Acta Scientiarum
http://www.periodicos.uem.br/ojs/
ISSN on-line: 1807-8621
Doi: 10.4025/actasciagron.v46i1.65159
CC BY
CROP PRODUCTION

Oil from crambe seeds treated with different resistance inducers: Oil yield and chemical characterization

Janaina Marques da Silva[1], Natália Stevanato[2], Djéssica Tatiane Raspe[3], Tiago Roque Benetoli da Silva[1] and Camila da Silva[4*]

[1]Programa de Pós-Graduação em Ciências Agrárias, Universidade Estadual de Maringá, Campus Umuarama, Estrada da Paca, s/n, 87507-190, Umuarama, Paraná, Brazil. [2]Programa de Pós-Graduação em Engenharia Química, Universidade Estadual de Maringá, Maringá, Paraná, Brazil. [3]Programa de Pós-Graduação em Agronomia, Universidade Estadual de Maringá, Maringá, Paraná, Brazil. [4]Departamento de Tecnologia, Universidade Estadual de Maringá, Umuarama, Paraná, Brazil. *Author for correspondence. E-mail: camiladasilva.eq@gmail.com

ABSTRACT. This study aimed to carry out the extraction and chemical characterization of oil from crambe treated with resistance inducers during its cultivation to promote greater efficiency in the defense system of plants. For this purpose, Agromos® and Ecolife® inducers were applied at rates of 0.5 and 1.0 L hectare^{-1} during crambe cultivation. Crambe seed oil was obtained in a Soxhlet extractor using *n*-hexane as a solvent and the oils were characterized in terms of fatty acid composition and minority compound contents (phytosterol and tocopherol). The oil obtained from seeds without the application of inducers (control) was also characterized. We determine the oxidative stability of oils with inducer application that presented higher minority compound contents. Crambe seeds that received the treatment with the Agromos® resistance inducer had higher oil content. However, in general, the fatty acid profile of the obtained oils was similar and showed a predominance of erucic and oleic acids (which represent ~82% of the composition). The application of the Agromos® inducer allowed obtaining seeds that provided oil with higher contents of phytosterols and tocopherols and higher oxidative stability.

Keywords: fatty acids; Agromos®; Ecolife®; phytosterols; tocopherols.

Received on September 26, 2022.
Accepted on January12, 2023.

Introduction

Crambe (*Crambe abyssinica* Hochst) belongs to the cruciferous family and is originated in the Mediterranean region, showing an easy adaptation to different climate conditions (Souza, Fávaro, Ítavo, & Roscoe, 2009). The oil extracted from crambe seeds has high resistance to oxidation, which can be seen as a result of the high induction time, mainly due to the presence of tocopherols, β-Sitosterol, and erucic acid (Iwassa, Saldaña, Cardozo-Filho, & Silva, 2021; Mello, Iwassa, Cuco, Garcia, & Silva, 2019). Moreover, erucic acid toxicity makes the oil unsuitable for consumption, but it can be applied industrially without competition with the food sector. Crambe oil has shown resistance to degradation and high oxidative stability when used for biodiesel production and industrial lubricants, allowing storage for long periods (Souza, Oliveira, Vieira, Faria, & Batista, 2021). The high erucic acid concentration in its fatty acid composition allows this oil to be used as an industrial lubricant, corrosion inhibitor, and as an ingredient in the manufacture of synthetic rubber, in addition to being used in the manufacture of plastic films, plasticizers, nylon, adhesives, antistatic, and electrical insulation (Oplinger et al., 2000).

Biodiesel production faces problems with the cost of raw materials, as it corresponds to around 75% of its final cost of production (Mahlia et al., 2020), which highlights the importance of raw materials that have a lower cost and higher productivity. The search for these new sources of oils for biodiesel synthesis is in line with the concepts of circular economy, aiming to meet the growing demand for bioproducts and bioenergy and reduce the use of edible crops (Krzyzaniak, Stolarski, Graban, Lajszner, & Kuriata, 2020).

Crambe has favorable agronomic characteristics, such as a short growth cycle (90–110 days) (Zanetti et al., 2016), tolerance to sandy and saline soils (Von Cossel et al., 2019; Hu et al., 2015), and adaptability to crop rotation (Acharya, Yan, & Berti, 2019; Samarappuli, Zanetti, Berzuini, & Berti, 2020). The cultivation of crambe requires reduced agronomic management (Jankowski, Sokólski, Szatkowski, & Kozak, 2022), but it has vulnerabilities as a crop despite its wide tolerance. Although it is relatively drought-tolerant, higher seed yields have been observed with increasing rainfall (Samarappuli et al., 2020).

In this context, crambe responds to fertilizers similarly to small grains, helping its cultivation, as there are still no specific recommendations for its sowing (Knights, 2005). However, the spread of crambe sowing raises concern about the diseases caused in the plants, which occur more frequently when the climate is unfavorable to the plant species and favorable to the pathogen, that is, periods in which there is higher precipitation, causing an increase in ambient and soil moisture (Pitol, Broch, & Roscoe, 2010).

As defense alternatives, there are leaf fertilizers with the potential for resistance inducers that increase the resistance levels of plants, activating a series of substances that prevent or delay the attack of pathogens by their own defense mechanisms (Durrant & Dong, 2004) via microbe-associated molecular patterns (Burketova, Trda, Ott, & Valentova, 2015). This process of induced resistance may lead to the priming of cells, usually defined as a memory state in which plants can respond to post-challenge stresses more rapidly even in distal parts from the original stress (Sandroni, Liljeroth, Mulugeta, & Alexandersson, 2020).

