next sections.

2 Description of crambe and camelina

Crambe and camelina are erect broadleaf oilseed species native to Mediterranean area and belonging to *Brassicaceae* family. They are characterized by high tolerance to drought and a shorter cycle compared to rapeseed. Crambe plants reach a maximum height of 1.20 m with a cycle length of 90–110 days (1300–1500 GDD, with a base temperature of 5 °C, Meijer and Mathijssen, 1996). Crambe shows the typical *Brassicaceae* morphological structure (Figs. 1a and 1b) with large, oval-shaped and smooth leaves, high number of very small white flowers clustered in racemes (Fig. 1c). The fruits are little, spherical, light brown seeds borne singly at or near the terminus of the branches. Each seed is enclosed in a pod or hull (Fig. 1d) that sticks on it at harvest as part of the yield (Lessman, 1990). The presence of this persistent and firm hull (11–40% of seed weight), that prevents the rapid seed emergence and worsens the establishment (Merrien *et al.,* 2012), represents an agronomic constraint for this species. Crambe hulled seed weight is 5–7.5 mg per seed (Earle *et al.,* 1966).

Alike crambe, camelina is a fast growing annual crop able to complete the cycle in only 90 days or less if seeded in springtime (1200–1300 GDD, with a base temperature of 4 °C, Gesch and Cermak, 2011). At full maturity, plants attain height of 0.90 m, and present a main stem with numerous lateral branches (Figs. 2b and 2e), which usually reach the same height. On the main stem, leaves are alternate on subsequent nodes; basal ones are usually oblanceolate and short-stalked (Figs. 2a and 2b), while upper ones are normally lanceolate and unstalked (Martinelli and Galasso, 2011).

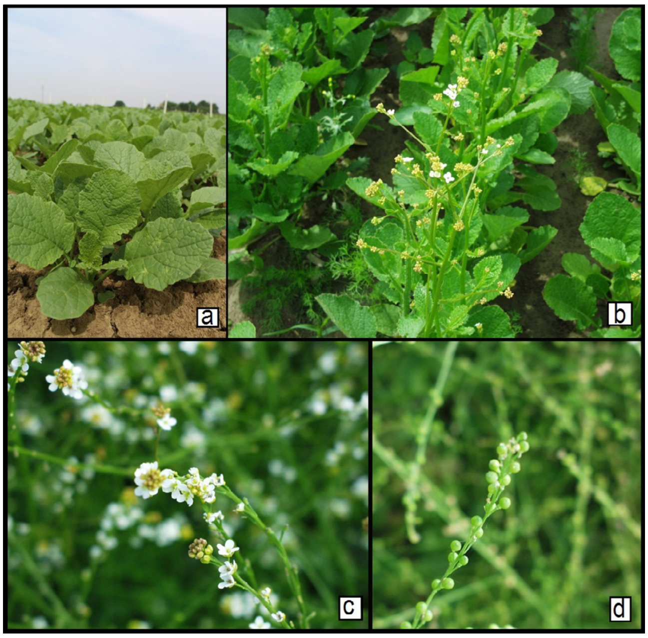

Fig. 1. Crambe plant at different development stages. (a) rosette stage; (b) stem elongation and flowering induction; (c) flowers at full flowering stage; (d) pods during seed filling stage.

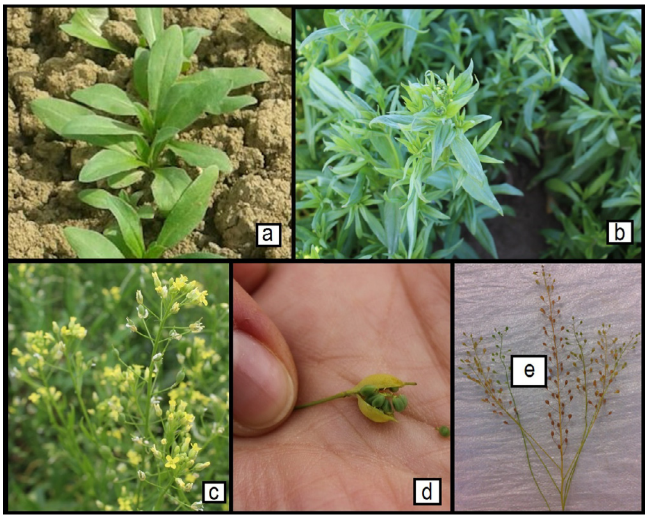

Fig. 2. Camelina plant at different development stages. (a) rosette stage; (b) stem elongation; (c) full flowering; (d) pod and seeds during seed filling stage; (e) plant at full maturity.

