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Prospects of crambe for the bioeconomy of the Swabian Alb in southwest Germany

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A R T I C L E I N F O

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A B S T R A C T

Crambe (*Crambe abyssinica* Hochst. ex R.E.Fr.) is a drought-tolerant, non-edible annual oil crop with low fertilization needs, and there are compelling opportunities for crambe to capitalize on market growth in natural cosmetics and the regional sustainability. It is therefore proposed for cleaner biomass production on marginal land, and the development of novel value chains and webs in rural areas. Therefore, this study assesses the prospects for growing and processing crambe in the Swabian Alb, a rural area in southwestern Germany large parts of which are characterized by marginal shallow stony soil. A literature review, stakeholder questionnaires, and a SWOT analysis were used to assess crambe's potential in the region. This informed a locally adapted value web, which combines multiple value chains and stakeholders into one interlinked diagram showing present potential valorization opportunities for crambe in the region. However, it was found that it is not currently possible to implement a value web for crambe in the Swabian Alb. Instead, a single value chain involving farmers, cosmetics companies, and biogas plants is possible. To expand this value chain opportunity into a value web, more information is needed for all stakeholders. European Innovation Action projects could help by providing more information about crambe cultivation and by ensuring ecologic and social sustainability. Economic sustainability, however, will require the involvement of other stakeholders in the value web, so that supply matches demand. Local institutions and networks can share knowledge to grow the currently possible value chain into a broader value web. This approach could also be used in other regions to assess the sustainability of novel biobased value chains across social, economic, and environmental dimensions.

1. Introduction

Humanity is unequivocally experiencing disruptions from anthropogenic climate change (Pörtner et al., 2022). Rising temperatures, altered precipitation cycles, and extreme events affect agriculture (Pörtner et al., 2022). Parallel to these environmental hardships, the population is increasing; demographers anticipate the world's population will exceed 9,700,000,000 in 2050 (United Nations Department of Economic and Social Affairs). In light of these challenges affecting both supply and demand of biomass, it is imperative that global societies optimize biomass production and use without limiting the ability of future generations to create and consume (Fritsche et al., 2020; Marting Vidaurre et al., 2020; Panoutsou et al., 2022). Indeed, sustainability, described by the United Nations (UN) as "*meeting the needs of the present without compromising the ability of future generations to meet their own needs*", is critical to solving these interlocking crises (World Commission on Environment and Development, 1987). Hence, beyond maximizing profits, sustainability works across economic, social, and ecologic dimensions (Fritsche et al., 2020; Kleine and von Hauff, 2009) and needs careful consideration by policy makers (Clifton-Brown et al., 2023; Panoutsou et al., 2021).

Against this backdrop, the bioeconomy framework (Fritsche et al.,

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2020; Lewandowski, 2018) is helpful for considering sustainable biomass flows that not only aim at meeting economic demands but also ensuring that social-ecological challenges are dealt with in a positive way (Marting Vidaurre et al., 2020; Von Cossel et al., 2019a). The bioeconomy is defined as "*the production, utilization, conservation, and regeneration of biological resources, including related knowledge, science, technology, and innovation, to provide sustainable solutions (information, products, processes and services) within and across all economic sectors and enable a transformation to a sustainable economy*" (Teitelbaum et al., 2020, p. 9). Thus, sustainability in its broader sense (economic, social and ecological) is core to the idea of the bioeconomy; some biobased resources are produced and used while others are conserved and regenerated (Von Cossel et al., 2019b). Furthermore, the bioeconomy, combined with circular economic principles (Romero-Perdomo et al., 2022; Stahel, 2016) and cascading use of sustainably produced biomasses (Keegan et al., 2013), can help advance climate change adaptation and mitigation (European Commission Directorate-General for Research and Innovation, 2019; Pörtner et al., 2022).