The use of insecticides has been increasing due to the attack of pests and diseases, generating higher production costs and possible environmental imbalance. In this context, alternative measures are necessary to maintain quality and productivity. The integration of the rational use of chemical pesticides with other control methods, such as crop rotation, genetic resistance, and, recently, resistance inducers, has been studied to control phytopathogens (Barros, 2011). Resistance inducers act by activating the defense system of plants because they have efficient forms of defense, which remain inert but are activated when exposed to the attack of pests and diseases (Resende et al., 2000). Some studies have shown promising results for Agromos® and Ecolife® products (Boava, Kuhn, Pascholati, Di Piero, & Furtado, 2010; Furtado, Rodrigues, Araújo, Silva, & Catarino, 2010; Gouvea et al., 2009).

Ecolife® is a commercial product that has in its composition bioflavonoids. It is an organomineral fertilizer that helps the plant under stress conditions and also acts as a resistance inducer to the attack of pathogens, such as bacteria and fungi. The product has simultaneous action of its components, that is, they act cooperatively so that its effect is better than when used alone (Furtado et al., 2010; Quinabra, 1996).

Agromos® was mentioned by Junqueira et al. (2011). It has as active ingredients phosphorylated mannan-oligosaccharides, which are extracted from the cell wall of *Saccharomyces cerevisiae*, a fungus studied as a plant defense, as it acts in several ways by activating forms of plant protection, such as the hydrolytic action of chitinase.

These inducers can activate several defense systems, including structural ones, delaying the pathogen infection. Other activated systems consist of proteins related to pathogenesis (Barros, 2011), with their effects on grain and oil production being unknown.

In this context, this study aimed to quantify the oil content from crambe seeds treated with doses of resistance inducers (Agromos® and Ecolife®) and determine the chemical composition of the obtained oils. The data were compared with seeds obtained without the application of inducers (control).

Material and methods

Crambe (*Crambe abyssinica* H.) seeds of the variety FMS Brilhante (Mato Grosso do Sul Foundation) were used for sowing. The plants were subjected to treatment with Agromos® and Ecolife® resistance inducers in the field during cultivation. The oil content in the seeds was determined using *n*-hexane (Synth, ⩾98.5%) as a solvent. The oil characterization in terms of fatty acid composition used potassium hydroxide (Synth, ⩾85%), methanol (Panreac, ⩾99.9%), sulfuric acid (Anhydrol, ⩾95%), heptane (Neon), and a mixture of fatty acid methyl esters (FAME) C8 to C24 (Supelco). Phytosterol content was determined using heptane (Neon), N,O-Bis(trimethylsilyl)trifluoroacetamide with 1% trimethylchlorosilane (BSTFA/TMCS, Sigma-Aldrich, 99%) and 5α-cholestane (Sigma Aldrich, >99.9%). Tocopherol content was determined using 2-propanol (Panreac, ⩾99.9%), ultrapure water (18 MΩ.cm, Simplicity® Water Purification System) and analytical patterns of α-, γ-, and δ-tocopherol (Sigma-Aldrich, >99.9%).

Cultivation and acquisition of seeds

The experiment was conducted under field conditions on the Farm of the State University of Maringá in the city of Umuarama, Paraná State, Brazil (latitude of 23°47′33″ S, longitude of 53°15′26″ W, and altitude of 402 m). The local soil is a typic dystrophic Red Latosol (Santos et al., 2018).

Sowing was carried out in August 2018, with an inter-row spacing of 0.25 m and a plant population of 750 thousand plants hectare^{-1}. Plots consisted of five rows with four meters in length, considering the three central rows as the useful area and discarding 0.5 m from both ends.

Fertilization was performed at crambe sowing using 150 kg hectare^{-1} of the 4-20-20 formula (% N, P_2O_5, and K_2O, respectively), according to Pitol et al. (2010). The experiment was conducted in a randomized block design with four replications. The treatments consisted of the leaf application of 0.5 and 1.0 L hectare^{-1} of Agromos® and Ecolife®. The lowest and highest rates applied to other crops, as in Boava et al. (2010), Furtado et al. (2010), and Gouvêa et al. (2009), were considered in this study since there is no recommended dose of these products for crambe plants. Thus, the smallest (0.5 L hectare^{-1}) and the highest doses found (1.0 L hectare^{-1}) were used.

The control sample was obtained without the application of the studied products. Weed was controlled by manual weeding and pests were controlled with insecticide application. Manual harvesting was carried out after the end of crambe cultivation, and impurities from the harvest were removed to keep the grains clean.

Oil extraction

Previously to extraction, the seeds were crushed in a food processor (Cadence) and granulometrically classified using a set of Tyler series sieves (Bertel) to obtain particles with a mean diameter of 0.725 ± 0.177 mm.

The extractions were performed in triplicate in a Soxhlet extractor (Satelit®, model HS 374-M), as recommended by the Instituto Adolfo Lutz (2005), in which approximately 3 g of the ground sample was used in each experiment and 150 mL of *n*-hexane was used as a solvent, for 480 minutes. The extraction temperature was kept constant above the reflux temperature of the solvent (68°C) using an electric heating mantle (Fisatom, 52). After the extraction period, the solvent remaining in the extracts was removed by evaporation in an air-circulation oven (Marconi, model MA 035) until constant weight. Oil yield was determined by the ratio between the obtained oil mass and the used seed mass.

