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Review

Crambe (*Crambe abyssinica* Hochst): A Non-Food Oilseed Crop with Great Potential: A Review

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Received: 27 July 2020; Accepted: 9 September 2020; Published: 12 September 2020

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Abstract: Crambe (*Crambe abyssinica* Hochst) is an oilseed crop in the *Brassicaceae* family. Crambe's ability to survive in diverse environmental conditions, its unique oil composition, the high oil content, suitability for the production of slip agents for plasticizers, the capacity to be easily included in common crop rotations, and its adaptability to equipment used for small grain cultivation has renewed the interest in this emerging crop. Crambe is considered one of the main sources of erucic acid, which can be up to 60% of its seed oil content. Erucic acid (C22:1) is a fatty acid with industrial importance since it is used to produce erucamide, key ingredient in the plastic industry. Inclusion of crambe into crop rotations can be beneficial because of its short life cycle, low fertility requirements, resistance to pest and diseases, and relative drought tolerance. Currently high erucic acid rapeseed (*Brassica napus* L.) (HEAR) is the principal source for erucic acid. However, the risk of contaminating food quality rapeseed (i.e., canola) by cross-pollination and the negative impact on climate, due to high inputs, are potential limitations to expand HEAR cultivation. Crambe has thus great potential to, at least, partially replace HEAR as a source of erucic acid, if the current knowledge-gap in agronomic management and crop improvement (seed yield and quality) can be addressed. Seed yield needs to be increased to be able to compete with HEAR. In addition, reducing glucosinolates and fiber in crambe meal may increase its inclusion in monogastrics rations. The objective of this review was to compile and summarize new and existing information on agricultural practices in crambe production and management to identify gaps in knowledge and areas for future research to increase the cultivation of crambe.

Keywords: erucic acid; erucamide; plasticizers; crambe meal; glucosinolates

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1. Erucic Acid Market: An Overview

Because of the importance placed on biodegradability, and renewability, there is an upward trend in producing chemical compounds for various industries utilizing plant-based feedstock. Erucic acid (*cis*-13-docosenoic acid) (C22:1) is a chemical ingredient used in industries to produce plastics, printing inks, food, personal care products, pharmaceuticals, and other products [1]. Erucic acid is found only in seed oil from plants belonging to *Brassicaceae* and *Tropaeolaceae* families [2]. Commercially, the global erucic acid market is categorized based on its source, end-use industry, produced region, application, and grade [1]. Based on the grade, erucic acid sources are segmented in two categories: erucic acid content of 43–50% and erucic acid content >50% [1]. Currently, erucic acid is mainly derived from high erucic acid rapeseed (HEAR) [1–3].

According to United States Department of Agriculture-Foreign Agriculture Service (USDA-FAS) statistics [4], global HEAR production increased from 37.4 to 75.0 million Mg, between 2010 and 2019.

Main HEAR producers are Canada, China, EU, and India. Canada HEAR seed production accounted for 22.3% of the global production in 2019 [4]. Canada is also the largest exporter of HEAR with 8.9 million Mg in 2020, while the EU is considered the largest importer, followed by China [4]. The price of HEAR oil has decreased from $647 in 2010 to $428 Mg^{-1} in 2019 [4]. Plastic manufacturing accounted for 49.5% of HEAR oil consumption in 2017 [5]. The market for HEAR oil (mainly for erucic acid) is predicted to grow at a rate of over 7% within the next five years, mainly because of the increasing demand from East Asian countries [5].

2. Alternatives to High Erucic Acid Rapeseed

High erucic acid rapeseed plants and seeds are identical to that of food quality rapeseed (canola), thus there is a high risk of cross-pollination, and accidental mixing of seeds at the processing plants [2,6]. Food contaminated with erucic acid can increase cardiovascular disease in humans [6]. According to EU food standards, erucic acid content should be less than 5% in food grade oils [7], and in infant formulas it should be less than 1% of total fatty acids [8]. As a result, USA, Canada, and EU cultivate HEAR as an identity-preserved crop under contract, to avoid erucic acid from entering the food chain [6]. Because of these strict restrictions, cultivation, transportation, processing and storage, and traceability can be time consuming and costly.

Therefore, there is a need to find alternatives, and possibly cheaper, sources of erucic acid. Alternative erucic acid sources, such as crambe, can help solving the current risks of growing HEAR. According to Qi et al. [2], the main advantages of crambe over HEAR include: (1) Crambe plant and seed morphology are both distinctively different from that of rapeseed, thus the risk of contamination by erucic acid is minimum; (2) crambe does not outcross with HEAR or canola; (3) crambe has a higher erucic acid content than HEAR; and (4) polyunsaturated fatty acids (PUFAs) content is lower in crambe oil compared with HEAR oil. In addition, cultivation of HEAR involves higher amounts of agronomic inputs (i.e., fertilizers and crop protection chemicals), resulting in negative environmental impacts compared with lower input crops, such as crambe [9]. Life cycle assessment (LCA) comparing crambe with HEAR resulted in the latter having the worst environmental impact in nine out of ten impact categories tested, including global warming potential, abiotic depletion, acidification, and eutrophication [9].