The European bioeconomy is already a growth engine, providing about 9% of jobs in the European Union's 27 (EU-27) member countries and about 4.7% of the EU-27's Gross Domestic Product (Fritsche et al., 2020). However, further research and innovation are needed to meet the ambitious climate targets of the European Union (EU). In this course, Horizon Europe, an EU research and innovation funding program, dedicates about ten billion euros over six years towards studies on bioeconomy, food, and natural resources (European Commission Directorate-General for Research and Innovation, 2023). One of the projects already funded under Horizon Europe is the MIDAS project ('Utilization of Marginal lands for growing sustainable industrial crops and developing innovative bio-based products'; Grant Agreement Number: 101082070) (Alexopoulou et al., 2023; MIDAS, 2023), part of which laid the groundwork for this study.

1.1. Biodiversity-friendly and climate-resilient non-edible crop cultivation on marginal land

The McKinsey Global Institute (New York City, New York, United Stated of America) estimates that "*as much as 60 percent of the physical inputs to the global economy could, in principle, be produced biologically*" (Chui et al., 2020). However, agricultural systems are increasingly exposed to the negative effects of biodiversity loss (Altieri, 1999; Gascuel-Odoux et al., 2022; Tscharntke et al., 2005) and climate change impacts (Pörtner et al., 2022). Other studies therefore outline the importance of additional ecosystem services than providing physical input (biomass) such as climate regulation, water purification, flood control, and habitat functioning (de Groot et al., 2012; Power, 2010; Von Cossel et al., 2020) as well as avoiding land use conflicts with food crop cultivation (Von Cossel et al., 2019b). Therefore, MIDAS promotes the use of marginal land for the biodiversity-friendly and climate-resilient cultivation of non-edible industrial crops and the development of innovative bio-based products (Alexopoulou et al., 2023; European Commission, 2022; MIDAS, 2023) by building on the results of both previous and ongoing projects (BECOOL, 2023; BeonNAT, 2023; BIKE, 2023; FIBRA, 2015; FIRST2RUN, 2019; FORBIO, 2018; GOLD, 2023; GRACE, 2023; LIBBIO, 2021; MAGIC, 2021; MULTIHEMP, 2017; OPTIMISC, 2016; PANACEA, 2021; SEEMLA, 2018; SUNLIBB, 2014). MIDAS, therefore, seeks to leverage marginal land, non-edible industrial crops, novel biodiversity-friendly cropping systems, and biobased products to support the European bioeconomy to build innovative value chain and webs while including social and interdisciplinary approaches "*to work with farmers and for farmers*" (Alexopoulou et al., 2023; MIDAS, 2023).

Dedicated to this purpose, MIDAS conducts large-scale field trials (hereafter referred to as "field trials") on marginal land in Central and Southern Europe and works closely with regional advisory groups composed of farmers and other potential stakeholders. One of these field trials is located in the German Swabian Alb region and is being supervised by researchers from the University of Hohenheim (UHOH, 2023). Here, UHOH is working to (i) increase the technological readiness level of different value chain components derived from a novel strip cropping system using annual and perennial non-edible crops, and (ii) to communicate the results and findings to local stakeholders based on the regional advisory groups and beyond (Alexopoulou et al., 2023; MIDAS, 2023). In addition, UHOH seeks to gain insights into the potential social-ecological benefits of this novel cropping system, with a particular focus on the promotion of biodiversity.

Vegetable oils are required in particular due to their good usability for different applications (Cavalheiro et al., 2023; Pawar et al., 2022), of which many, such as cosmetics or special chemicals, are in the high-value sectors (Alexopoulou et al., 2023; MIDAS, 2023). However, these are scarce and expensive compared to starch, sugar, or lignocellulose. Therefore, this study focuses on the annual oil-delivering crop crambe. For crambe, many unanswered questions arose early on regarding its suitability for large-scale cultivation in the Swabian Alb region (Reinhardt et al., 2022), from which the research questions for this study were derived as follows.