Oil characterization

Fatty acid composition

Oil samples (60 mg) diluted in 2 mL of methanolic KOH solution (2 mol L^{-1}) were subjected to vigorous stirring for 5 min to determine the fatty acid composition. The test tube containing the mixture was placed in a heating bath (Nova Etica, model 314/8) at 100°C for 5 min. Subsequently, 5 mL of methanolic solution of H_2SO_4 (5%, v/v) was added and the mixture was heated again at 100°C for 15 min. Then, 2 mL of heptane was added to the test tube. The upper phase was collected (after 24h) and FAME was analyzed on a gas chromatograph (Shimadzu, GC-2010 Plus) equipped with a flame ionization detector (FID) and an SH-Rtx-Wax™ capillary column (Shimadzu, 30 m × 0.32 mm × 0.25 µm) under the chromatographic conditions described by Trentini et al. (2018). The identification of fatty acids was performed by comparing the retention times of the peaks of the injected samples and the mixture of standards (C8 to C24). For quantification, the percentage of individual FAME was performed relative to the total area of the chromatogram peaks (normative area).

Phytosterol content

Oil samples (40 mg) were dissolved in 40 µL of BSTFA/TMCS and the silylation reaction proceeded at 60°C in an oven (Marconi, model MA033/1) for 30 min. An aliquot of the 5α-cholestane standard was added to the derivatized oil (for quantification of compounds) and, subsequently, the solution was diluted in heptane. The silylated compounds were analyzed in a gas chromatograph coupled to a mass spectrometry device (Shimadzu, CGMS-QP2010 SE), following the chromatographic analysis conditions described by Stevanato and Silva (2019). The identification was carried out from the similarity research of mass spectral data available in the database of the National Institute of Standards and Technology (2014 version).

Tocopherol content

Oil samples were diluted in 2-propanol, stirred vigorously, and filtered through a syringe filter (45 µm). The α-, γ-, and δ-tocopherol were identified and quantified by high-performance liquid chromatography (Shimadzu, model LC-20A Prominence), using the equipment described by Stevanato, Iwassa, Cardozo-Filho, and Silva (2020). The isocratic elution system consisted of a methanol-to-water mixture (96:4, v/v) pumped at a 1 mL min.$^{-1}$ flow. The detection wavelength was set at 298 nm and the column was kept at room temperature. The quantification was performed using external standards of α-, γ-, and δ-tocopherol injected at concentrations ranging from 0.5 to 12 mg mL^{-1}.

Oxidative stability

Oxidative stability was determined using Professional Biodiesel Rancimat (Metrohm™, model 823). The samples (2.5 g) were transferred to reaction vessels and placed in the heating block at 130°C, where they were subjected to an airflow rate of 20 L h^{-1}. Outlet gases were collected in an electrical conductivity measuring vessel containing 50 mL of deionized water (25°C) as an absorption solution. The induction time is defined as the time before accelerated oxidation and was automatically determined by the second derivative of the conductivity curve.

Statistical analysis of data

Extractions and analyses were carried out in triplicates (n = 9) and the results were expressed as means followed by the standard deviation. The comparison between means was performed using Tukey's test with a 95% significance level and the data from the analysis of variance were generated by the Excel® 2007 software.

Results and discussion

Table 1 shows the oil content obtained from different treatments carried out on crambe seeds with resistance inducers and for the seeds without treatment (control), as well as the fatty acid composition of the obtained oils. The oil content present in the seeds of plants that received applications of Agromos® was higher than those that received the application of Ecolife® and the control. The average oil content in the seeds was 22.12 wt% (Table 1), below that found by Mello et al. (2019) and Vazquez, Lazarini, Camargo, Ferreira, and Peres (2014), who obtained values of 38.83 wt% and 30.22 wt%, respectively. The Mato Grosso do Sul Foundation (2007) found an oil content of the FMS Brilhante variety ranging from 34 to 38 wt%, while Reginato, Souza, Silva, and Rafull(2013) obtained the maximum value of 34.0 wt%.

Table 1. Oil content in crambe seeds cultivated with doses of Agromos® and Ecolife® resistance inducers and fatty acid composition of the obtained oils. Control (plants cultivated without inducer application).

Treatment		Control	Agromos®0.5 L ha^{-1}	Agromos®1.0 L ha^{-1}	Ecolife®0.5 L ha^{-1}	Ecolife®1.0 L ha^{-1}
Oil content (wt%)		19.83±0.68^{b}	23.05±0.7^{a}	23.49±0.79^{a}	21.34±1.17^{ab}	18.92±0.32^{b}
Fatty acid (%)	Palmitic	1.80±0.03^{a}	2.16±0.01^{b}	1.58±0.02^{c}	2.17±0.06^{b}	1.63±0.01^{c}
	Palmitoleic	0.09±0.01^{a}	0.07±0.00^{abc}	0.56±0.01^{c}	0.09±0.00^{ab}	0.63±0.00^{bc}
	Stearic	0.87±0.03^{a}	0.59±0.02^{b}	0.85±0.07^{a}	0.61±0.01^{b}	0.84±0.00^{a}
	Oleic	15.35±0.28^{a}	14.28±0.3^{b}	12.98±0.2^{c}	15.10±0.01^{ab}	13.23±0.13^{c}
	Linoleic	7.65±0.05^{a}	7.35±0.01^{b}	6.50±0.08^{c}	8.00±0.01^{d}	6.87±0.08^{e}
	Arachidic	2.69±0.04^{a}	3.12±0.02^{bc}	2.96±0.06^{c}	3.76±0.01^{d}	3.19±0.06^{b}
	Linolenic	3.17±0.00^{a}	2.82±0.05^{b}	2.85±0.05^{b}	2.93±0.09^{b}	2.81±0.01^{b}
	Erucic	66.93±0.21^{a}	66.28±0.2^{a}	69.68±1.19^{b}	65.92±0.07^{a}	69.65±0.29^{b}
	Lignoceric	1.42±0.23^{a}	3.28±0.04^{a}	2.50±1.20^{a}	1.40±0.03^{a}	1.69±0.00^{a}