3. Industrial Uses

Crambe is considered a dedicated industrial crop since its high erucic acid content in the oil and the large amount of glucosinolates in the meal limit any possible food/feed use. Erucic acid is the main fatty acid found in crambe oil, which ranges between 50% and 65% [10,11]. Erucic acid is a monounsatured, long-chain fatty acid, non-edible, and with specific industrial uses.

Erucic acid has attracted wide interests as raw material for hydraulic fluids, oleochemicals, lubricants, additives, and as a starting material for new fibers, resins, plastics, lacquers, and other products [12,13]. Wazilewski et al. [14] reported that the oxidative stability of crambe oil-derived biodiesel is higher than soybean [*Glycine max* (L.) Merr.] oil-derived biodiesel, opening another potential use for crambe. Crambe meal has high protein and fiber content. But the presence of high levels of glucosinolates, which are toxic for monogastric animals, needs additional steps in removing/inactivating the glucosinolates before using crambe meal as animal feed [10]. Otherwise, the crambe by-products (i.e., seed meal including hulls (= siliques)), would only have industrial uses, such as an adsorbent material to remove toxic compounds from contaminated water [15,16]. The most recent uses of crambe oil and seed meal are summarized in Table 1.

Table 1. Crambe oil and meal uses and research reported between 2010 and 2018.

Product	References
Crambe oil	
Biodiesel, jet fuel	[9,13,14,17]
Crambe meal	
Biosorbent	[13,16,18]
Nematicide	[19]
Cow/steer-feed	[20,21]
Sheep/lamb feed	[22–26]
Fish feed	[27,28]
Other	[29]

4. Crambe Origin and Distribution

Crambe is believed to be native to the eastern region of Africa from Ethiopia and Tanzania [10,17,30–32]. It can be found as spontaneous species in Mediterranean areas of Europe and in the Middle East [33]. Crambe was first utilized as a crop in former USSR during 1933 before it was introduced into the United States in the 1940s [31,32]. Thereafter, it has been cultivated in several US States, particularly in the Midwest. By 1992, there were about 10,000 ha grown in the United States. In North Dakota, in 1996, it was estimated 16,000 ha of crambe was in production [34]. The number of cultivars currently available for commercial production is limited, with Meyer, BelAnn, BelEnzian, Indy, Westhope, Galactica, Mario, and Prophet as the prominent cultivars (Table 2).

Table 2. Crambe seed yield and seed oil content as reported in the reviewed literature under different environmental conditions.

Country	Seed Yield (kg ha^{-1})	Oil Content (%)	Genotype Tested	Main Factor Studied	References
Austria	972–3328	22–38	Gross Enzersdorj, Gleisdorj	Breeding lines	[35]
Brazil	290–1225	32–41	FMS Brilahnte	Phosphorus fertilization	[36]
	317–524	27–30	FMS Brilahnte	Sowing dates & fungicides	[37]
China	612–1558	34–44	Meyer	Sowing dates	[38]
England	3000–3500	n.a.	Carmen, Galactica, Nebula	Cultivars	[39]
Italy	2500–2840 †	32–37	BelEnzian, BelAnn, Meyer, 47112, C-29, Mario	Breeding lines	[40]
	1650–2110	42–47	Galactica, Nebula, Mario	Years	[11]
	751–1940	28–38	MG 300605, MG 300621	Sowing dates	[41]
Netherlands	2490–2970	36–57	BelEnzian	Sowing dates	[42]
Poland	1360–3190	n.a.	Galactica	N fertilization	[43]
Portugal	95–742	26–34	FMS Brilhante	Years	[44]
USA/North Dakota	1321–1430	n.a.	BelAnn, Meyer, Westhope	Breeding lines	[45]
USA/Arizona	1440–3200	33–36	Meyer	Sowing dates	[46]

† Autumn sowing in southern Italy; n.a. = data not available.

However, the production declined thereafter in the leading states (North Dakota and Montana) to less than 8500 ha by 2002 [34]. Recently, the 2019 North Dakota crop report indicated 314 ha of crambe was grown that year [47]. Hebard [6] reported that the global cultivation of crambe declined to less than 810 ha by 2016. Premature commercialization, higher prices for other crops, establishment difficulties, decreasing government support for research were the main reasons that contributed to the decline [48].

Crambe is a cool-season crop and can tolerate low temperatures down to −5 °C [32,46,49]. Crambe is considered both as a spring crop and as a winter crop in Europe [17]. Crambe is reported to be cultivated from sea level to 2000 m and in some parts of Africa it has adapted up to 2500 m [49]. Crambe can grow in areas with cumulative annual rainfall ranging from 350 to 1200 mm [17]. Even though crambe is a relatively drought-tolerant crop, as with most annual oilseed crops, seed yield increases as rainfall increases.