The number of lateral branches is extremely variable and highly dependent on both plant density and environmental conditions (Martinelli and Galasso, 2011). Camelina owns pale yellow flowers (Fig. 2c); about fifteen seeds are enclosed into each pear-shaped pods (Figs. 2d and 2e). The seed weight ranges from 0.8 to 1.8 mg (Zubr, 1997).

2.1 Adaptation and establishment

Crambe and camelina can be grown in a wide range of climatic and soil conditions. Crambe is adaptable to a broad range of soils including saline and contaminated (heavy metals) ones (Artus, 2006; Paulose *et al.,* 2010). It is also a drought tolerant crop able to grow successfully in marginal or semiarid land (Francois and Kleiman, 1990; Fowler, 1991; Lonov *et al.,* 2013). Camelina is also characterized by high resilience and can be planted on marginal soils under semiarid conditions (Rodríguez-Rodríguez *et al.,* 2013).

Ideally, both crambe and camelina could be grown as summer crops or winter ones; however, crambe is less tolerant than camelina to cold stress. Interestingly real winter camelina varieties (Berti *et al.,* 2014) are now available in the market broadening the possible cultivation environment for this species. It is worth noting that optimal planting dates for both crambe and camelina are critical management issues significantly affecting the final yield and oil composition. In particular, as reported by Adamsen and Coffelt (2005) for crambe an anticipation of sowing in autumn could negatively impact seed yield, in case of frost occurrence, conversely also a delay of sowing in spring could lead to lower yield performances. For camelina, Berti *et al.* (2011) and Gesch and Cermak (2011) demonstrated in different environments (*i.e.*, Chile and USA) that an anticipation of sowing in autumn is able to significantly increase seed yield, since the positive effect of milder temperatures during flowering period.

2.2 Rotation

Crop diversification is a major objective of the new CAP (Common Agricultural Policy). It has been widely documented that optimized crop rotations generally lead to a reduction of fertilizers, weeds, pests and diseases, resulting in an overall increase of cropping system sustainability (Kirkegaard *et al.,* 2008) and a significant reduction of management costs. Intercropping, double and relay cropping show detectable environmental benefits (Gaba *et al.,* 2015; Lithourgidis *et al.,* 2011), and increase land equivalent ratio. In view of their short cycle, crambe and camelina are good candidates to be included in new rotational schemes, as highlighted by recent studies (Gesch and Archer, 2013; Krupinsky *et al.,* 2006); however, information on rotational effects of these crops is very scarce and almost all related to Northern American environments. According to Gesch and Archer (2013), the yields of double-cropped soybean and sunflower with winter camelina are respectively 82% and 72% of their equivalent monocrops, but the revenues derived from the sale of camelina seeds provided net return when double cropping system was adopted. Gesch *et al.* (2014) confirmed also the agronomic viability of relay-cropping of soybean with winter camelina compared with respective mono-crops full-season soybean. Furthermore, in a water limited environment for dual cropping systems, the low water use (WU) of camelina would benefit the subsequent crop (Gesch and Johnson, 2015; Hunsaker *et al.,* 2011).

To the best of our knowledge, in literature there is very limited study on the rotational effects of crambe (Allen *et al.,* 2014; Krupinsky *et al.,* 2006); nonetheless, in view of its short cycle, crambe would fit as a perfect preceding crop for winter cereals, freeing early the soil thus allowing tillage operations to be done on time.

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Table 2. Seed yield (Mg ha^{-1}) and oil content (%) of camelina and crambe grown in different localities of northern, central and southern Europe.