1.2. Research question and relevance of the work

The goal of this research is to assess the prospects of crambe grown and processed in the Swabian Alb region, Southwest Germany (Fig. 1). In the MIDAS project, agronomic innovations are combined with industrial and social goals including value network mapping (in the following referred to as 'value web mapping'). Value web mapping should enable (i) strategic pivots and targeted policies that support sustainable agricultural development, and (ii) a better utilization of the potential of farmers and the industry (Dentoni et al., 2022). Key friction and traction points can be uncovered, and resources can be more efficiently used and shared. Therefore, this research aimed at mapping the value web of crambe, thereby providing regional and social contexts relevant to crambe growth and conversion into economically valuable products in the Swabian Alb.

2. Method

For the field trial, a randomized block design with 12 m by 30 m plots (four replicates) was used. Each block consists of a total of four plots, with one plot on the far left or far right (random selection) of the block planted with miscanthus (*Miscanthus* × *giganteus* Greef et Deuter), while the other three plots per block were assigned three non-edible annual industrial crops grown in crop rotation (Fig. 1). These annual crops are crambe (*Crambe abyssinica* Hochst. ex R.E.Fr.), fiber hemp (*Cannabis sativa* L. var. FUTURA 83) (Hempoint, 2022), and yellow melilot (*Melilotus officinalis* L.).

To achieve this study's main goal, a value web for crambe produced and processed was informed by a literature review, an open-ended questionnaire for stakeholders, and a strengths, weaknesses, opportunities, and threats (SWOT) analysis.

Biomass production from crambe, the initial step of the crambe value generation process, involves many other stakeholders in using and valorizing crambe resources. Generally, complicated relationships exist between those providing biomass (primary producers) and those using it (intermediate producers and consumers). The idea of a value chain, pioneered by Michael Porter in the 1980s, helps conceptualizing the interdependencies between actors, processes, and products from cultivation to consumption. Kaplinsky and Morris (2001) describe a value chain as "*the full range of activities which are required to bring a product or service from conception, through the different phases of production (…), delivery to final consumers, and final disposal after use*."

In an agricultural context, the value chain development for a crop like crambe includes provisioning inputs (seeds, fertilizers, crop protection products, fuel and machinery); drying, milling, or processing