5. Morphological Description

Crambe has a short growth cycle and harvesting occurs usually at 90–110 days after sowing [17,50]. Growth cycle accumulates between 1300 and 1500 growth degree-days (GDD), with a base temperature of 5 °C [51]. In the Mediterranean region, cycle length might be longer if seeded in autumn as a winter annual crop, reaching up to 180 days [11]. Crambe is an annual herbaceous species, which normally grows to a height between 1 and 1.20 m [50], but Falasca et al. [17] reported maximum heights of 2 m. Plant height depends on the growing conditions such as season, plant density, and soil fertility [17]. The plant is characterized by an erect habit and the presence of numerous branches.

This species has a tap-root that can reach soil depths exceeding 1 m [11,52]. The robust root system confers to crambe a wide adaptability to drought and soil salinity. The cotyledons of crambe are heart-shaped (Figure 1A), while it has oval-shaped leaves (Figure 1D) with a smooth surface of a light-green color [49,50]. Crambe is a self-pollinated plant; however, natural crossing can occur [35,53]. Flowering is indeterminate (Figure 1B), and it can last over two months [10]. The flowers are small; they can be either white or light-yellow in color and arranged in a raceme (Figure 1E) [17,50].

Crambe seeds are produced in small sphere-shaped siliques (Figure 1C) that are initially green but they become yellow-brown as they mature (Figure 1F, [54]) with a single seed per silique, also known as pod. Mature seeds are greenish-brown in color with 0.8 to 2.6 mm in diameter [17] (Figure 1G). Siliques are indehiscent, preventing shattering and seed losses during harvest [11]. The pericarp accounts for 25% to 30% of the silique volume [17], and 11% to 40% of silique weight [50]. Hulled crambe 1000-seed weight ranges between 6 and 10 g [17].

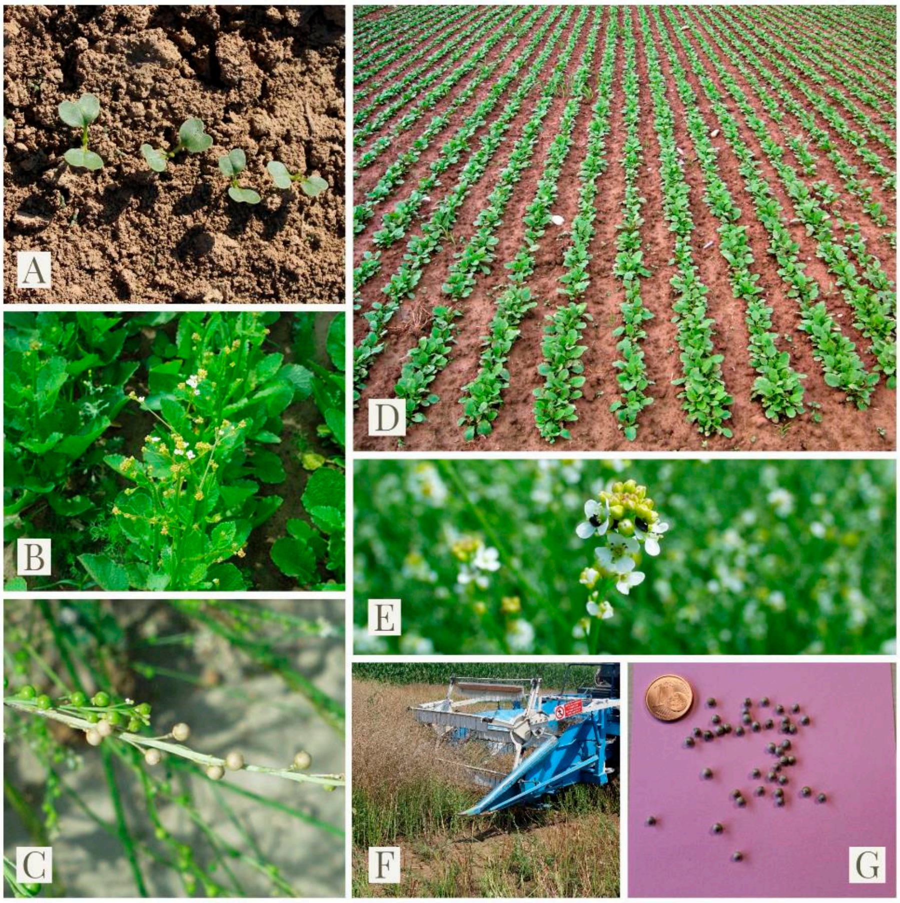

Figure 1. Details of crambe plants: (**A**) cotyledons at emergence stage; (**B**) crambe plants at bolting stage; (**C**) crambe siliques (hulls) during seed filling stage; (**D**) crambe at rosette stage; (**E**) crambe flowers; (**F**) crambe stand at harvest; (**G**) crambe seeds. (Photos by F. Zanetti).

