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Production costs and residues evaluation of *Crambe abyssinica* as an energy feedstock*

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ABSTRACT

In Europe, like in other parts of the world, plant species predisposed for use as energy crops are searched for. Among the oil plants grown in European countries, rape is most important although rape oil is mainly a food product. On the other hand, *Crambe abyssinica* is an oil plant species which is not used to make human food or animal feeds. Besides, *Crambe abyssinica* oil has a high content of erucic acid, hence it has the potential to be processed into many different products in the power generation or chemical industries. This paper documents results of a field experiment conducted in north-eastern Poland, at the Experimental Station of the University of Warmia and Mazury in Olsztyn, located in Łężany (53°35′ N, 20°36′ E). The aim of this experiment was to determine costs of production of *Crambe abyssinica* grown in two variants (with and without herbicides). In addition, the quality of by-products (straw and cake) as energy feedstocks was evaluated. Costs of production of *Crambe abyssinica* seeds in the variant with herbicides were nearly 140€·ha^{-1} higher than in the variant without herbicides. The yield of pure seeds was by over 110kg·ha^{-1} higher in the herbicide-treated variant than in the treatment without weed control. However, the yield of straw was higher on fields without application of herbicides, but that straw had a higher moisture content due to the presence of weeds. The lower heating value of crambe straw was 15.3MJ·kg^{-1} on average and the straw content of ash was 5.68% D.M. The cake obtained from the crop had a much higher lower heating value (21.95MJ·kg^{-1}) and ash content 6.41% D.M. Moreover, it was found to contain much more carbon and hydrogen, as well as five-fold more sulfur than straw.

INTRODUCTION

Studies aimed at identifying new energy crops have been carried out in Europe and elsewhere around the world. Of the European oil crops, rape is currently the most important, but rapeseed oil is mainly a food product. Meanwhile, crambe (*Crambe abyssinica*) is an oil plant species with no food or fodder uses. Crambe oil contains high concentrations of erucic acid, which makes it potentially useful in the power and chemical industries (Christou et al. 2013; Falasca et al. 2010; Laghetti et al. 1995). Numerous experiments have been conducted in Poland on the effect of agrotechnical factors on the yield on *Crambe abyssinica* and the composition of oil produced as a raw material to be used in chemical processing (Dembiński et al. 1962; Jabłoński 1967, 1970; Kulig et al. 1996, 1998, 2004; Mysakowska-Paleolog 1996). However, the species has not been widely cultivated in Poland due to agrotechnical problems as well as variable and lower yield compared to rape.

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Now that potential integrated biorefineries producing chemicals and fuels have shown interest in crambe oil, it seems justified to resume the research into the potential for commercial production of *Crambe abyssinica*. Therefore, the aim of this study was to determine the production cost on a production plantation of crambe in two cultivation variants (with and without herbicides) and to evaluate the quality of post-production residues (straw and cake) as feedstock for energy production.

MATERIAL AND METHODS

In spring 2012, a commercial field trial of crambe (*C. abyssinica*) was established in the north-east of Poland, at the Didactic and Research Station in Łężany (53°35' N, 20°36' E), which is a unit of the University of Warmia and Mazury in Olsztyn. The soil was prepared according to good agricultural practice. Winter triticale was used as a preceding crop. The following procedures were conducted before sowing in the spring 2012: ploughing to a 20cm depth, harrowing and cultivating (shortly before sowing). Seeds at $15 kg \cdot ha^{-1}$ were sown by drill and the inter-rows on both plantations were 12.5cm. Crambe was sown on a total area of 2ha. Chemical weed control agents were used on one plantation with an area of 1ha, whereas no chemical weed control was used on the other plantation, also with the area of 1ha.

Spraying with glyphosate at $5L \cdot ha^{-1}$ was applied before the crambe plantation was set up. Subsequently, immediately after sowing, the soil-applied herbicide Butisan Star 416 SC was applied at $2.7L \cdot ha^{-1}$. No herbicide was applied on the other crambe plantation. The same mineral fertilisation was used in both cultivation variants. Before the experiments were set up, phosphorus as triple superphosphate was sown at $40kg \cdot ha^{-1}$ P_2O_5, potassium as potassium chloride at $60kg \cdot ha^{-1}$ and K_2O and nitrogen as ammonium nitrate at $40kg \cdot ha^{-1}$. Subsequently, another dose of the same nitrogen fertiliser was applied as top dressing at $60kg \cdot ha^{-1}$.