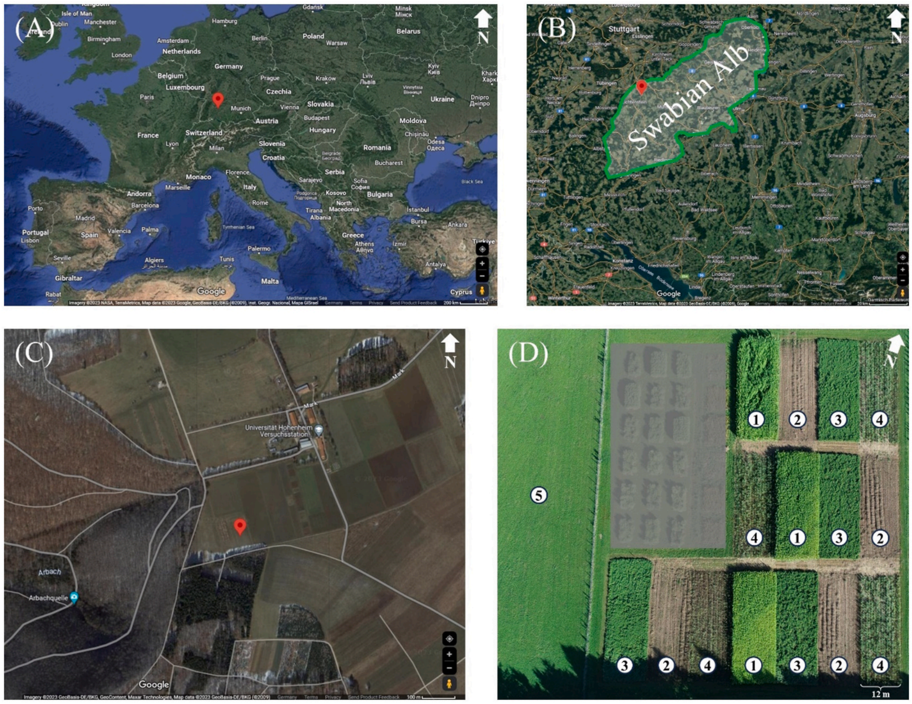

Fig. 1. Location of the field trial of the University of Hohenheim (UHOH) shown by satellite images from 200 km (A), 20 km (B, highlighting the region 'Swabian Alb'), 100 m altitude (C), and drone image (D, about 40 m altitude). The drone image also shows the crop assignment to the plots in vegetation year 2023 for hemp (*Cannabis sativa* var. FUTURA 83) (D1), crambe (*Crambe abyssinica* Hochst. ex R.E.Fr.) (D2), yellow melilot (*Melilotus officinalis* L.) (D3), miscanthus (*Miscanthus* × *giganteus* Greef et Deuter) (D4), and the reference field cultivated with extensively managed grassland (D5). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

plants; transporting to intermediate producers; marketing to consumers; and recycling of waste which are embedded in a local system (Wohlfahrt et al., 2019). This complexity inherent to modern value chains has led to the conception of a value web or a value net. Value webs have non-linear linkages and join several value chains into one network (Ricciotti, 2020). Instead of focusing on one product and one value chain, value webs allow pathways for multiple products to be visualized in one system (Scheiterle et al., 2018). Value webs also unveil social and regional contexts that affect economic outcomes (Virchow et al., 2016). Actors work together in surprising ways to move products along the value web; actions taken upstream in the value web may affect downstream actors like final producers and consumers. In sustainable agriculture, value webs are strategic tools that show whole crop use, via cascading pathways which eliminate waste, to maximize value (Lewandowski, 2017). Value webs, therefore, are key tools in building a sustainable bioeconomy (Scheiterle et al., 2018).

A literature review is foundational to the work; it provided agro-economic data about crambe and socio-economic data about the Swabian Alb and its industries. The main Scopus® search string used for compiling data on crambe was: '(TITLE-ABS-KEY (crambe)) AND (abyssinica)'. The search time interval was May to June 2023, and documents found in the reference lists of the identified documents were also considered. Further, four major stakeholder groups were identified as playing crucial roles in crambe cultivation and valorization within the Swabian Alb: (1) regional sustainability officials (regional governance), (2) local industries, (3) academia, and (4) farmers. This selection of stakeholder is similar to those selected by Boulestreau et al. (2022) who investigated coupled innovations induced by a change of farming practices in a European country. For each stakeholder group, individuals, institutions, and/or companies were contacted (Supplemental material A). Potential interviewees received up to five questions about crambe and their understanding of its prospects in the region; questions were tailored to each stakeholder group. Most responded, and a complete list of our contacted stakeholders can be found in Table 1. The selected stakeholder received questionnaires with an open set of questions (maximum five); open questions were chosen to allow free and independent answers. The questionnaires, as well as the contact with the stakeholders, were conducted in German. Stakeholders were given approximately three weeks to respond, with follow-up emails and calls to encourage them to answer. The answers were translated into English using DeepL (DeepL SE, Cologne, Germany) and discussed as a group. During the discussion, the answers were summarized, and the most relevant aspects were highlighted to better inform the SWOT analysis. This method was applied to gain information about the social and regional environment in the Swabian Alb as well as to find out about the stakeholder's attitude towards the development of a regional crambe value web. Furthermore, this complemented the research's sustainability focus and added new perspectives to the SWOT analysis, making it more realistic and comprehensive.

