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Life cycle assessment of *Crambe abyssinica* production for an integrated multi-product biorefinery

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ABSTRACT

For decades, energy and chemical industry markets have been dominated by resources acquired from fossil fuels. The resources are steadily shrinking and access to them is becoming increasingly difficult. Therefore, alternative methods of producing fuels or chemicals from renewable sources are being sought. The crambe (*Crambe abyssinica*) is an oil plant with a high content of erucic acid, regarded as a feedstock for integrated biorefineries. Production of fuels or chemicals from biomass should be conducted in a sustainable way. Therefore, the aim of the study was to use the life cycle assessment method to determine the impact on the environment of the production of crambe compared to spring rape. The results showed that spring rape affected the environment more strongly in 9 out of 10 impact categories by the CML 2000 baseline method, considering the impact per 1ha. The cultivation of crambe with (Crambe II) and without herbicides (Crambe I) had the greatest impact in the category of terrestrial ecotoxicity. When an impact per 1kg of seeds was considered, it was noted that spring rape had a greater effect only in 1 out of 10 effect categories – human toxicity. The differences were associated with a much lower yield of crambe obtained in the experiment compared to spring rape. In conclusion, the environmental impact of the "weak links" in the crambe production, mineral fertilisation and a low yield, should be minimised.

INTRODUCTION

For decades, the fuel, energy and chemical industry markets have been dominated by resources acquired from fossil fuels. These resources are steadily shrinking and access to them is becoming increasingly difficult, both for financial and technological reasons. Global energy consumption is growing despite the many programs which impose obligations to increase the energy efficiency (IEA 2012). It is also a serious problem for many countries, including Poland, that they are dependent on supplies of fossil fuels from abroad (Eurostat 2012), which may bring on instability of energy prices on their market and attempts at "energy blackmail". Moreover, the use of such fuels should be limited because of the global warming. One of the reasons for global warming is the emission of greenhouse gases, produced inter alia by the use of fossil fuels. Global warming and the increase in greenhouse gas emission are closely associated with industrial processes and the common use of fossil fuels. Therefore, alternative methods of generating energy, producing fuels or chemicals from renewable sources are being sought.

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One such material is biomass, which has long been regarded as a fuel of the poor, used only in low-efficiency energy generation. The global resources of biomass for energy purposes are estimated to be between 350 and as much as 2900EJ·year^{-1} (Fischer and Schrattenholzer 2001; Rosillo Calle 2007). The efforts aimed at using the renewable energy sources in modern conversion technologies have been increasing every year. Studies have been conducted not only on using biomass as the primary or secondary fuel, but also as a component of complex chemicals with a high market value (Liu et al. 2012).

Oil plants with a high content of erucic acid are regarded as one of the feedstocks used in modern integrated biorefineries. The crambe (*Crambe abyssinica* Hochst. ex R.E. Fries) is an oil plant from the Brassicaceae family. The yield of seeds may range from 1.2 to 3.2tonnes·ha^{-1} and depends on the climate. The oil content in seeds ranges from 31% to 37%, with erucic acid accounting for more than 54% (Kulig and Pisulewska 2000; Laghetti et al. 1995; Lazzeri et al. 1994). Crambe oil can be used in the production of biodiesel, lubricants, rubber additives, nylon, base for paints and coatings, high temperature hydraulic fluids, waxes and other products (Falasca et al. 2010; Wang et al. 2000).

Production of fuels, energy and chemicals from energy biomass should be carried out in a sustainable manner with as minimal an impact on the environment as possible. The life cycle assessment is a tool used to investigate or compare the impact of industrially used plants (or any other product) on the environment. According to the ISO 14040 standard, life cycle assessment is a compilation and evaluation of the inputs, outputs and the potential environmental impact of a production system throughout its life cycle (ISO 2006a). Owing to the method, it will be possible to assess the full impact of the means of production, machines, devices and energy on the environment during the crambe production process. As oil obtained from the plant seeds is to be a substitute for fossil fuels, it is important to determine its impact on the environment, and to compare it to the requirements set before renewable energy sources. Therefore, the aim of the study was to determine, by the life cycle assessment (LCA) method, the impact on the environment of the production process of the crambe, cultivated for use by an integrated biorefinery.

MATERIAL AND METHODS

The impact of crambe production on the environment was examined based on the standards: EN ISO 14040 (ISO 2006a) and EN ISO 14044 (ISO 2006b). The environmental analysis was performed with SimaPro 7.3.2. software issued by PreConsultants.