Geographical Zone	Camelina				Crambe			
	Location	Seed yield (Mg ha^{-1})	Oil content (%)	Ref.	Location	Seed yield* (Mg ha^{-1})	Oil content* (%)	Ref.
Northern Europe	Germany, UK, Sweden, Denmark, Finland, Ireland	1.27–2.36	42	1	Netherlands	2.49–2.97	35.2–36.1	5
Central Europe	Austria	1.85	43.7	2	Austria	0.97–3.33	22.6–38.4	6
	Romania	1.99–2.24	32.7–35.9	3				
Southern Europe	Central Italy	/	23.6–27.5	4	Northern Italy	2.34–3.25	33.9–36.8	7
	Southern Italy				Southern Italy	0.44	34.8	8

[1] Zubr, 1997, 2003, [2] Vollmann *et al.,* 2007, [3] Toncea *et al.,* 2013, [4] Angelini *et al.,* 1997; [5] Meijer *et al.,* 1999; [6] Vollmann and Ruckenbauer, 1993; [7] Fontana *et al.,* 1998; [8] Laghetti *et al.,* 1995. * Considering encapsulated seed.

2.3 Plant nutrition

It is generally agreed that camelina and crambe need limited nitrogen fertilization; nonetheless, the information on correct N doses is still controversial: the optimal N dose for camelina was found to range from 44 to 185 kg N ha^{-1} (Solis *et al.,* 2013; Urbaniak *et al.,* 2008; Wysocki *et al.,* 2013). Otherwise, Solis *et al.* (2013) found that N rates exceeding 75 kg N ha^{-1} negatively affect plant lodging and seed shattering. The antagonistic effect of N application on camelina oil content was observed by Johnson and Gesch (2013) and Wysocki *et al.* (2013). Urbaniak *et al.* (2008) showed a negative relationship between N fertilization and all principal FAs of camelina, with the only exception of erucic acid.

With regard to crambe, the response to soil fertility is similar to that of other *Brassicaceae* species such as mustard and rapeseed (Knights, 2002), but specific fertilizer recommendations are missing for this crop (de Brito *et al.,* 2013).

2.4 Diseases and weed control

Unlike rapeseed, crambe and camelina are naturally resistant to several plant diseases (Lazzeri, 1998; Vollmann and Eynck, 2015). Crambe was found resistant to insect feeding (Anderson *et al.,* 1992; Kmec *et al.,* 1998) possibly in relation to the considerable glucosinolate content. Glucosinolates act in plants as natural pesticides and against herbivore predation (Martínez-Ballesta *et al.,* 2013). Unfortunately, the competition of crambe against weeds is very low and still remains a vulnerability factor of this crop causing possible reduction on seed yield (Souza *et al.,* 2014).

Camelina is resistant to several plant pathogens such as *Alternaria* spp. and *Leptosphaeria maculans* probably in relation to the production of antimicrobial phytoalexins in its leaves (Browne *et al.,* 1991; Pedras *et al.,* 1998); it is however susceptible to clubroot (*Plasmodiophora brassicae* Woronin), white rust (*Albugo candida* [Pers.] [O.] Kunze) and aster yellow (*Candidatus Phytoplasma asteris*) (Vollmann and Eynck, 2015). Interestingly, camelina owns allelopathic effect, releasing secondary metabolites that constrict weed development (Lovett and Jackson, 1980).

3 Productive performances

3.1 Seed yield

High seed yields are important to make new oilseeds competitive with the established crops (Meijer *et al.,* 1999). Literature refers that camelina seed yield can be up to 2.5–3.2 Mg ha^{-1} when grown in not-limiting conditions (Gugel and Folk, 2006; Pavlista *et al.,* 2016); crambe was shown to exceed 3 Mg ha^{-1} of seed yield (Adamsen and Coffelt, 2005), but values include the hull weight (Tab. 2). Fontana *et al.* (1998) tested crambe in the Mediterranean basin, demonstrating that adverse environmental conditions (*i.e.*, crust formation, temperatures below 10 °C at rosette stage, and very high temperatures during seed filling) are negatively affecting yields. The major constraint to reach high seed yields in crambe seems the low heritability in the progenies and the influence of adverse environmental conditions (*e.g.*, temperature, uneven rainfall distribution). Furthermore, the inefficient radiation use of the crambe pods during seed formation, caused by their small surface, differently from rapeseed, seems negatively impacting on final seed yields (Mejier *et al.,* 1999).

Also camelina productive performance appears dependent on environmental conditions during the main growing phases (*i.e.*, emergence, flowering and seed ripening). Waterlogging during reproductive phases, or persistent drought conditions decreased seed yield by 25–30% (Gugel and Folk, 2006; Gesch and Cermak, 2011). Moreover, because of the small seed size (Fig. 3) a modified harvesting equipment should be adopted for camelina while for crambe the machineries for rapeseed could be easily adapted.