Means followed by the same letter (in each line) show no significant difference ($p > 0.05$).

The difference shown in the oil content of crambe seeds may have been influenced by the extraction methods, which used different solvents, temperatures, and extraction times. Climate factors can also explain these differences since a period of drought with subsequent rainfall was observed during sowing, causing water stress to the plants. Maršalkienė, Žilėnaitė, and Karpavičienė (2020) obtained crambe seeds with oil contents from 23.4 to 36.6%, which was attributed to the precipitation during the generative stage and mean temperatures during ripening and generative stages. Costa, Almeida, Alvim-Ferraz, and Dias (2019) cultivated crambe seeds of the FMS Brilhante variety in Portugal and reported seeds with 26 wt% oil, a result attributed to lower water availability during the first two months of the vegetative cycle. Crambe requires high soil moisture to germinate and establish, as well as accumulated rainfall from 150 to 200 mm until full flowering (Pitol et al., 2010). According to data provided by Instituto Agronômico do Paraná [IAPAR] (2018), rainfall ranged from 54.3 to 0.0 mm in the first months after crambe sowing, reaching 231.3 mm at flowering, a value lower than that recommended for the crop.

Additionally, the use of inducers may not result in effective plant development because resistance activation promotes a high energy demand for the synthesis of defense mechanisms (Kant et al., 2015; Silva, Arf, & Soratto, 2003), which, associated with the climate issues already discussed, justifies the low oil content in the seeds compared to previous studies using the same cultivar.

Table 1 shows that the fatty acid profile of oils extracted from seeds that had their plants treated with resistance inducers was little influenced by the different treatments evaluated even when compared to the control. The predominant fatty acids in the crambe seed oil were erucic (~66.89%), oleic (~14%), and linoleic (~7.27%).

The high erucic acid content has desirable properties for several applications, but it restricts its use as a food raw material due to the harmful effects related to human health (Imamura et al., 2013). Therefore, it is a potential alternative for biodiesel production, being no longer part of the oilseed statistics that conflict with its use in human food (Mitrović et al., 2020). Oils with a high erucic acid content contain a longer polymethylene chain that gives high oxidative stability to biodiesel (Pullen & Saeed, 2012). Furthermore, the oil can be used as a lubricant due to this characteristic since this compound gives the same properties as mineral oils, being more environmentally advantageous due to its biodegradability (Sajeeb & Rajendrakumar, 2019). Fanigliulo et al. (2021) reported the application of crambe oil as a hydraulic fluid with stable performances during fluid efficiency tests.

Table 2 shows the identification of phytosterols and tocopherols present in oils obtained from crambe seeds in the present study, as well as the content of each compound. The phytosterols detected were stigmasterol, campesterol, and β-sitosterol, the latter present at a higher concentration, as found by Aguiar et al. (2017), Mello et al. (2019), and Iwassa et al. (2021). Crambe seeds treated with Agromos® at the concentration of 1.0 L ha^{-1} showed the highest content of total phytosterols among the analyzed treatments, reaching 287.16 mg 100 g^{-1}, a value higher than that reported by Mello et al. (2019), who obtained approximately 171 mg 100 g^{-1} using the same extraction method, and close to the values of Iwassa et al. (2021), who extracted oil using subcritical propane and obtained content of 260.13 mg 100 g^{-1}. Γ-tocopherol was predominant in the analyzed oil, representing ~55% of the identified tocopherols, followed by α- and δ-tocopherol. Total tocopherol contents ranged from 30.89 to 38.60 mg 100 g^{-1} according to each treatment, values higher than that reported by Trentini, Mello, Cabral, and Silva (2020), who obtained 21.24 mg 100 g^{-1} oil using the conventional extraction method and seeds of the same cultivar.

Table 2. Phytosterol and tocopherol contents in crambe seed oil obtained from plants cultivated with different doses of Agromos® and Ecolife® resistance inducers. Control (plant cultivated without inducer application).