Parallel to the questionnaire, a preliminary value web was created based upon the findings from literature. To test the preliminary value web for reasonability and practicality, a SWOT framework was applied. SWOT analysis, a tool primarily used in business to assess competition and develop strategy, assesses a project's status quo as well as potential optimization measures. The preliminary value web was evaluated using the SWOT framework to elaborate and compare the status quo in the Swabian Alb with the potentials of crambe. Strengths, weaknesses, opportunities, and threats were identified based on the results of the interviews. Finally, the findings from literature, stakeholders, and analysis were combined to adapt the potential value web to fit to the current local conditions. The "currently possible" value web includes economic, social, and ecologic aspects, thereby providing a view from a sustainable perspective on the potential value of crambe for the Swabian Alb.

3. Results and discussion

In this section, the research results of crambe and its bioeconomic relevance as well as information about the Swabian Alb are presented.

Table 1
Stakeholders contacted for input about the prospects of crambe in the Swabian Alb, Southwest Germany. For those who have not yet responded, the intention is to be able to collect their opinions in the further course of the project.

Stakeholder category	Stakeholder name	Description
Regional Offices and Institutions	BIOPRO Baden-Württemberg GmbH (https://www.bio-pro.de/)	State organization, promoting the transformation of economy and society focusing on bioeconomy
	Landratsamt Alb-Donau-Kreis (https://www.alb-donau-kreis.de/startseite.html)	Central contact point for the bioeconomy at the Alb-Donau district administration office
Industry – Fibers	Fiber industry stakeholder 1 [a]	International company producing plant fiber products
	Fibers365 GmbH (https://fibers365.com/)	Producing non-wood virgin fibers for paper and packaging purposes as well as high value side streams
Industry – Cosmetics	Dr. Hauschka by WALA Heilmittel GmbH (https://www.drhauschka.de/)	Well-established natural cosmetic company
	Seifenreich Naturkosmetik Manufaktur (https://www.seifenreich.com/)	Natural cosmetics company producing soaps and other body care products
	Duschbrocken GmbH (https://duschbrocken.de/)	Start-up selling shower bars and other solid cosmetic products
Academia	Hochschule Albstadt Sigmaringen (https://www.hs-albsig.de/)	Applied University, with strong innovation in sustainable engineering
	Hochschule Reutlingen (https://www.reutlingen-university.de/)	Applied University with strong innovation in textiles (fibers)
Farmers	Lauteracher Alb-Feld-Früchte (https://lauteracher.de/)	Farmers cooperation in the Swabian Alb focusing on cultivation and marketing of organic crops
	Farmers 1–3 [a]	Three individual farmers from the Swabian Alb

[a] Anonymized at the request of the stakeholder.

Further, the potential value web is described, and the SWOT framework is used to assess competitiveness.

3.1. Characteristics and cultivation practices of crambe

Crambe is as drought-tolerant (Moura et al., 2018) and low fertilizer-demanding (Costa et al., 2019; Jankowski et al., 2022) oilseed crop from the *Brassicaceae* family (FNR, 2001; Pushkarova and Yemets, 2022). Crambe consists of 20 species (Samarappuli et al., 2020). However, mainly *C. abyssinica* is of agricultural interest (FNR, 2001; Pushkarova and Yemets, 2022). It originated in the Ethiopian plateaus and spread across the Mediterranean and the globe (Samarappuli et al., 2020). Nowadays crambe is grown in the Americas, Asia, Europe, and tropical and sub-tropical Africa (Zhu, 2016). It is a cool season crop, tolerant to temperatures down to −5 °C (Zanetti et al., 2016). Even though it originated in high plateaus, the plant grows from 0–2000 m above mean sea level (Berzuini et al., 2021). The plant can adapt to various precipitation ranges from 350–1200 mm cumulative annual precipitation, but usually 100–150 mm of precipitation is sufficient from sowing to harvest to fulfill its needs to maximize yield, meaning it can be considered a drought-tolerant crop (Berzuini et al., 2021).