Description and location of the crambe plantation

The crambe plantation was set up near the village of Samławki (53°35' N, 20°36' E) at the Didactic and Research Station in Łężany, owned by the University of Warmia and Mazury in Olsztyn (UWM). The experiment was set up on brown soil formed from medium loam on the substrate of slightly-loamy sand. It is classified as soil class IVa and as defective wheat complex. Plants were sown in the first week of May 2012 on two plots with the area of 1ha each, at 15kg of seeds per hectare. No herbicides were used on the first plot (Crambe I), whereas they were used on the second (Crambe II). No fungicides or insecticides were used in the experiment. The aim of the procedure was to minimise the environmental impact of the production of crambe which was to be used by an integrated refinery. In August, desiccation was performed on both plots in order to ensure uniform ripening of the plants. Crambe fruits (seeds) were harvested in one stage, in the last week of August, with a New Holland TC 56 combine harvester.

The LCA methodology

Definition of the goal and scope

The aim of the study was to perform a simplified, comparative life cycle assessment for the production process of the crambe in two variants of production, compared to the cultivation of spring rape. Moreover, the aim of the study was to identify the stages with the most negative impact on the environment, to minimise them in the future.

Functional unit

The impact of the cultivation system on the area of 1ha was the functional unit adopted in the study. However, due to a different yield of seeds, which can be obtained from the same area of cultivation of crambe and spring rape, a different functional unit was also used in the study – 1kg of seeds of the cultivated plants.

System description

The production process to the farm gate was taken as the impact examination study area. The study system was to include (depending on the cultivation technology) preparation of the plot, acquisition of the seeding material, sowing, cultivation measures, plant protection measures, desiccation, single-stage harvest and seed transport to the warehouse situated 5km away (Figure 1). The study took into account the effect of emissions from the production of the herbicides, fertilisers and the emissions associated with using fertilisers in the cultivation procedures. It did not include the CO_2 balance associated with sequestration and the emission of soil organic carbon. On the other hand, the study took into account the impact of the emissions from the machines used in the production process.

The first system examined in the study was the cultivation of the crambe (Crambe I). The system included the production of seeds with no herbicides. The crambe straw was ploughed into the field. In the second system of crambe cultivation (Crambe II), a herbicide was used twice to protect the plants against weed. The straw after harvest was also left in the field. The third system included in the life cycle assessment was the cultivation of spring rape (rape). This was chosen as the reference plant because of the well-mastered production technology in the conditions prevalent in Poland and because of