3.2 Oil production and quality

Seed quality is particularly affected by environmental factors such as temperature, precipitation, solar radiation, evapotranspiration and air circulation (Zubr, 2003). For this reason, a significant variation in seed quality can be expected across different locations and/or planting dates. Table 2 shows that oil content of camelina can vary from 26% to 43% moving from south to north Europe, respectively. Gesch and Cermak (2011) refer that the oil content of winter type camelina increased

Table 3. Oil composition of camelina and crambe in comparison with high erucic acid rapeseed (*Brassica napus* L. HEAR) and linseed (*Linum usitatissimum*).

Species	Principal fatty acids (%)							
	C16:0	C18:0	C18:1	C18:2	C18:3	C20:1	C22:1	Ref.
Camelina	5.2−7.0	2.3−3.2	14.5−18.5	14.7−20.4	29.9−35.1	14.4−17.6	2.4−4.0	1
Linseed	5.4−5.7	4.0−4.7	18.1−23.8	13.6−14.6	52.2−57.9	Tr	Tr	2
Crambe	1.8−2.2	0.7	16.5−17.2	8.7−9.3	4.8−5.2	3.4−4.7	56.2−62.5	3,4
HEAR	3.1−3.5	0.8−0.9	10.7−14.5	12.5−14.0	7.4−10.5	7.5−8.0	48.1−50.3	5

[1] Vollmann *et al.,* 2007; [2] Soto-Cerda *et al.,* 2014; [3] Wang *et al.,* 2000; [4] Boldioli *et al.,* 1998; [5] Zanetti *et al.,* 2009. Tr = Traces.

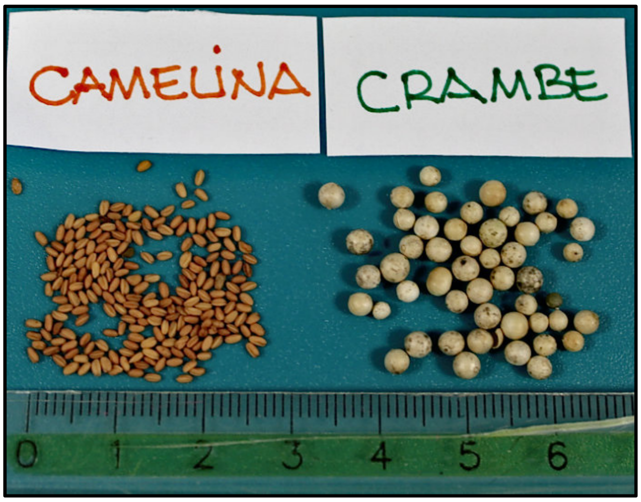

Fig. 3. Details of camelina (left) and crambe (right) seeds at full maturity. Crambe seeds are singly encapsulated in hulls at harvest.

when delaying the planting date. Pecchia *et al.* (2014) studied winter vs. spring sown of camelina and they concluded that oil content seldom increased by anticipating the sowing to autumn. In contrast, the oil content of crambe resulted in very stable values across different environmental conditions of north and south Europe (Tab. 2).

Camelina and crambe oils are characterized by the high content of uncommon long chain FAs (Tab. 3) having specific properties (viscosity, solubility, double bound position, melting point). Camelina oil (Tab. 3) is characterized by a very high content of PUFAs (*i.e.*, linoleic acid and linolenic acid), low erucic acid content (<5%), and high eicosenoic acid content (C20:1) (~15%), the latter being very uncommon in plants, while it is normally contained in fish oils. Eicosenoic acid could be used as a source of MCFAs (Medium Chain Fatty Acid), which nowadays are not produced in Europe being totally derived from palm and coconut oils. Camelina has an exceptional high content in tocopherols (Budin *et al.,* 1995), the latter conferring a reasonable oxidative stability despite the high desaturation level, differently from linseed oil.

The main characteristic of crambe oil is the outstanding content of erucic acid, up to 65% of the total FAs, that is significantly higher than those accumulate in high erucic acid rapeseed (HEAR) varieties, with a maximum of 50−55% (Meijer *et al.,* 1999). Erucic acid is a very long chain MUFA with technical characteristics (oxidative stability) similar to oleic but allowing diverse chemical transformations.