Crambe requires coarse to fine textured soil, with slightly acidic to neutral pH, and it is deemed suitable for poor soil conditions (Costa et al., 2019; Jankowski et al., 2022). Crambe also tolerates a range of salinities (Costa et al., 2019; FNR, 2001). Good soil drainage is important, therefore, locations with heavy, waterlogged soils should be avoided (Von Cossel et al., 2019b). Crambe farming started in 1933 in the Union of Soviet Socialist Republics (USSR) and in the 1940s in the United States of America (USA). Today, about 10,000 ha of crambe are being cultivated in North Dakota alone (Samarappuli et al., 2020).

3.1.1. Morphology and physiology

Crambe is an annual herbaceous species (Fig. 2), with an average height of 1.00–1.20 m (Zhu, 2016). The height might vary due to growth conditions like soil fertility, soil depth, sowing time, and plant density (Samarappuli et al., 2020). Crambe roots reach down up to 1 m into the soil under normal conditions (Ionov et al., 2013), and crambe can adapt the root architecture via increasing the distribution of roots in the soil to withstand dry conditions (Moura et al., 2018). The overall growth is erect with numerous branches (Zhu, 2016). The cotyledons are heart-shaped, while after maturing the leaves are oval, smooth-surfaced, and light green (Samarappuli et al., 2020). The plant produces small white to light yellow-colored flowers distributed racemically, which are mostly self-pollinated, with a rate of cross-pollination of about 30% (Fig. 2-B). The pods change from green to yellow brown during maturation (Fig. 2-C). They are small with a diameter of 0.8–2.6 mm (Fig. 2G and H). They are formed in circular siliques, which are indehiscent. The thousand grain weight lays between 6 and 10 g, and the dry matter grain yield of crambe ranges from 1579 ± 819 (in Southern Europe) to 2990 ± 260 kg ha^{-1} (in Northern Europe) (Samarappuli et al., 2020).

With a base temperature of 5 °C, the required growing degree day (GDD) lays between 1300 and 1500 °C d (Berzuini et al., 2021; Costa et al., 2019). It has a rather short growth cycle; the harvest takes place around 90–110 days after sowing (Samarappuli et al., 2020).

3.1.2. Cultivation

Crambe cultivation cycle begins with sowing. Due to the seeds' small size, the bed needs to be firmly well-packed (FNR, 2001). The soil should be kept weed-free since the plant develops slowly in the first four weeks after emergence (Samarappuli et al., 2020). To reduce the competition with weeds, early sowing in spring is crucial, as well as optimal row spacing and sowing rates and dates. Cold and early establishment usually increases seed yields but slows down the emergence process (FNR, 2001; Zanetti et al., 2016). In addition, early sowing shortens the time between flowering and seed maturity. The seeds can be broadcasted or in rows; throughout cultivation inputs need to be considered. Even though crambe has low nutrient requirements, the yield can be increased with precise fertilizing, with phosphorous for example (FNR, 2001). Nitrogen fertilization of up to 120 kg N ha^{-1} (Klaus and Makowski, 1996) increases the plant growth (because of higher sodium availability). Some studies reported a decrease of seed oil content and changes the fatty acid composition at the expense of the erucic acid content with increasing N fertilization (FNR, 2001; Jakob et al., 1999) whereas other studies report no effects of N fertilization on oil content and fatty acid composition (Klaus and Makowski, 1996). For phytosanitary reasons, however, the amount of nitrogen fertilizer should not exceed the site-specific optimum, as this could lead to changes in planting density and humidity within the microclimate of the plant stands in which *Sclerotinia sclerotiorum* Lib de Bary infections could follow (Samarappuli et al., 2020).

Regarding plant protection, there are no major pests reported to affect crambe mainly due to high contents of glucosinolates (Anderson et al., 1992; Zanetti et al., 2016). However, diseases, like turnip yellow mosaic virus and black spot, need to be considered (FNR, 2001). The latter can be prevented by treating the seeds before sowing. As with other *Brassicaceae*, a long interval in the crop rotation is an important measure to protect against soil-borne diseases (FNR, 2001). Crambe has a low weed suppression potential so that weed management is necessary (Costa et al., 2019).