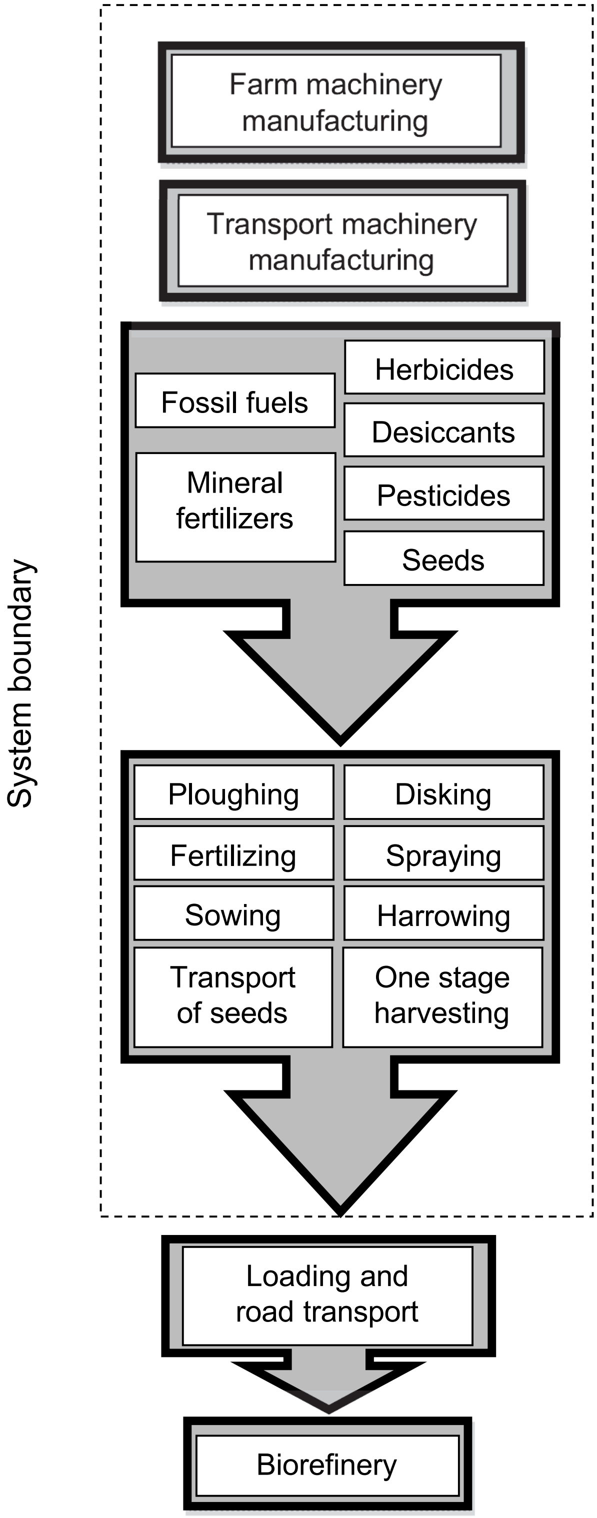

Figure 1. System boundaries and input of the Crambe I, Crambe II and spring rapeseed production.

its common cultivation. Another reason is its stable yield, high price on the market and farmers' willingness to grow it. The production of spring rape involved the use of herbicides, fungicides and pesticides as in a typical system of rape production. It was assumed in the study that the straw was ploughed into the field.

Table 1. Inventory table of the processes of crambe production in the "no herbicides" variant (Crambe I).

Specification	**Means of production**	**Diesel fuel** (L·ha^{-1})
Winter ploughing	Diesel	20
Cultivating	Diesel	13
Fertilization (P and K)	P_2O_5 40kg·ha^{-1} triple superphosphate, K_2O 60kg·ha^{-1} potassium chloride, diesel	5
Fertilization (N)	N- 40+60kg·ha^{-1} ammonium nitrate, diesel	10
Harrowing	Diesel	8
Sowing	Seeds 15kg·ha^{-1}, diesel	15
Desiccant spraying	Klinik 360 SL Glyphosate, 4L·ha^{-1} , diesel	4
Harvesting	Diesel	20
Seeds transport on field and to store	Diesel	10t·km*

*units in tonne·kilometer

Table 2. Inventory table of the processes of crambe production in the "herbicides" variant (Crambe II).

Specification	**Means of production**	**Diesel fuel** (L·ha^{-1})
Herbicide spraying	Roundup 360 SL glyphosate, (N-(Phosphonomethyl) glycine) 5L·ha^{-1}, diesel	4
Winter ploughing	Diesel	20
Cultivator	Diesel	13
Fertilization (P and K)	P_2O_5 40kg·ha^{-1} triple superphosphate, K_2O 60kg·ha^{-1} potassium chloride, diesel	5
Fertilization (N)	N- 40+60kg·ha^{-1} ammonium nitrate, diesel	10
Harrowing	Diesel	8
Sowing	Seeds 15kg·ha^{-1}, diesel	15
Herbicide spraying	Butisan star 416 SC (metazachlor+quinmerac) 2.7L·ha^{-1}, diesel	4
Desiccant spraying	Klinik 360 SL Glyphosate, (N-(Phosphonomethyl) glycine) 4L·ha^{-1}, diesel	4
Harvesting	Diesel	20
Seeds transport on field and to store	Diesel	10t·km*

*units in tonne·kilometer

All the inputs and products included in these systems of production were included in the inventory analysis, which covered gathering data and the computational procedures aimed at the quantitative evaluation of significant inputs to the plant cultivation system. The data for these cultivation systems were gathered from this experiment, from the EcoInvent database, literature, estimated values and surveys. The data for the crambe production in variant I and II are shown in Table 1 and Table 2, while the data for spring rape are shown in Table 3. The crambe seed yield from this experiment was taken as the basic yield for the life cycle assessment. Data for the spring rape plantation were based on those from the Warmia and Mazury Centre for Agricultural Consulting.

Emissions from the nitrogen and phosphorus fertilisers

According to IPCC (IPCC 2007), nitrous oxide emission may range from 0.25% to 2.25% of the nitrogen contained in the fertiliser which has been applied. The recommended default value is 1.25%. However, according to the findings of some studies, emission of the gas may be even several times higher than that recommended by IPCC (Crutzen et al. 2008). Therefore, in order to avoid its underestimation, the upper value of 2.25%$N_2O \cdot kg^{-1}N$ from a mineral nitrogen fertiliser was taken for the study. The emission of ammonia to the atmosphere from the nitrogen fertiliser used in the study was taken from an ECETOC report (ECETOC 1994), where the average emission amounts to 2.00%$NH_3 \cdot kg^{-1}N$. Emission of nitrates caused by leaching nitrogen out of mineral fertilisers was taken to be 14% $NO_3^- \cdot kg^{-1}N$, and leaching out phosphates as 1% $PO_4^{2-} \cdot kg^{-1}N$ (Iriarte et al. 2010).