6. Seed Yield Potential

Crambe seed yield varies with cultivar, climate, soil characteristics, and management practices [10,55]. Different studies reporting crambe seed yield and seed oil content across different environments and cultivation practices are summarized in Table 2. Among different climates, seed yield was higher with spring sowing than autumn sowing [44,56], but Zanetti et al. [11] reported similar seed yield in Mediterranean climate with autumn sowing. New studies on crambe testing different cultivars in new locations are necessary to better assess the environment by genotype interaction on seed yield potential.

7. Agronomic Management

7.1. Establishment

A firm, well-packed seedbed is critical for crambe establishment because of its small seed size. Crambe prefers a moderately coarse to fine-textured soil, and well-drained soil with a pH between 5 and 7.8. It is less tolerant to heavy soils, prone to waterlogging [10,32,57,58]. In tropical regions, soil compaction caused by lack of crop rotation and machine traffic needs to be considered in crambe establishment [12]. Bassegio et al. [59], have proposed a cover crop rotation system using sunnhemp (*Crotalaria juncea* L.) to reduce soil compaction before crambe cultivation. In addition, using a cover crop can improve soil fertility resulting in higher crambe grain yield [60]. Crambe shows moderate tolerance to saline soils [61]; however, seed oil content decreased with increasing salinity in irrigation water [55].

Crambe requires a cool environment during germination and establishment. Early sowing typically results in higher seed yield, decreased days from sowing to flowering and physiological maturity, and in reduction in weed pressure [58,62]. Sowing is usually done in the spring, past the time when frost can damage emerging seedlings in northern climates [31,32,62]. In environments characterized by a mild winter (i.e., southern Mediterranean basin), the establishment in late autumn/early winter permits to achieve seed yields higher than spring-sown crambe by avoiding summer heat and drought during the seed filling phase [11]. In midwestern USA, sowing dates vary from late March to early May depending on location and year. Early March to the first week of April is preferred in Nebraska, mid- to late-April in Wisconsin and southern Minnesota, and early-May is recommended in North Dakota [32,58,62]. Planting later than these dates reduces seed yield, seed oil content, and increases weed pressure [62]. In North Dakota, Johnson et al. [58] reported that sowing crambe after 15 May resulted in reduced seed yield, and oil content, and recommended sowing crambe before 1 May if field conditions allow it. Seed yield reduction in later sowing dates can be attributed to hot and dry conditions, where water stress conditions can reduce seed germination and vigor [63].

Crambe can be solid-seeded or in rows. Crambe solid seeding can be done in a field with low weed pressure, using equipment such as a small grain drill or a cultipacker seeder [32]. Row planting can improve uniform maturity, reduce losses due to soil crusting, and reduce seed cost. Row spacing in crambe ranges between 0.12 and 0.90 m in width. Narrow row spacing of less than 0.30 m improved seed yield by enhancing weed competition, decreasing branching, and promoting uniform maturity [32,41]. Wider row spacing increased lodging [10], but it might be of interest in drier environments [64]. Maize (*Zea mays* L.) seeder fitted with maize or soybean plates can be used to plant crambe in rows of 50 and 76 cm. In Brazil, row spacing varies between 17 and 50 cm, mainly depending on the availability of seeding equipment [12].

Seeding rates vary with row spacing. Carlson et al. [65] recommended a seeding rate between 11 and 22 kg ha^{-1} for crambe. A seeding rate of about 20 kg ha^{-1} is recommended if row spacing is below 0.3 m [11,66]. For row spacing above 0.3 m, a seeding rate between 8 and 15 kg ha^{-1} is adequate [40,62,67].

Planting depth is another critical factor in achieving a good stand. In a well-prepared seedbed with adequate soil moisture, planting depth recommended for crambe ranged between 0.6 and 1.9 cm [57,62]. However, in soils with less moisture, crambe can be sown at 2.5 cm depth [32].

The use of high-quality seed for sowing can be one of the best practices to reduce production costs. For crambe, it is recommended to sow seeds with no less than 80% germination rate [62]. The pericarp of the silique remains attached to the seed after harvest, which protects the seed from pathogens and insects but at the same time hinders seed germination. To analyze crambe seed viability Rezende et al. [68] recommended performing a tetrazolium test, by soaking the seeds in a 0.075% tetrazolium solution for 18 or 24 h. Lima et al. [69], identified that accelerated aging test using water for 72 h, and conducting an electrical conductivity test on pre-soaked crambe seeds were effective in evaluating crambe seed quality. A recent study by Kwiatkowski et al. [70], reporting a thorough evaluation of crambe seed vigor and viability in response to genotype and growing conditions, showed how the latter became important in determining crambe seed quality, even if all tested genotypes were characterized by germination rate above 95%.