Desiccation of the plants was performed before seeds of crambe were harvested on both plantations (Klinik 360 SL at $4L \cdot ha^{-1}$) to ensure uniform ripening of plants and the harvest was performed with a combine harvester in the second decade of August 2012.

An analysis of the cost of production of crambe seeds in both variants was based on the plantation costs, without the service provider's profit. The unit cost of using agricultural equipment was taken into account (Muzalewski 2010). Other data taken into account in the analysis included literature data, market information and the authors' assumptions regarding the efficiency of the agricultural equipment, purchase and use of fertilisers and crop protection agents, prices of the sowing material, etc. The cost of human labour was taken as the average monthly wages in agriculture (GUS 2010). Individual stages of production of crambe in the two variants are presented in Table 1.

Table 1. Cost of production of *Crambe abyssinica*, depending on the cultivation variant (€·ha⁻¹).

Specification	Chemical weed control		Without chemical control	
	$€ \cdot ha^{-1}$	%	$€ \cdot ha^{-1}$	%
Herbicide spraying (total)	45.5	5.6	0.0	0.0
Winter ploughing	55.3	6.9	55.3	8.3
Cultivator	30.5	3.8	30.5	4.6
Fertilization (P and K)	79.1	9.8	79.1	11.9
Fertilization (N)	47.9	5.9	47.9	7.2
Harrowing	17.2	2.1	17.2	2.6
Seeds and sowing	198.0	24.6	198.0	29.7
Herbicide spraying (soil-applied)	93.4	11.6	0.0	0.0
Fertilization (N)	65.6	8.1	65.6	9.8
Herbicide spraying (desiccation)	39.5	4.9	39.5	5.9
Harvesting	93.8	11.6	93.8	14.1
Transport of seeds	16.2	2.0	16.2	2.4
Agricultural tax	24.1	3.0	24.1	3.6
Total	806.1	100.0	667.2	100.0

After the harvest of crambe plants, straw samples from both plantations were taken for laboratory analyses. After the oil was pressed, the parameters of the cake were determined. Since oil was pressed jointly from the seeds from both the plantation where the protection agent had been applied and from the other plantation, this paper presents the average values of the thermophysical and chemical parameters of the cake. Samples of the straw biomass and cake were packed into plastic bags and transported to the laboratory of the Department of Plant Breeding and Seed Production of the UWM in Olsztyn. The biomass moisture content was then determined in a laboratory, with the drying and weighing method. The biomass was dried at 105±2°C until a constant mass was obtained. Next, the individual biomass samples were ground in an IKA KMF 10 basic analytic mill using a 0.25mm mesh sieve. The ash content was determined in the prepared analytical samples at a temperature of 550°C in an ELTRA TGA-THERMOSTEP automatic thermogravimetric analyser. In addition, the higher heating value of dry biomass was determined in an IKA C 2000 calorimeter using the dynamic method. The lower heating value of the fresh biomass was calculated on the basis of the higher heating value and moisture content of the biomass. The carbon, hydrogen and sulfur content were also determined by means of an ELTRA CHS 500 automatic analyser. The nitrogen content was determined with the Kjeldahl method, using a K-435 digestion unit and a B-324 BUCHI distiller. All the analyses were performed in three replications. The energy value of the straw was calculated as the product of the straw yield and its lower heating value.

The mean arithmetic values of the examined characteristics were calculated. The LSD values for the examined characteristics were determined by means of a Student test with the significance level set at $p=0.05$.

RESULTS AND DISCUSSION

The total cost of production of seeds of *C. abyssinica* when weed-control agents were applied amounted to 806.1€·ha^{-1} and was higher by nearly 140€·ha^{-1} than in the other variant (Table 1). The cost structure in both variants of the seed production was dominated by the cost of purchase and sowing of seeds (24.6% and 29.7%, respectively). Nitrogen fertilisation was another important item on the cost list, accounting for 17% in the variant with no weed control and 14% in the other variant. This was followed by the cost of harvest and the application of the soil-applied herbicide (11.6%). In the variant without weed control, harvest and phosphorus-potassium fertilisation were used.

The majority of the cost in the cost structure of crambe production were associated with the purchase of materials (seeds, fertilisers, weed control agent). They accounted for 51.2% and 55.8%, in the variants without and with chemical weed control, respectively (Figure 1). This was followed by the cost of using the tractors and machines. The cost of human labour ranged from 4.2 to 4.6%.