Life cycle impact assessment

The stage of the life cycle impact assessment for the willow coppice was determined by the CML 2000 baseline method, in which the following categories of environmental impact are identified: depletion of fossil fuel resources, acidification, eutrophication, global warming, ozone layer depletion, human toxicity, aquatic (freshwater) ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, photochemical oxidation. After entering the inputs and outputs to the SimaPro 7.3.2 program (classification), calculations were made of the environmental impact (characterisation) for above mentioned categories.

RESULTS AND DISCUSSION

A comparative analysis of the life cycle assessment with the functional unit of 1ha has shown that cultivation of spring rape has the most negative environmental impact in 9 out of 10 categories (Figure 2).

Table 3. Inventory table of the processes of spring rape production (Rape).

Specification	Means of production	Diesel fuel ($L \cdot ha^{-1}$)
Plough skimming with harrowing	Diesel	13.8
Fertilization PK	P_2O_5 60kg·ha^{-1} triple superphosphate, K2O 100kg·ha^{-1} potassium chloride, diesel	5.0
Winter ploughing	Diesel	21.6
Cultivating (pre-sowing tillage)	Diesel	15.3
Sowing	Seeds 3kg·ha^{-1}, diesel	19.7
Fertilization N	N- 100kg·ha^{-1} ammonium nitrate, diesel	5.0
Spraying	Metaz 500 S.C. 2L·ha^{-1}, diesel	2.4
	Alert 375 S.C. 1L·ha^{-1}, diesel	2.4
	Fury 100 EW 0.6L·ha^{-1}, diesel	2.4
	Diazinon 10 GR 10kg·ha^{-1}, diesel	2.4
	Nu-Film 96 EC 2L·ha^{-1}, diesel	2.4
Transport	Diesel	15t·km*
Harvesting	Diesel	20.0