Treatment		Control	Agromos®0.5 L ha^{-1}	Agromos®1.0 L ha^{-1}	Ecolife®0.5 L ha^{-1}	Ecolife®1.0 L ha^{-1}
Phytosterol (mg per 100 g seed)	Stigmasterol	50.12±0.75^{a}	59.46± .93^{b}	63.42±1.09^{b}	62.88±3.16^{b}	61.94±0.80^{b}
	Campesterol	54.59±0.77^{a}	57.40±2.45^{ab}	62.39±2.16^{b}	53.10 ± 0.70^{a}	52.70±0.33^{a}
	β-Sitosterol	134.36±1.45^{a}	153.79±5.49^{b}	161.35±0.93^{b}	129.79±0.81^{a}	124.60±0.46^{a}
	Total	239.08±2.97^{a}	270.64±9.88^{b}	287.16±4.18^{b}	245.77±3.27^{a}	239.23±1.59^{a}
Tocopherol (mg per 100 g seed)	α	8.37±0.00^{a}	6.24±0.32^{b}	11.07±0.51^{c}	8.41±0.15^{a}	9.90±0.20^{d}
	δ	5.83±0.10^{a}	4.23±0.30^{b}	6.28±0.25^{a}	5.96±0.36^{a}	5.36±0.23^{a}
	γ	15.17±0.02^{a}	14.97±0.64^{a}	21.24±0.05^{b}	19.48±0.72^{bc}	19.08±0.26^{c}
	Total	29.36±0.08^{a}	25.44±0.66^{b}	38.59±0.71^{c}	33.86±0.51^{d}	34.35±0.68^{d}

Means followed by the same letter (in each line) show no significant difference ($p > 0.05$).

Phytosterols and tocopherols are important natural lipid-soluble antioxidants. Regarding β-sitosterol, Winkler and Warner (2008) indicated excellent anti-polymerization potency of this compound. Stevanato et al. (2020) attributed the greater oxidative stability of radish seed oil to the concentration of β-sitosterol.

The presence of high γ-tocopherol contents has a great effect on enhancing vegetable oil oxidative stability (Fernández-Cuesta, Velasco, & Ruiz-Méndez, 2014) and preventing polymerization of fatty acid methyl esters(Wang, Hicks, & Moreau, 2002), as γ-tocopherol could prevent autooxidation of polyunsaturated fatty acids (Mohamed, Fernández, Pineda, & Aguilar, 2007).

The combined analysis of the minority compound concentration (Table 2) and oil yield (Table 1) indicates that the application of Agromos® and Ecolife® at concentrations of 1.0 and 0.5 L ha^{-1}, respectively, provided seeds with higher oil and target compound content (under the experimental conditions evaluated in the present study). In this sense, Figure 1 shows the results of the oxidative stability of these oils (conductivity curves) and the control sample. The increase in conductivity was slower and the accelerated oxidation stage was delayed for the oil with the highest content of phytosterols and γ-tocopherol (obtained from seeds treated with Agromos®) (Figure 1). Iwassa et al. (2021) obtained an induction time of ~4.2h for crambe seed oil obtained from extraction using pressurized propane.

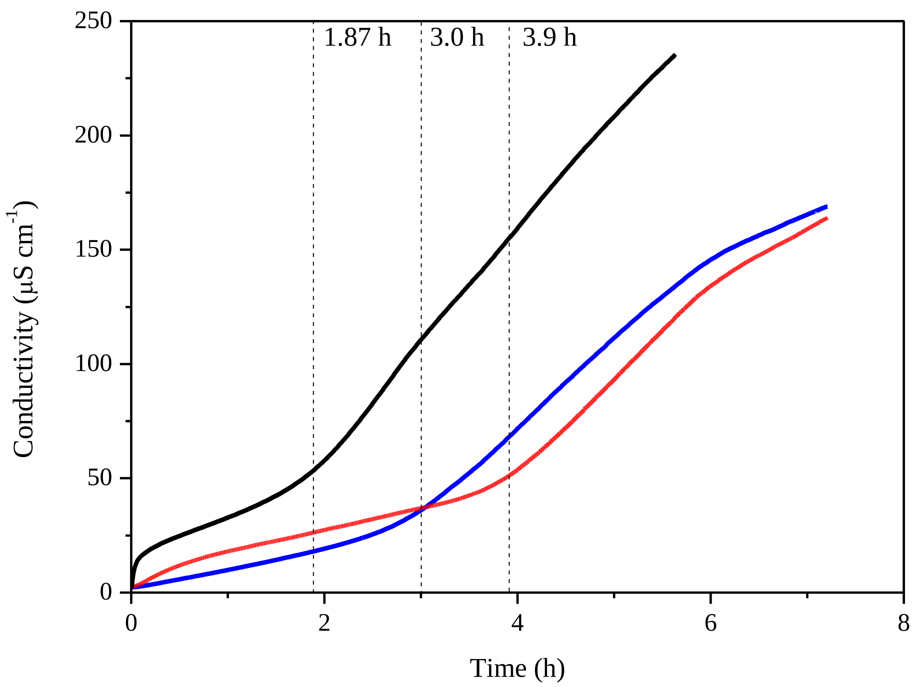

Figure 1. Oxidative stability of oil from crambe seeds cultivated with the resistance inducers (-) Agromos® (1.0 L ha^{-1}) and (-) Ecolife® (0.5 L ha^{-1}) and the control sample (-).

The obtained oils had a longer inclusion period than other oils commonly used for biodiesel production, such as radish seed oil (2.73h) (Stevanato et al., 2020), soybean oil (2.77h) (Wang et al., 2010), and rapeseed oil (2.05h) (Symoniuk, Ratusz, & Krygier, 2017). Crambe oil has a high content of monounsaturated fatty acids, increasing the oxidative stability of the oil, as oxidation increases exponentially with the number of double bonds present in the fatty acid molecules (Mello et al., 2019).