7.2. Fertilization

There is limited amount of information available with regard to specific fertilizer recommendations for crambe [71,72], even if this oilseed crop is usually considered as low input. Knights [48] indicated crambe nutrient requirements are similar to that of rapeseed. Phosphorus and potassium recommendations for small grain crops with approximately 50 and 89 kg ha^{-1} of P_2O_5, and K_2O, respectively should be adequate for crambe production [32].

Rogerio et al. [36], determined the effect of phosphorus (0, 15, 30, 50, and 90 kg ha^{-1} P_2O_5) on crambe seed yield reporting higher seed yield with increased phosphorus rates; however, seed oil content was not affected. In contrast, Alves et al. [71] reported that increased phosphorus rates up to 80 kg ha^{-1} P_2O_5, favored root and shoot development in crambe resulting in increased seed yield, but also in oil content. Da Silva et al. [73] reported that applying phosphorus at seedling stage increased seed oil content and 1000-seed weight.

Crambe also responded positively to N fertilizer from approximately 89 to 150 kg ha^{-1} of N [10]. Similarly to rapeseed, it is expected that crambe may respond to sulfur fertilizer, especially on sandy soils [32]. Increasing the soil base saturation level to 47–48% can increase seed yield, oil content, and biomass yield of crambe [71].

Summarizing, the fertilization usually reported for crambe is in the range of 30–160, 40–120, and 60–120 kg ha^{-1} of N, P, and K respectively [11,43,74,75]. It is important to keep in mind that even higher N rates increase seed yield, an increase in N fertilization significantly reduces the seed oil content and causes an overall worsening of the environmental impact of the crop [43].

7.3. Pests, Diseases, and Weed Management

One of the key advantages of crambe over other potential biofuel feedstock is its ability to tolerate pests and diseases. Flea beetles [*Phyllotreta cruciferae* (Goeze)] are the main pest of rapeseed and canola in the United States and Canada, while crambe is more resistant to flea beetles, compared with rapeseed [76]. Several studies on crambe have not identified any major insect that causes significant seed yield losses [77–79]. The resistance to pest may be due to the presence of high levels of glucosinolates [62,76]. However, some insects are attracted by glucosinolates, such as diamondback moth (*Plutella xylostella* L.), which might cause damage in occasions [80], but needing only seldom insecticide application to control them.

Crambe is highly susceptible to turnip yellow mosaic virus (TYMV). Symptoms include mosaic and yellowing of outer leaf edges. Flea beetles and grasshoppers are the known vectors of TYMV. Crop rotation along with eradicating crambe volunteers is considered the most effective methods of managing TYMV [62]. Black spot caused by *Alternaria brassicae* is another devastating disease that crambe is susceptible to [32,62]. Plants are infected by spores, which overwinter in infected plants or debris. Control measures include utilizing a long-term rotation, using disease-free seeds, and controlling volunteers and weeds in the *Brassicaceae* family [62]. Seeds can be treated with a fungicide or soaked in warm water (60 °C) for about 20 min [32]. White mold or stem rot caused by *Sclerotinia sclerotiorum* Lib de Bary affects crambe, especially in the US Midwest. A sclerotium is a dormant overwintering stage of the fungus. Sclerotinia can survive in the soil for long periods of time. High plant densities, increased humidity, higher inoculum levels, and excessive N fertilizer rates can create conducive conditions for an infection. Rotation with non-host crops and use of certified seed are considered the most effective control methods of this disease [62]. Fungicide treatments are not recommended for any of the fungal disease of crambe [81]. However, biological control agents such as *Trichoderma asperellum* and *Bacillus subtilis* are promising to control fungal diseases in crambe [82].

Crambe seedlings are not very competitive against weeds. This is the result of slow initial growth up to four weeks after emergence [32]. Negative effects of weed competition generally show 60 to 70 days after emergence [12]. Therefore, it is critical to maintain a weed-free environment by canopy closure. Uniform thick stand is effective in controlling weeds. Use of high-quality seed, optimal row spacing, early sowing, and adequate sowing rates are some of the methods that can be used to reduce weed competition [32,62]. Common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus* sp.), kochia (*Kochia scoparia*), wild mustard (*Brassica kaber* L.), and foxtail (*Setaria* spp.) have been reported to hinder crambe production [10,62]. Weeds can emerge through the canopy when crambe reaches maturity and can cause problems during harvest. Tall, green weeds at harvest increase seed moisture and can disrupt seed drying post-harvest, if a desiccant is not used [32]. Common ragweed (*Ambrosia artemisifolia* L.), and redroot pigweed are reported to cause problems during combining [62]. Trifluralin and metazachlor have shown to be selective when used as a soil-applied pre-emergence [41,62,83].

Souza et al. [83] reported about the potential use of clethodim + fenoxaprop-p-ethyl, fluazifop-p-butyl, quinclorac, sethoxydim, and clethodim as post-emergence herbicides.