*units in tonne·kilometer

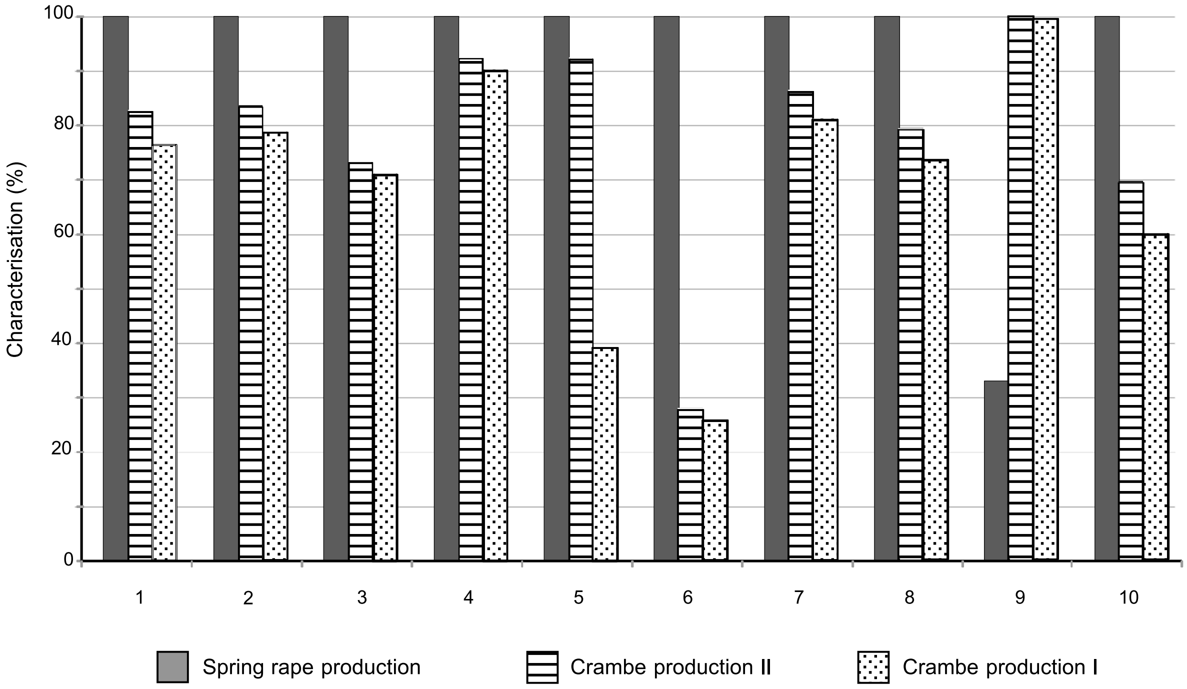

Figure 2. Characterisation results of comparative life cycle impact assessment for the three cultivation systems under study. Functional unit, area of 1ha. 1-abiotic depletion, 2-acidification, 3-eutrophication, 4-global warming (GWP 100), 5-ozone layer depletion (ODP), 6-human toxicity, 7-freshwater aquatic ecotoxicity, 8-marine aquatic ecotoxicity, 9-terrestrial ecotoxicity, 10-photochemical oxidation.

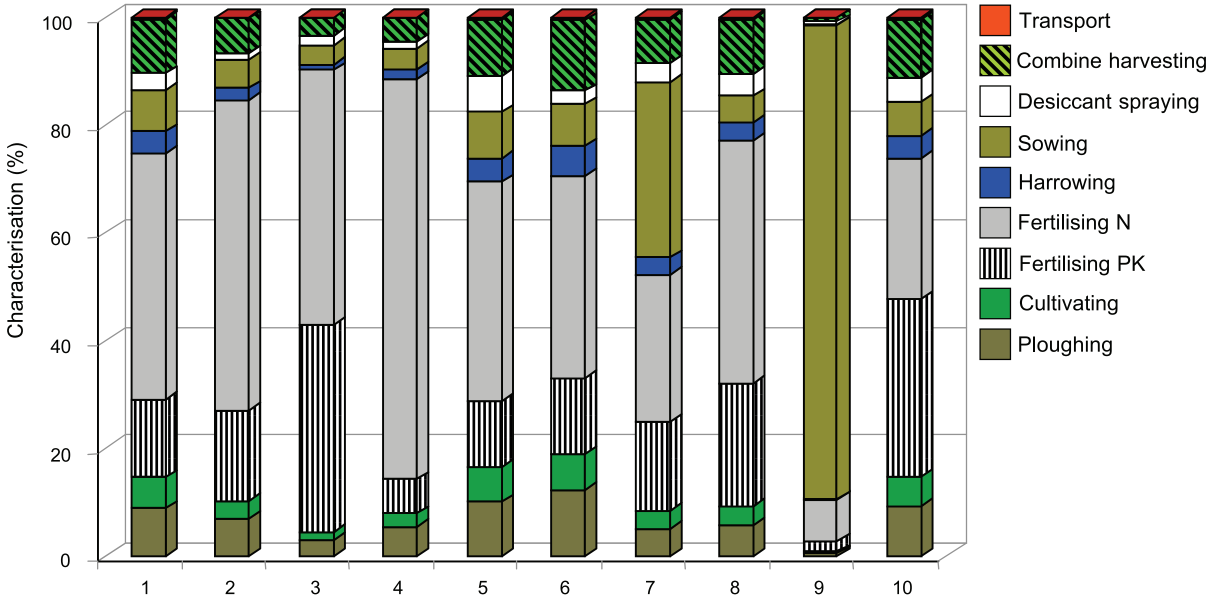

Figure 3. Results of the characterisation of the Crambe I cultivation system. 1-abiotic depletion, 2-acidification, 3-eutrophication, 4-global warming (GWP 100), 5-ozone layer depletion (ODP), 6-human toxicity, 7-freshwater aquatic ecotoxicity, 8-marine aquatic ecotoxicity, 9-terrestrial ecotoxicity, 10-photochemical oxidation.

The impact of the crambe in variant II was lower by 8% in the global warming and ozone layer depletion categories and up to 72% in the human toxicity category. On the other hand, the environmental impact of crambe cultivation in variant I was lower than that of rape cultivation (by 10% in the global warming category and up to 74% in the human toxicity category). The higher values of the impact category indexes were closely connected with using larger amounts of the means of production in the rape cultivation system. Only in the terrestrial ecotoxicity category did cultivation in variant I and II exceed the environmental impact of spring rape, by 66% and 67%, respectively. A larger impact in this category was associated with the amount of the seeding material used for sowing: 3kg·ha^{-1} for rape and 15kg·ha^{-1} for crambe.