Conclusion

The acquisition and chemical characterization of crambe oil obtained from seeds treated with resistance inducers during their cultivation have been reported. The analyses show that the unfavorable climate conditions for sowing crambe directly affected the oil content present in the seeds. The application of resistance inducers allowed to obtain seeds with higher oil content, but the treatment did not influence the fatty acid composition of the obtained oils. Oils obtained from seeds with Agromos® application have higher contents of minority compounds (phytosterols and tocopherols) in their composition and, therefore, higher oxidative stability.

Acknowledgements

This study was financed in part by the *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior*- Brazil (CAPES) - Finance Code 001.

References

Acharya, K., Yan, G., & Berti, M. (2019). Can winter camelina, crambe, and brown mustard reduce soybean cyst nematode populations? *Industrial Crops and Products*, *140*, 1-28. DOI: https://doi.org/10.1016/j.indcrop.2019.111637

Aguiar, C. M., Sampaio, S. C., Santos, K. A., Silva, E. A., Piana, P. A., Richart, A., & Reis, R. R. (2017). Total fatty acid content, antioxidant composition, antioxidant activity, and content of oil from crambe seeds cultivated with phosphorus. *European Journal of Lipid Science and Technology*, *119*(10), 1700043. DOI: https://doi.org/10.1002/ejlt.201700043

Barros, R. (2011). Estudo sobre a aplicação foliar de Acibenzolar-S-metil para indução de resistência à ferrugem asiática em soja e cercosporiose em milho. *Arquivos do Instituto Biológico*, *78*(4), 519-528. DOI: https://doi.org/10.1590/1808-1657v78p5192011

Boava, L. P., Kuhn, O. J., Pascholati, S. F., Di Piero, R. M., & Furtado, E. L. (2010). Efeito de indutores bióticos e abióticos na atividade de quitinase e peroxidase e no controle da ferrugem causada por *Puccinia psidii* em eucalipto. *Summa Phytopathologica*, *36*(2), 168-172. DOI: https://doi.org/10.1590/S0100-54052010000200012

Burketova, L., Trda, L., Ott, P. G., & Valentova, O. (2015). Bio-based resistance inducers for sustainable plant protection against pathogens. *Biotechnology Advances*, *33*(6), 994-1004. DOI: https://doi.org/10.1016/j.biotechadv.2015.01.004

Costa, E., Almeida, M. F., Alvim-Ferraz, C., & Dias, J. M. (2019). The cycle of biodiesel production from *Crambe abyssinica* in Portugal. *Industrial Crops and Products*, *129*, 51-58. DOI: https://doi.org/10.1016/j.indcrop.2018.11.032

Durrant, W. E., & Dong, X. (2004). Systemic acquired resistance. *Annual Review of Phytopathology*, *42*, 185-209. DOI: https://doi.org/10.1146/annurev.phyto.42.040803.140421

Fanigliulo, R., Pochi, D., Bondioli, P., Grilli, R., Fornaciari, L., Folegatti, L., ... Lazzeri, L. (2021). Semi-refined *Crambe abyssinica* (Hochst. EX R.E.Fr.) oil as a biobased hydraulic fluid for agricultural applications. *Biomass Conversion and Biorefinery*, *13*, 1859-1871. DOI: https://doi.org/10.1007/s13399-020-01213-y

Fernández-Cuesta, Á., Velasco, L., & Ruiz-Méndez, M. V. (2014). Novel safflower oil with high γ-tocopherol content has a high oxidative stability. *European Journal of Lipid Science and Technology*, *116*(7), 832–836. DOI: https://doi.org/10.1002/ejlt.201300208

Furtado, L. M., Rodrigues, A. A. C., Araújo, V. S., Silva, L. L. S., & Catarino, A. M. (2010). Utilização de Ecolife® e Acibenzolar-s-metil (ASM) no controle da antracnose da banana em pós-colheita. *Summa Phytopathologica*, *36*(3), 237-239. DOI: https://doi.org/10.1590/S0100-54052010000300009

Gouvea, A., Kuhn, O. J., Mazaro, S. M., Mio, L. L. M., Deschamps, C., Biasi, L. A., & Fonseca, V. C. (2009). Controle de doenças foliares e de flores e qualidade pós-colheita do morangueiro tratado com *Saccharomyces cerevisiae*. *Horticultura Brasileira*, *27*(4), 527-533. DOI: https://doi.org/10.1590/S0102-05362009000400020

Hu, J., Deng, Z., Wang, B., Zhi, Y., Pei, B., Zhang, G., ... Huang, B. (2015). Influence of heavy metals on seed germination and early seedling growth in *Crambe abyssinica*, a potential industrial oil crop for phytoremediation. *American Journal of Plant Sciences*, *6*(5), 582-590. DOI: https://doi.org/10.4236/ajps.2015.61017

Imamura, F., Lemaitre, R. N., King, I. B., Song, X., Steffen, L. M., Folsom, A. R., ... Mozaffarian, D. (2013). Long-chain monounsatrated fatty acids and incidence of congestive heart failure in 2 prospective cohorts. *Circulation*, *127*(14), 1512-1521. DOI: https://doi.org/10.1161/circulationaha.112.001197

Instituto Adolfo Lutz (2005) *Métodos físico-químicos para análises de alimentos* (4. ed.). Brasília, DF: Instituto Adolfo Lutz.