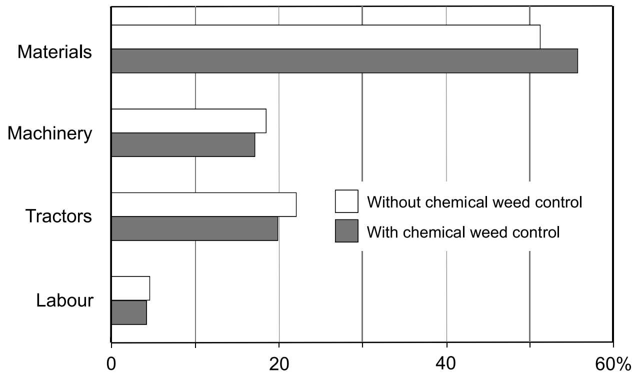

Figure 1. Structure of production costs of *Crambe abyssinica*.

The yield of seeds obtained in the harvest on the plantations ranged from 1,140 to 1,260kg·ha^{-1}, in the variants with and without chemical weed control, respectively (Table 2). Therefore, it was higher in the variant without the chemical weed control. However, the purity of seeds in this variant was only 70.6% and it was lower by 17% than in the variant with the weed control applied. For this reason, the yield of pure seeds was higher by over 110kg·ha^{-1} in the variant with the weed control than in the other variant. The moisture content in the seeds ranged from 19.78 to 23.50%. The average oil content in seeds was determined to be 26.06%. This was found to be higher (34.48%) in other studies (Wang et al. 2000). Moreover, Fontana et al. (1998) found the oil content to range from 32% to 37% depending on the season and the cultivar. However, studies conducted in Poland have shown that the oil content in seeds was variable and ranged from 29.8% to 31.6% (Kulig and Pisulewska 2000) and from 26.1% to 37.9% (Toboła and Muśnicki 1999).

It has been found in foreign studies that the yield potential of selected cultivars of crambe can be quite high, especially in a warm climate (Fontana et al. 1998). In the study cited above, the productivity of six cultivars of crambe was found to range from 2.50 to 2.91 tonnes of seeds per ha. In a study conducted in Austria by Vollmann and Ruckenbauer (1993), the yield of seeds ranged from 0.97 to 3.33tonnes·ha^{-1}. The yield in a study conducted in China ranged from 0.61 to 1.56tonnes·ha^{-1} (Wang et al. 2000), while that on a commercial plantation in the USA from 1.09 to 1.70tonnes·ha^{-1} (Glaser 1996). Studies conducted in Poland have shown that the yield of crambe is usually lower than that of spring rape, although it can sometimes be comparable. One of the studies showed how elements of the yield structure affect the yield of spring rape both protected and unprotected against pests, with various levels of nitrogen fertilisation (Budzyński and Jankowski 2003). The rapeseed yield in the studies cited above, depending on the variant, ranged from 1.38tonnes·ha^{-1} to 2.43tonnes·ha^{-1}. Furthermore, the study of the yield and chemical composition of six genotypes of crambe showed that the three-year average yield of its fruits was high and amounted to 2.40tonnes·ha^{-1} (Kulig and Pisulewska 2000). However, the yield of crambe was highly varied over the years of study. A very high yield of the fruit was recorded in 1995 (3.57tonnes·ha^{-1}, on average) and the lowest was in 1997 (1.21tonnes·ha^{-1}). In another study, the average yield of crambe fruit was shown to be 1.5tonnes·ha^{-1} and it varied depending on the amount of seeds used for sowing, ranging from 1.19 to 1.78tonnes·ha^{-1} (Kulig et al. 2004). The high variability of the yield of crambe in Poland has been confirmed by the data gathered during the 20 years of study at the Experimental Station in Przybroda (Tobola and Muśnicki 1999). The study examined the variability of yield of 8 species of spring oil plants of the Cruciferae family and assessed the fat content and other significant features. The study cited above showed a distinct variability of yield, reaction to the sieving date and the hydrothermal conditions of the critical period between the species under study. The yield of crambe was shown to be variable. The date of sowing was of particular importance because the later it was, the lower the recorded yield was. The study showed that the average multi-year yield of crambe was 1.38tonnes·ha^{-1} and it ranged from 0.31 to 3.04tonnes·ha^{-1}.