Figure 3 shows the results of characterisation of crambe in the Crambe I cultivation system. One can note the highest environmental impact of production and using nitrogen fertilisers in 7 out of 10 categories (from 41% for ozone layer depletion do 74% for global warming). Seed production and sowing had a considerable impact on the freshwater aquatic ecotoxicity category (33% of the total impact on the environment) and terrestrial ecotoxicity (as much as 88%). Such a high impact may be caused by adopting the crambe seed production data based on the conventional production of rapeseed. This may also be affected by a larger sowing dose than for rapeseed. When totalled, the use of all the mineral fertilisers (NPK) had a dominant impact in 9 out of 10 categories. Their impact in the characterisation stage ranged from 44% in the freshwater aquatic ecotoxicity category to 86% for eutrophication. The production and use of mineral fertilisers also had a high impact on global warming (80% of all processes) and acidification (74%).

Nitrogen fertilisation in the Crambe II cultivation system also dominated in the majority (six) of the impact categories (Figure 4). As in the Crambe I cultivation system, the largest impact of fertilisation in the characterisation stage was recorded in the global warming category (72%). The LCA results also showed all mineral fertilisers (NPK) dominated in 8 categories of impact. The process of seed production and sowing had very high influence on terrestrial ecotoxicity and it accounted for up to 87% of the environmental impact. On the other hand, the use of a herbicide containing metazachlor had a significant impact (54%) on the ozone layer depletion (herbicide 2).

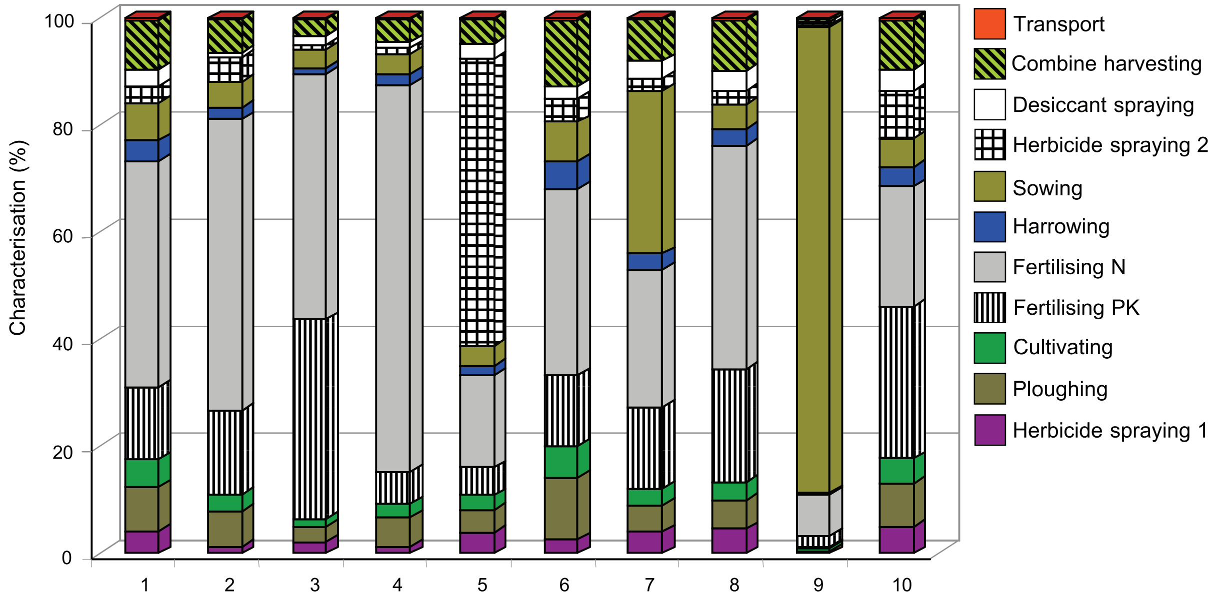

Figure 4. Results of the characterisation of the Crambe II cultivation system. 1-abiotic depletion, 2-acidification, 3-eutrophication, 4-global warming (GWP 100), 5-ozone layer depletion (ODP), 6-human toxicity, 7-freshwater aquatic ecotoxicity, 8-marine aquatic ecotoxicity, 9-terrestrial ecotoxicity, 10-photochemical oxidation.