Crambe is considered more tolerant to salinity, cold temperature, heat, and moisture stress compared with other oilseed crops [58,84]. Artus [85] reported crambe being less susceptible to heavy metals such as arsenic, when compared with Indian mustard [*Brassica juncea* (L.) Czern].

7.4. Harvest, Post-Harvest, and Storage

Crambe seeds mature rapidly after flowering, usually within two to five weeks, depending on sowing date and environmental conditions. Harvesting at correct maturity is important to minimize high shattering losses [31]. Physiological maturity in crambe is attained when 50% of seeds have turned brown [31]. Harvesting should be done as soon as last of the seed-bearing branches reach maturity, evident by seed pods turning to light tan in color [32]. By that time seed moisture level will be around 10% [62].

Combine-harvester with available equipment for cereals [31,86] can easily harvest crambe. According to Jasper et al. [87], crambe harvest cost is the most significant among all other oilseeds, because of non-uniform stand and difficulties in collecting and cleaning the seed. This can be avoided by using a desiccant before harvesting. Cangussu et al. [88] reported the use of the herbicide glyphosate [N-(phosphonomethyl) glycine] as a desiccant at 2.0 L a.i. ha^{-1} when 90% of the seeds turned brown, without negatively affecting seed germination or vigor.

Crambe has a low bulk density, which is about 340 kg m^{-3} [12]. Since crambe seeds are small and light weight, transport and storage facilities need to be tight to avoid seed losses. Storage facilities need to be in close proximity to the fields to reduce transportation costs. Before drying and storage, seed should be cleaned to avoid foreign material, which can cause heating problems, and increase in drying costs [62]. Clean, insect-free bins with perforated floors with fans are preferred for seed storage. Drying and storage conditions directly affect seed quality and seed oil properties of crambe. Prolonged storage can negatively affect the physiological quality of the seed [89]. Crambe seed should be stored with less than 10% seed moisture content, and maximum drying temperature should be less than 43.3 °C [31]. Crambe seeds that dried in the plant before harvest had the best seed oil quality compared with artificial drying using heated air, interestingly, the drying method did not influence the quality of biodiesel made from crambe oil [90].

7.5. Environmental Impact of Crambe Cultivation

In recent years, crambe cultivation has attracted the interest of many researchers and industries all over the world because of its lower input requirement compared with other oilseed crops, such as rapeseed [36]. As it already has been mentioned, crambe seed oil can be used for producing biodiesel, jet fuels, hydraulic fluids, and biolubricants [17,38,43]. But before promoting crambe as an alternative to HEAR, it is important to estimate the environmental impacts associated with crambe cultivation, since agricultural activities and inputs are responsible for 70% to 80% of the greenhouse gases emissions in most crops [91]. Life cycle assessment and energy efficiency indices in crambe cultivation revealed that the negative environmental impacts are mainly related to diesel and electricity consumption used for sowing, growing, and harvesting the crop, in a scenario of low nitrogen fertilization [44]. Substituting mineral diesel with biodiesel might be a solution to improve the environmental performance of the system allowing the reduction of impacts on climate change and eutrophication. Overall, crambe cultivation presents lower environmental impacts than other crops such as canola or maize [44].

8. Research Advances and Future Prospects

Even though in the past crambe was cultivated in some countries, it is not yet widely produced. Currently, crambe can be considered a specialty niche-crop. Crambe oil has a market as ingredient in specific personal care products. The cosmetic industry pays a higher price for crambe oil, about \$6.0 kg^{-1}, compared with the price of HEAR oil which it is less than \$1.5 kg^{-1} [6].

From an economic perspective, higher production cost per kg of oil and lower seed yield are the main drawbacks of crambe when compared with HEAR [9,92]. In addition, crambe has about 10% lower oil content, up to four times higher sulfur content in the oil, higher meal to seed proportion, and higher levels of fiber and glucosinolates in the meal (which can be high as seven-fold) compared with HEAR [6].

Because of the above-mentioned drawbacks, there is great need for innovation and improvement in crambe production and utilization, to be considered a viable alternative to HEAR. There are several areas that would benefit from further research in crambe production and processing, such as adding value to crambe meal, improving seed yield, erucic acid content, and lowering sulfur content in the oil and glucosinolates in the meal.

8.1. Crambe Meal Uses

Crambe meal, which is the remaining product after oil extraction, is an important resource, which needs to be utilized effectively. Dehulled crambe meal can contain up to 50% crude protein (compared with 27% with hull), with a digestibility level similar to soybean meal, but at a third the cost of the latter [93,94]. Fiber content depends on the proportion of hulls that are in the meal. Fiber content can vary between 6.5% (totally dehulled) and 22% (with-hull) [95]. However, the high glucosinolate content in the meal can cause detrimental effects to livestock [96]. Glucosinolates cause toxicity issues in monogastric animals such as swine and poultry [93]. Increased use of crambe meal in lamb (*Ovis aries* L.) diet has resulted in poor performance, increased hepatic injuries to animals, poor meat quality, and meat containing higher erucic acid content than the limit allowed as safe for human consumption [97]. Oppositely, Itavo et al. [25] and Syperreck et al. [26] reported no negative effects on lamb carcass quality and animal performance when crambe meal was less than 20% of the ration.