As for other oil crops, environmental conditions and genotypes are considered the main factors influencing camelina and crambe FA profile (Vollmann and Ruckenbawer, 1993; Vollmann *et al.,* 2007; Zubr, 2003). High temperatures during seed filling period interfere with the activity of enzymes responsible for PUFA metabolism (Cheesbrough, 1989), thus explaining why the temperature effect on FA composition (Schulte *et al.,* 2013) is considerable in camelina and negligible in crambe, as the latter mainly contain MUFAs (*i.e.*, erucic acid). Laghetti *et al.* (1995) confirmed that erucic acid is only lightly affected by environmental conditions.

3.3 Seed meal

Defatted camelina seed is composed of residual fats (5−10%), significant levels of high quality proteins (45%), soluble carbohydrates (10%) and different phytochemicals, such as glucosinolates (Zubr, 2010; Das *et al.,* 2014). It is worth noting that compared to other *Brassicaceae*, not improved for this trait (*e.g.*, "00" rapeseed), the glucosinolate content in camelina is rather low (10−40 μmol g^{-1}, Gugel and Falk, 2006), but it is anyway exceeding the legal limit (<30 μmol g^{-1}), thus not allowing the full use as livestock feed (Russo *et al.,* 2014). Sinapine is an alkaloidal amine found in numerous *Brassicaceae*, it is responsible for the bitter taste of *Brassica* meal thus reducing its palatability, and causing disagreeable taste of milk and meat from cows and calves fed on it. Unfortunately camelina meal contains also significant amount of sinapine, but the content is normally lower than that of conventional rapeseed meal (Colombini *et al.,* 2014).

Crambe seed meal is also characterized by good quality proteins, but the huge amounts of glucosinolates (70−150 μmol g^{-1}) and tannins dramatically limit its use as feed (Wang *et al.,* 2000).

4 Uses

The growing interest for camelina and crambe is related to the wide range of products and by-products that can be obtained from their oil and crop residues. For example, high-erucic oils are fundamental raw materials for both oleochemical transformations (*i.e.*, production of behenic, brassilic and

Table 4. Pros and cons of crambe in Europe.

Positive traits	Implications	Ref.	Negative traits	Implications	Ref.
Agronomy					
Short cycle	Several combinations of crop rotation	1	High frost sensitivity	Chilling stress risks in winter sown	7
Low input management	Environmental benefits, low management costs	2,3	Low radiation use efficiency by pods	Low seed yield	8
Adaptability to marginal lands	Use of abandoned land (avoid food/non-food debates, nature conservation programmes)	4, 5, 6			
Seed and by-product quality					
Positive traits	Implications	Ref.	Negative traits	Implications	Ref.
High content of erucic acid (up to 60%)	Erucamide production, several oleochemical streams	9			
High content of glucosinolates	Bio-based compounds for plant protection and human health	10, 11, 12	High content of glucosinolates	Limitation as livestock feed	14
Encapsulated seeds	Prevention against abrasion and shocks, no seed shattering	13	Encapsulated seeds	High managing costs, difficult emergence	15

[1] Lenssen *et al.,* 2012; [2] Rogério *et al.,* 2013; [3] Dos Santos *et al.,* 2013; [4] Francois and Kleiman, 1990; [5] Fowler, 1991; [6] Lonov *et al.,* 2013; [7] Adamsen and Coffelt, 2005; [8] Mejier *et al.,* 1999; [9] Bondioli *et al.,* 1998; [10] Avato *et al.,* 2013; [11] Bohinc *et al.,* 2013; [12] Sapone *et al.,* 2007; [13] Costa *et al.,* 2013; [14] Wang *et al.,* 2000; [15] Merrien *et al.,* 2012.

pelargonic acids) and direct use in producing erucamide – a slip agent enabling manufacture of extreme-temperature resistant plastic films (Walker, 2004; Zanetti *et al.,* 2006).

Several studies tested camelina and crambe as potential biodiesel crops (Fröhlich and Rice 2005; Wazilewski *et al.,* 2013), but due to their peculiar oil composition they would likely deserve higher consideration as a source for bio-based industry. Recently camelina oil has been identified as potential feedstock for the production of aviation fuel at both European and international level (Li and Mupondwa, 2014; Natelson *et al.,* 2015). In particular, the European project ITAKA (www.itaka-project.eu) addressed the potentiality of camelina as a source of renewable paraffinic biofuels for aviation with encouraging results. The first flights totally fuelled by camelina-derived kerosene were successfully completed in 2012. Furthermore, the high contents of ω-3 PUFAs and tocopherols (Zubr and Matthaus 2002) in the camelina oil make it of great interest also for nutritional uses. Recent studies investigating the possibility to use camelina oil in the diet of several commercial fishes (*e.g.*, salmon, trout, etc.) showed encouraging results (Burke, 2015; Ye *et al.,* 2016).