In the reference system of cultivation, i.e. rape, nitrogen fertilisation had the highest negative impact in 6 out of 10 categories (from 22% for freshwater aquatic ecotoxicity to 67% for global warming), and all the fertilisers (including phosphorus and nitrogen ones) in 8 categories (Figure 5). However, the percentage for this process was lower than for the Crambe I and Crambe II systems. This was caused by a larger number of processes (inputs) in rape production, e.g. use of pesticides, fungicides and a larger number of agri-technology measures.

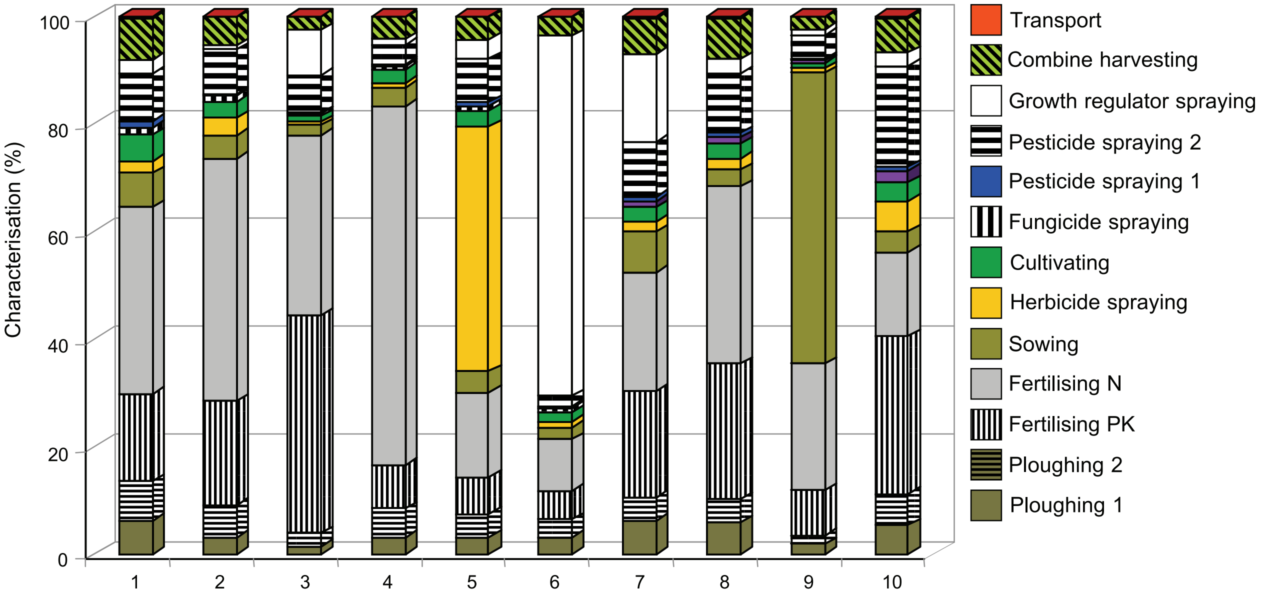

Figure 5. Results of characterisation of the spring rape cultivation system. 1-abiotic depletion, 2-acidification, 3-eutrophication, 4-global warming (GWP 100), 5-ozone layer depletion (ODP), 6-human toxicity, 7-freshwater aquatic ecotoxicity, 8-marine aquatic ecotoxicity, 9-terrestrial ecotoxicity, 10-photochemical oxidation.

The high environmental impact of mineral fertilisation has also been observed in other studies of the life cycle assessment. Iriarte et al. (2010) report that mineral fertilisation in rape and sunflower cultivation causes the highest environmental impact. Moreover, another Spanish study on the cultivation of the oil plant *Brassica carinata* has