New technologies for glucosinolate detoxification, such as chemical and physical treatments, reducing the amount to 450 mg kg^{-1} DM on crambe meal, could allow the full substitution of soybean meal in ruminant diets [98]. Recent studies reported that crambe meal can be valuably included in fish diets (i.e., silver catfish, *Rhamdia quelen*) as sustainable replacement of fish meal [27,28].

Crambe meal odor and flavor reduces palatability and some animals tend to select out crambe meal when possible. Nevertheless, the potentially cheaper price and high protein content in crambe meal, compared with alternative oilseed meals, have led to increased research to studies on optimum levels of crambe meal that can be mixed with other components [95,99]. There is still opportunity for further developments and research, to find effective and cheaper methods to remove hulls from seed, as meal quality improves with dehulling [95].

Crambe seed meal has been reported to have insecticidal activity. Peterson et al. [100], identified two compounds from crambe seed meal [phenylethyl cyanide and 2-(S)-1-cyano-2-hydroxy-3-butane] which can act against house flies (*Musca domestica*). Vaughn and Berhow [101] evaluated crambe seed meal as an effective soil amendment to minimize soil pathogens and weed seedbank. They identified a phytotoxic chemical compound (1-cyano-2-hydroxy-3-butane) seemly responsible for the reported activity. Walker [102] reported a nematicidal effect of crambe meal in 1997. Recent studies reported crambe meal extract have nematicidal effect. In fact, Coltro-Roncato et al. [19] reported satisfactory results against *Meloydogine incognita* in tomato (*Lycopersicon esculentum* L.), while Tavares-Silva et al. [103] tested it against *Pratylenchus brachyurus* in soybean.

Another possible way of valorization of crambe seed meal is the extraction of proteins, which can be used to develop bio-based products such as plasticizers and adhesives [104]. Unfortunately, first attempts using crambe meal resulted in products of poor performance. This indicates that conversion technologies applied on crambe protein concentrates in the near future need to improve to increase protein performance for the production of molded plastic films [105].

8.2. Crambe Breeding and Genetic Modification of Oil Quality

Increasing genetic variability and discovering genotypes more suitable for different environmental conditions can be beneficial, as future agriculture needs to adapt to climate change [106,107]. Low seed yield, poor seed germination, disease resistance, high sulfur content in seed oil, and high glucosinolates and fiber content in the meal are some of the critical areas that need to be addressed through breeding and improvement. A recent study in Brazil reported 10% to 49% genetic gain in seed yield in tested crambe lines after selection and evaluating 82 progenies of cultivar FMS Brilhante [108]. A screening study, conducted in Poland by Kwiatkowski et al. [70] with 10 crambe genotypes, was able to identify three breeding lines, from the University of Wageningen Research program (The Netherlands), characterized by larger fruits (siliques) and increased seed vigor, which resulted in higher seed viability and rapid germination.

Genetic modification might complement conventional breeding for improving crambe plant traits, but the success of these approaches depends, among other factors, on the regeneration efficiency of explants and transgene integration [109]. Unfortunately thus far, there is a lack of regeneration protocols for crambe. Using different plant growth regulator combinations on crambe cv. Galactica hypocotyl explants, Li et al. [110] were able to achieve high regeneration frequency of 60%. In a separate study using crambe cv. BelAnn hypocotyl explants, Chhikara et al. [111] obtained transformation frequencies between 6.7% and 8.3% with a regeneration frequency of up to 70%.

Li et al. [3] successfully achieved the goal to increase erucic acid level in the seed oil by using *Agrobacterium tumefaciens*-mediated transformations. Transgenic lines able to produce wax esters (WE) and higher oleic acid contents in the seed oil have been selected by Li et al. [112]. Wax esters, are esters of fatty acids and fatty alcohols, with relevant properties in lubricants production [10]. Li et al. [113] were able to develop new crambe lines producing high WE content, through genetic engineering. The new lines had seed oil containing more than 25% of WE and this trait was stable over several generations.

Erucamide is the primary product derived from erucic acid, and a key ingredient in plastic manufacturing. It is estimated that production cost of erucamide decreases by 50% with every 10% increase in erucic acid content in the seed oil [3]. In order to increase the erucic acid content in crambe seed oil, gene-stacking methods have been used to develop transgenic crambe lines which resulted in 13% increase (total erucic acid content of 73% in seed oil) in erucic acid content compared with the wild type [3]. When the erucic acid content in the oil is greater than 90%, crambe seed oil can be used directly without going through erucamide production, thus greatly reducing production costs [3]. Increasing the erucic acid content along with decreasing the PUFAs levels in the oil can improve the fractionation efficiency of erucic acid, thus reducing the production cost. Qi et al. [2] reported promising results developing transgenic crambe lines that contain lower amount of PUFAs in its seed oil.