Instituto Agronômico do Paraná [IAPAR]. (2018). *Desvio de precipitação mensal*. Retrieved on Aug. 10, 2022 from https://www.idrparana.pr.gov.br/

Iwassa, I. J., Saldaña, M. D. A., Cardozo-Filho, L., & Silva, C. (2021). Yield and quality parameters of pretreated crambe seed oil extracted using C_3H_8, CO_2 and C_3H_8+CO_2 mixtures under pressurized conditions. *The Journal of Supercritical Fluids*, *175*, 105277. DOI: https://doi.org/10.1016/j.supflu.2021.105277

Jankowski, K. J., Sokólski, M., Szatkowski, A., & Kozak, M. (2022). Crambe – Energy efficiency of biomass production and mineral fertilization. A case study in Poland. *Industrial Crops and Products*, *182*, 1-28. DOI: https://doi.org/10.1016/j.indcrop.2022.114918

Junqueira, K. P., Faleiro, F. G., Uesugi, C. H., Junqueira, N. T. V., Bellon, G., Santos, E. C., & Ramos, L. N. (2011). Desempenho agronômico de maracujazeiros tratados com produtos alternativos e fertilizantes foliares. *Revista Brasileira de Fruticultura*, *33*(1), 40-47. DOI: https://doi.org/10.1590/S0100-29452011005000019

Kant, M. R., Jonckheere, W., Knegt, B., Lemos, F., Liu, J., Schimmel, B. C. J., ... Alba, J. M. (2015). Mechanisms and ecological consequences of plant defence induction and suppression in herbivore communities. *Annals of Botany*, *115*(7), 1015-1051. DOI: https://doi.org/10.1093/aob/mcv054

Knights, E. G. (2005). *Crambe: a North Dakota case study*. Kingston, CA: A Report for the Rural Industries Research and Development Corporation, RIRDC Publication No.W02/005.

Krzyzaniak, M., Stolarski, M. J., Graban, Ł., Lajszner, W., & Kuriata, T. (2020). Camelina and crambe oil crops for bioeconomy-Straw utilisation for energy. *Energies*, *13*(6), 1-8. DOI: https://doi.org/10.3390/en13061503

Mahlia, T. M. I., Syazmi, Z. A. H. S., Mofijur, M., Abas, A. E. P., Bilad, M. R., Chyuan, H., & Silitonga, A. S. (2020). Patent landscape review on biodiesel production: Technology updates. *Renewable and Sustainable Energy Reviews*, *118*, 1-5. DOI: https://doi.org/10.1016/j.rser.2019.109526

Maršalkienė, N., Žilėnaitė, L., & Karpavičienė, B. (2020). Oil content and composition in seeds of *Camelina sativa* and *Crambe abyssinica* cultivars. *Journal of Elementology*, *25*(4), 1399-1412. DOI: https://doi.org/10.5601/jelem.2020.25.3.20237

Fundação do Mato Grosso do Sul. (2007). *Culturas para biodiesel, Crambe*. Maracaju, MS: Fundação MS.

Mello, B. T. F., Iwassa, I. J., Cuco, R. P., Garcia, V. A. S., & Silva, C. (2019). Methyl acetate as solvent in pressurized liquid extraction of crambe seed oil. *The Journal of Supercritical Fluids*, *145*, 66-73. DOI: https://doi.org/10.1016/j.supflu.2018.11.024

Mitrović, P. M., Stamenković, O. S., Banković-Ilić, I., Djalović, I. G., Nježić, Z. B., Farooq, M., ... Veljković, V. B. (2020). White mustard (*Sinapis alba* L.) oil in biodiesel production: A review. *Frontiers in Plant Science*, *11*(299), 1-22. DOI: https://doi.org/10.3389/fpls.2020.00299

Mohamed, R., Fernández, J., Pineda, M., & Aguilar, M. (2007). Roselle (*Hibiscus sabdariffa*) seed oil is a rich source of γ-tocopherol. *Journal of Food Science*, *72*(3), 207-211. DOI: https://doi.org/10.1111/j.1750-3841.2007.00285.x

Oplinger, E. S., Oelke, E. A., Kaminski, A. R., Putman, D. H., Teynor, T. M., Doll, J. D., ... Noetzel, D. M. (2000). *Crambe: alternative field crops manual*. St. Paul, MN: University of Wisconsin and University of Minnesota.

Pitol, C., Broch, D. L., & Roscoe, R. (2010). *Tecnologia e produção: crambe*. Maracaju, MS: Fundação MS.

Pullen, J., & Saeed, K. (2012). An overview of biodiesel oxidation stability. *Renewable and Sustainable Energy Reviews*, *16*(8), 5924-5950. DOI: https://doi.org/10.1016/j.rser.2012.06.024

Quinabra (1996). *Boletim técnico*: Ecolife. São José dos Campos, SP: Quinabra - Química Natural Brasileira Ltda. Retrieved on Feb. 11, 2019 from www.quinabra.com.br

Reginato, P., Souza, C. M. A., Silva, C. J., & Rafull, L. Z. L. (2013). Agronomic performance and seed quality of crambe at different sowing dates and depths. *Pesquisa Agropecuária Brasileira*, *48*(10), 1410-1413. DOI: https://doi.org/10.1590/S0100-204X2013001000013

Resende, M. L., Nojosa, J. B. A., Aguilar, M. A. G., Silva, L. H. C. P., Niella, G. R., Carvalho, G. A., ... Castro, M. C. (2000). Perspectivas da indução de resistência em cacaueiro contra *Crinipellis perniciosa* através do benzotiadiazole (BTH). *Fitopatologia Brasileira*, *25*, 149-156.