From the economical point of view, the valorization of by-products of camelina and crambe as source of feed protein would considerably increase the economic sustainability (Matthaus and Zubr, 2000); nonetheless, the use of crambe and camelina press cake as animal feed is thwarted by the high glucosinolate and tannin contents. Gonçalves *et al.* (2013) showed an interesting use of by-products from oil extraction of crambe seeds in the treatment of wastewater with high toxic metals content (*e.g.*, Cd, Pb, Cr). Franca *et al.* (2014) identified crambe press cake as a suitable candidate for the productions of adsorbents to remove cationic dyes from wastewaters without previous treatment.

5 The European Project COSMOS and the perspectives of crambe and camelina in the European bio-based economy

The EU project COSMOS (Camelina and crambe Oil crops as Sources of Medium-chain Oils for Specialty oleochemicals) started on March 2015 and will end on September 2019 (http://cosmos-h2020.eu/). The general scope of the project is to limit the European dependence on imported oils (*i.e.*, coconut and palm kernel oils) as sources of MCFAs (C10−C14) as the cost of these oils is extremely volatile. Camelina and crambe have been selected as promising candidates for substituting coconut and palm kernel oils. Considering that European customers show very low acceptance for products derived from GMOs, the project aims to develop value chains based on non-GMO oils.

According to the biorefinery concept, the whole biomass should be also valorised by converting vegetative tissues (pods, straw, leaves, *etc.*) to valuable fats and proteins through insect metabolism by innovative "insect biorefinery" approaches. Finally, oleochemical co-products would be also valorised as feedstocks for flavour and fragrance precursors, high value polyamides and high performance synthetic lubricant based oils.

The COSMOS project will boost the research to overcome existing limits to crambe and camelina cultivation (Tabs. 4 and 5) and demonstrate the feasible use of the whole produced biomass to obtain high added value products. In particular, for camelina the selection of improved varieties, with contemporaneous maturity and the set up of tailored harvesting machineries will drastically reduce seed losses in the short cut.

Table 5. Pros and cons of camelina in Europe.

Agronomy					
Positive traits	Implications	Ref.	Negative traits	Implications	Ref.
High and quick emergence	Increased competition with weeds	1	Small seed size	Difficulties at sowing/emergence	1
Short-season Low water use	Several solutions for innovative rotation systems	2, 3	Little knowledge on cultivation practices	High yield gap	3, 6
Low-input practices	Sustainable cropping systems	4	Uneven plant maturity. Seed shattering	Harvesting problems Considerable seed losses	1
Adaptability to marginal lands	Use of abandoned lands. No competition with food crops	5			
Seed and by-product quality					
Positive traits	Implications	Ref.	Negative traits	Implications	Ref.
High content of PUFAs, mostly omega ω-3 f	Interesting oleochemical pathways, high value food/feed supplements	7	Sinapine	Low palatability of meal	9
High content of eicosenoic acid	Source of MCFAs		Glucosinolates legal limits	Content exceeding	9
High content of tocopherols	Food applications Increased oil stability	8	High PUFAs	Low oxidative stability	10
High content of valuable protein	Possible use as poultry feed	7			

[1] Lenssen *et al.,* 2012; [2] Gesch and Archer, 2013; [3] Gesch and Johnson 2015; [4] Solis *et al.,* 2013; [5] Rodríguez-Rodríguez *et al.,* 2013; [6] Gesch *et al.,* 2014; [7] Zubr, 1997; [8] Budin *et al.,* 1995; [9] Colombini *et al.,* 2014; [10] Bernardo *et al.*, 2003.

For crambe, the optimization of the extraction process of glucosinolates will turn a problem into an opportunity, since they own several applications in human health, as anticancer, and agriculture, as biofumigants for crop protection. Finally to get a reliable and stable introduction of these new species in new environments COSMOS will attempt to demonstrate to farmers and farmers' organizations the feasible use of available technologies and machineries also in crambe and camelina management.

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