8.3. Agronomic Management

A lack of recent studies on agronomic management of crambe, compared with other emerging oilseed crops, such as camelina [*Camelina sativa* (L.) Crantz], field pennycress (*Thlaspi arvense* L.), and carinata (*Brassica carinata* L.) can be easily observed from the literature (Table 3). Studies to identify fertilization rates, weed management strategies, pest and disease management to optimize seed yield are some of the critical areas that need to be addressed in crambe production.

Table 3. Research publications in crambe compared with other emerging oilseed crops from the *Brassicaceae* family.

Crop	Scientific Name	Total References †	Year of the Oldest Publication	Percent of Published References between 2015 and 2019 (%)	Number of Published Papers from 2015 to 2019
Crambe	*Crambe abyssinica*	488	1957	26.3	131
Camelina	*Camelina sativa*	761	1959	51.4	422
Pennycress	*Thlaspi arvense*	331	1930	27.0	93
Carinata	*Brassica carinata*	830	1942	26.5	224

† Database search was done in the Scopus database including all article types between 2015 and 2019. Total references were calculated from the oldest publication to the newest in 2019.

The main limitation for crambe to achieve higher productivity has been attributed to its inefficient use of solar radiation during seed development [42]. Siliques undergoing active seed filling were only able to intercept lower amount of radiation, compared with stems and senescing leaves, which intercepted higher proportion of the radiation [42], thus partially explaining the yield gap between crambe and HEAR.

Crambe seeds can undergo post-harvest dormancy thus resulting in low germination rates, sometimes as low as 42% [114]. Seed dormancy could be also the result of abiotic stresses or nutrient deficiencies during seed development, which is controlled by hormones [115,116]. Foliar application of indole butyric acid and gibberellic acid during late vegetative-early flowering stages of crambe resulted in increasing seed germination percentage [117]. Even if the seeds are not dehulled before sowing, the presence of the hulls can create problems, particularly when using precision pneumatic seeders. Seed hulls can break exposing the seed to pathogens in the soil reducing the final stand density.

Finally, the possibility to set up a low-input organic agronomic management for crambe will increase the value of the seed oil, especially for personal care products and cosmetics, but to date this has not been reported.

8.4. Ecosystem Services Provided by Crambe Cultivation

Although not extensively studied, crambe can be used as an annual cover crop. It can provide benefits to cropping systems such as nutrient cycling, improving soil structure, reducing soil erosion, and weed control, similar to other annual crops in the *Brassicaceae* family [118,119].

Recent studies have reported on the use of crambe for soybean cyst nematode (SCN) (*Heterodera glycines* Ichinohe) management. When crambe was cultivated in SCN infested soil, a significant reduction in the number of adult SCN female and cysts was observed during the 90-day period of the experiment [120]. After the incorporation of crambe residues, nematicidal activity continued to the subsequent season. Acharya et al. [121], reported crambe as a poor host to SCN, and the evaluated crambe cultivar could in fact support SCN reproduction, but in a very low level. This emphasizes the need for further research to identify crambe cultivars with nematicidal activity towards different SCN populations.

9. Conclusions

The high erucic content in crambe oil makes it an ideal candidate to replace, at least in part, high erucic acid rapeseed. However, crambe low seed yield, the need for dehulling, the high glucosinolates and fiber in the meal, and the lower seed oil content than HEAR limit its development as a competitive cash crop. Efforts in plant breeding to increase seed yield, increase erucic acid content in the oil, and reduce glucosinolates in the meal will be key for crambe to compete in the market of high erucic acid producing crops.

In addition, research in agronomic management (conventional and organic) is needed to optimize seed yield to make crambe competitive for end-uses such as personal care products and the cosmetic industry.

Author Contributions: D.S. conducted the database search, compiled the information, wrote the first draft of the review, and edited the last version. F.Z. complemented the review, wrote the genetics and breeding section, added the figures, and edited the last draft. S.B. wrote the environmental impact section and edited the review and last draft. M.T.B. arranged the funding for this research, wrote project proposal, organized review outline, heavily edited the first draft and corrected the last draft before submission. All authors have read and agreed to the published version of the manuscript.

Funding: This review was possible because of the funding provided by the National Science Foundation under NSF ND EPSCoR Track 1 Grant Award OIA-1355466, the North Dakota State University Agricultural Experimental Station project ND 01557, and the PANACEA project that has received funding from the European Union's Horizon 2020 Research and Innovation program under Grant Agreement 773501.

Acknowledgments: The authors also wish to thank Erika Facciolla for taking care of the photo formatting.

Conflicts of Interest: The authors declare no conflict of interest.

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