The yield of straw in this study was higher in the variant where no weed control was applied (2.86tonnes·ha^{-1}), but the moisture content in the straw was higher (17.56%) due to a higher content of weeds (Table 2, 3). The average higher heating value of crambe straw was 18.65MJ·kg^{-1} D.M. (Table 3). However, when moisture content was taken into account, the lower heating value was calculated to be average 15.30MJ·kg^{-1} and it was higher in straw from the field where chemical weed control was applied (15.64MJ·kg^{-1}). The energy value of the straw obtained in the cultivation in which chemical weed control was applied was 37GJ·ha^{-1} and it was lower by 13.5% than the energy value of the straw obtained in cultivation without using the chemical weed control agents. The study conducted by Jankowski and Budzyński (2004) showed that the calorific value of straw of *C. abyssinica* was close to the findings recorded in this study and was close to 40.8GJ·ha^{-1}; it was slightly higher than the calorific value of straw of spring camelina (*Camelina sativa*), although the calorific value of the whole yield (seeds and straw) of camelina in the study cited above was higher than that of *C. abyssinica*.

Table 2. Yield, purity, moisture and oil content in crambe seeds and yield and energy value of straw.

Item	Yield of seeds on the field [kg·ha^{-1}]	Seeds purity [%]	Yield of pure seeds [kg·ha^{-1}]	Moisture content [%]	Oil content [% D.M.]	Yield of straw on the field [kg·ha^{-1}]	Energy value of straw on the field [GJ·ha^{-1}]
Chemical weed control	1,140.0	87.90	1,002.06	19.78	25.66	2,365.0	37.00
Without chemical control	1,260.0	70.60	889.56	23.50	26.46	2,860.0	42.78
Average	1,200.0	79.25	945.81	21.64	26.06	2,612.5	39.97
$LSD_{0.05}$	ns	3.56	52.45	2.24	ns	ns	ns

ns = not significant

The average ash content in straw was 5.68% D.M. The straw obtained in cultivation of crambe with chemical weed control contained more carbon, hydrogen and sulfur, and less nitrogen. On the other hand, cake was characterised by higher higher heating value and higher lower heating value (21.95MJ·kg^{-1}) and higher content of ash (6.41% D.M.) compared to straw (Table 3). Moreover, cake was found to contain more carbon and hydrogen and nearly 5 times more sulfur than straw. The thermophysical properties of cake and straw of *Crambe abyssinica* are comparable to those of other oil plants. It was found in other studies that rapeseed cake was characterised by a significantly higher lower and higher heating value and higher ash content compared to rape straw. Also, the content of the main elements under study was higher in cake than in straw. The higher heating value and the lower heating value of crambe residues, especially cake, make it a material with a high energy value compared to other sources of solid biomass. However, the high content of undesirable elements, i.e. much higher content of ash and sulfur than in straw of cereals, energy grass (e.g. *Miscanthus giganteus*) or wood of short rotation coppices (Stolarski et al. 2013), can be a problem in its use.

In summary, the cost of production of seeds of *C. abyssinica* in the variant with weed control amounted to 806.1€·ha^{-1} and it was higher by 140€·ha^{-1} than in the variant without the weed control. The yield of pure seeds was higher by over 110kg·ha^{-1} in the variant with weed control than in the variant without. On the other hand, the yield of straw in the variant without weed control was higher, but the moisture content in the straw was higher due to a higher mass of weeds. The average lower heating value of straw was 15.3MJ·kg^{-1} and the ash content was

Table 3. Characteristics of crambe straw and cake.

Item	Straw			Cake	$LSD_{0.05}$
	Chemical weed control	Without chemical control	Average		
Moisture content [%]	14.24	17.56	15.90	7.16	1.98
Higher heating value [$MJ \cdot kg^{-1}$ D.M.]	18.65	18.66	18.65	23.83	1.74
Lower heating value [$MJ \cdot kg^{-1}$]	15.64	14.96	15.30	21.95	1.52
Ash content [% D.M.]	5.93	5.42	5.68	6.41	1.12
Volatile matter [% D.M.]	73.35	73.36	73.36	75.39	0.98
Fixed carbon [% D.M.]	17.48	17.90	17.69	16.51	ns
N [% D.M.]	6.53	6.99	6.76	3.82	1.82
C [% D.M.]	48.24	47.20	47.72	53.85	1.67
H [% D.M.]	4.99	4.83	4.91	7.21	1.31
S [% D.M.]	0.203	0.173	0.188	0.918	0.123

ns = not significant

5.68% D.M. The energy value of the straw obtained in the variant with chemical weed control was $37 GJ \cdot ha^{-1}$ and it was lower by 13.5% than the energy value of straw obtained in the variant without chemical weed control. The cake was characterised by a much higher lower heating value, a higher content of ash, carbon and hydrogen and nearly a 5-fold higher content of sulfur compared to straw.

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