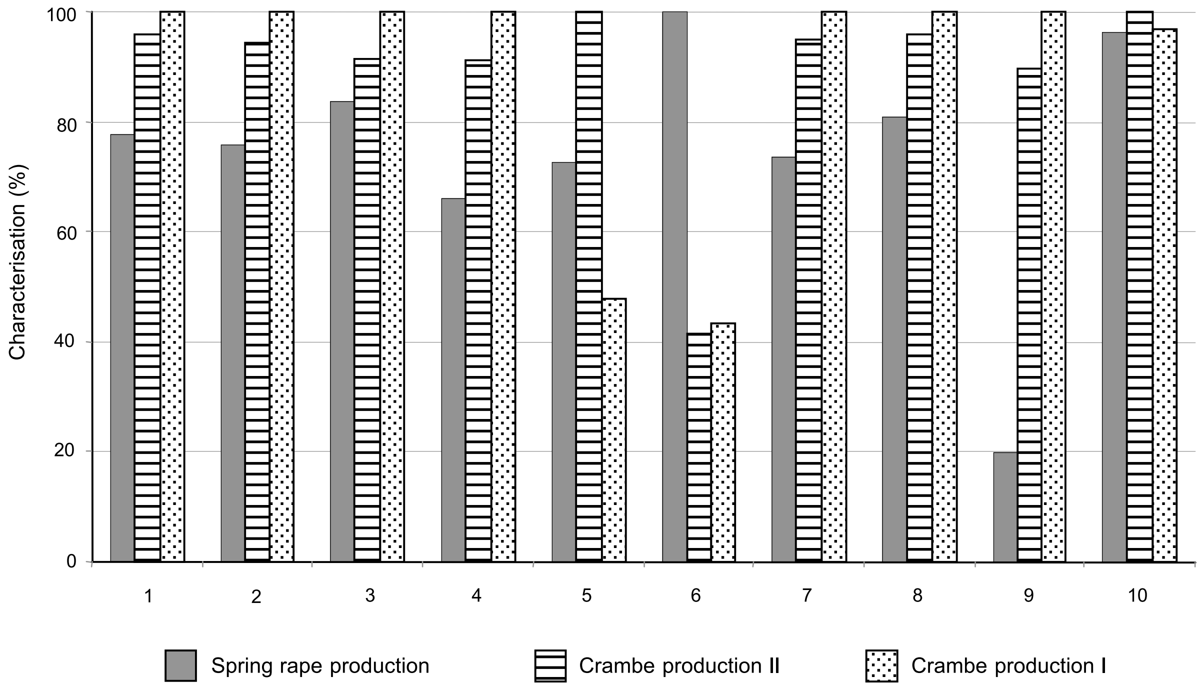

Figure 6. Characterisation results of the life cycle assessment of the three cultivation systems under study. Functional unit, 1kg of seeds. 1-abiotic depletion, 2-acidification, 3-eutrophication, 4-global warming (GWP 100), 5-ozone layer depletion (ODP), 6-human toxicity, 7-freshwater aquatic ecotoxicity, 8-marine aquatic ecotoxicity, 9-terrestrial ecotoxicity, 10-photochemical oxidation.

shown that the use of fertilisers had the highest impact in 6 out of 10 categories of impact by the CML 2000 baseline method (Gasol et al. 2012). The study on the life cycle assessment in short rotation coppice cultivation for energy generation, conducted by these authors, also showed the dominant environmental impact of the use of mineral fertilisers. In willow coppice cultivation in an annual harvest cycle, the process dominated in all 10 categories of the impact of the CML 2000 baseline method (from 41% to 93%), and in 9 out of 10 categories in a triennial harvest cycle (85% to 22%) (Krzyżaniak et al. 2013). It should be emphasised that mineral fertilisation is responsible for the highest emission of greenhouse gas in this and in other studies (Bernesson et al. 2004; Gasol et al. 2007; Iriarte et al. 2010).

The findings on the environmental impact of the systems of crambe and rape cultivation differed when the functional unit was changed from 1ha to 1kg of seeds obtained in the process (Figure 6). Here, the Crambe I cultivation system had the highest environmental impact in 7 categories The Crambe II cultivation system dominated in two categories of impact, whereas cultivation of spring rape dominated only in human toxicity.

The difference in the results of the life cycle assessment, with the functional unit of 1kg of seeds, is caused by a much lower yield of crambe obtained in this study. The yield of seeds in the Crambe I cultivation system was 0.89tonnes·ha^{-1} of seeds and in the Crambe II cultivation system it was 1.00tonne·ha^{-1}, it was assumed that the yield of spring rapeseed was 1.50tonnes·ha^{-1}. An over 30% difference in the yield in the Crambe II system and over 40% difference in the Crambe I results in a considerable burden on the environment when converted to this functional unit. However, the crambe yield obtained in this study should be regarded as low. The yield potential of the crambe in Poland could be as high as 1.80tonnes·ha^{-1} (Kulig and Pisulewska 2000). The plant production process should probably be intensified by applying higher doses of fertilisers, more plant protection measures, by the choice of higher class soil or the selection of a region where the climatic requirements of the plant are met. In that case, the crambe could be an attractive crop for biorefineries because it provides desirable erucic acid; for farmers, it would be an alternative to spring rape and it would also be good for the environment because its impact could be lower than that of traditional oil plants. However, the environmental impact of the “weak links” in the crambe production, mineral fertilisation and a low yield, should be minimised.

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