Sajeeb, A., & Rajendrakumar, P. K. (2019). Comparative evaluation of lubricant properties of biodegradable blend of coconut and mustard oil. *Journal of Cleaner Production*, *240*, 118255. DOI: https://doi.org/10.1016/j.jclepro.2019.118255

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), 1-18. DOI: https://doi.org/10.3390/agronomy10091380

Sandroni, M., Liljeroth, E., Mulugeta, T., & Alexandersson, E. (2020). Plant resistance inducers (PRIs): Perspectives for future disease management in the field. *CAB Reviews*, *15*, 1-10. DOI: https://doi.org/10.1079/pavsnnr202015001

Santos, H. G., Jacomine, P. K. T., Anjos, L. H. C., Oliveira, V. A., Lumbreras, J. F., Coelho, M. R., & Cunha, T. J. F. (2018). *Sistema brasileiro de classificação de solos* (5. ed.). Brasília, DF: Embrapa.

Silva, T. R. B., Arf, O., & Soratto, R. P. (2003). Adubação nitrogenada e resíduos vegetais no desenvolvimento do feijoeiro em sistema de plantio direto. *Acta Scientiarum. Agronomy*, *25*(1), 81-87. DOI: https://doi.org/10.4025/actasciagron.v25i1.2447

Souza, A. D. V. de, Fávaro, S. P., Ítavo, L. C. V., & Roscoe, R. (2009). Chemical characterization of seeds and presscakes of physic nut, radish and crambe. *Pesquisa Agropecuaria Brasileira*, *44*(10), 1328-1335. DOI: https://doi.org/10.1590/s0100-204x2009001000017

Souza, M. C. G., Oliveira, M. F., Vieira, A. T., Faria, A. M., & Batista, A. C. F. (2021). Methylic and ethylic biodiesel production from crambe oil (*Crambe abyssinica*): New aspects for yield and oxidative stability. *Renewable Energy*, *163*, 368-374. DOI: https://doi.org/10.1016/j.renene.2020.08.073

Stevanato, N., & Silva, C. (2019). Radish seed oil: Ultrasound-assisted extraction using ethanol as solvent and assessment of its potential for ester production. *Industrial Crops and Products*, *132*, 283-291 DOI: https://doi.org/10.1016/j.indcrop.2019.02.032

Stevanato, N., Iwassa, I. J., Cardozo-Filho, L., & Silva, C. (2020). Quality parameters of radish seed oil obtained using compressed propane as solvent. *Journal of Supercritical Fluids*, *159*, 104751.DOI: https://doi.org/10.1016/j.supflu.2020.104751

Symoniuk, E., Ratusz, K., & Krygier, K. (2017). Comparison of the oxidative stability of cold-pressed rapeseed oil using Pressure Differential Scanning Calorimetry and Rancimat methods. *European Journal of Lipid Science and Technology*, *119*(5), 1600182. DOI: https://doi.org/10.1002/ejlt.201600182

Trentini, C. P., Fonseca, J. M., Cardozo-Filho, L., Reis, R. R., Sampaio, S. C., & Silva, C. (2018). Assessment of continuous catalyst-free production of ethyl esters from grease trap waste. *The Journal of Supercritical Fluids*, *136*, 157-163. DOI: https://doi.org/10.1016/j.supflu.2018.02.018

Trentini, C. P., Mello, B. T. F., Cabral, V. F., & Silva, C. (2020). Crambe seed oil: Extraction and reaction with dimethyl carbonate under pressurized conditions. *The Journal of Supercritical Fluids*, *159*, 104780. DOI: https://doi.org/10.1016/j.supflu.2020.104780

Vazquez, G. H., Lazarini, E., Camargo, F. P., Ferreira, R. B., & Peres, A. R. (2014). Productivity, physiological quality and chemical composition of crambe seeds in different doses of phosphorus. *Bioscience Journal*, *30*(3), 707-714.

Von Cossel, M., Lewandowski, I., Elbersen, B., Staritsky, I., Van Eupen, M., Iqbal, Y., ... Alexopoulou, E. (2019). Marginal agricultural land low-input systems for biomass production. *Energies*, *12*(16), 1-25. DOI: https://doi.org/10.3390/en12163123

Wang, T., Hicks, K. B., & Moreau, R. (2002). Antioxidant activity of phytosterols, oryzanol, and other phytosterol conjugates. *Journal of the American Oil Chemists' Society*, *79*(12), 1201-1206 DOI: https://doi.org/10.1007/s11746-002-0628-x

Wang, Y., Zhao, M., Tang, S., Song, K., Han, X., & Ou, S. (2010). Evaluation of the oxidative stability of diacylglycerol-enriched soybean oil and palm olein under rancimat-accelerated oxidation conditions. *Journal of the American Oil Chemists' Society*, *87*(5), 483-491. DOI: https://doi.org/10.1007/s11746-009-1521-1

Winkler, J. K., & Warner, K. (2008). Effect of phytosterol structure on thermal polymerization of heated soybean oil. *European Journal of Lipid Science and Technology*, *110*(11), 1068-1077. DOI: https://doi.org/10.1002/ejlt.200800089

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. *Industrial Crops and Products*, *90*, 152–160. DOI: https://doi.org/10.1016/j.indcrop.2016.06.023