The growing cycle ends at harvest, which should begin after the last

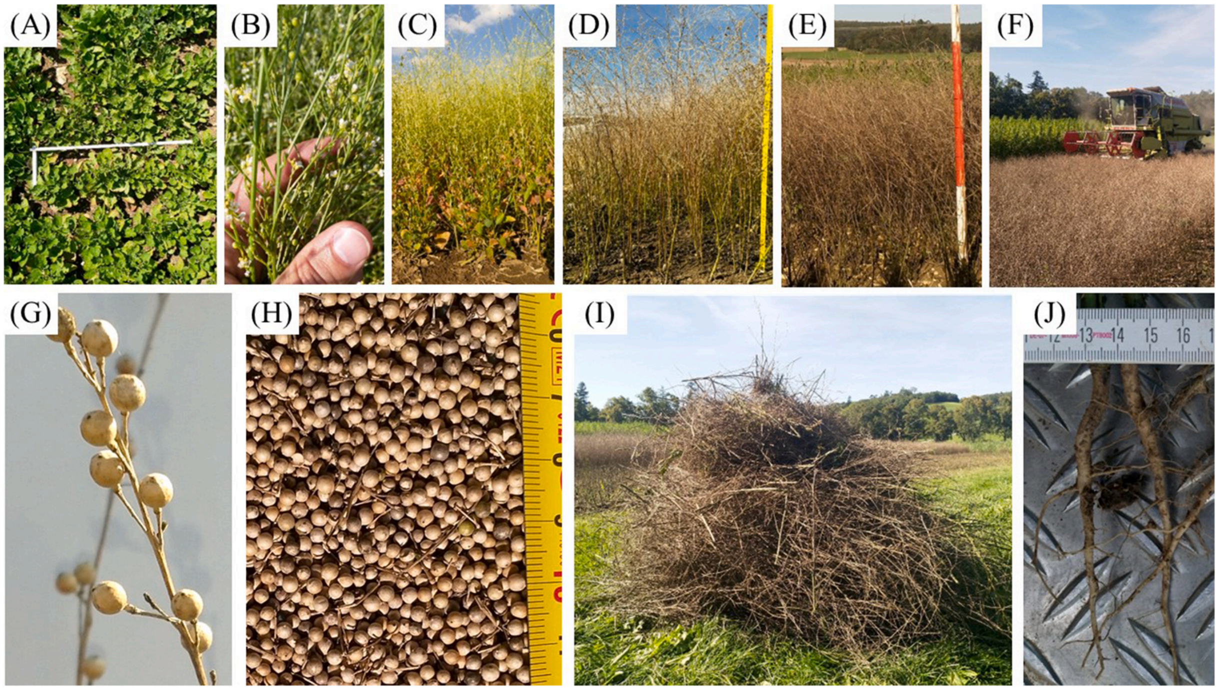

Fig. 2. Impressions of crambe growing on a shallow stony soil in the Swabian Alb, Southwest Germany. After about a month and a half of development of the rosette of leaves on the ground (A) begins flowering (B), which can last for several weeks. The leaves that grow on the stalk (C), which is about 80 cm long (D), fall off completely until harvesting (E), so that the grains can be harvested without any problems using conventional technology (comparable to rapeseed harvesting technology) (F) with dry matter grain yields ranging from 1579 ± 819 (in Southern Europe) to 2990 ± 260 kg ha^{-1} (in Northern Europe) (Samarappuli et al., 2020). However, the pods sit loosely on the stalk (G), so that harvesting should not be delayed too long, otherwise there may be increased grain loss before and during harvesting. Each crambe seed is enclosed in a spherical pod, about 2 mm in diameter (H). On average, about 2–4 Mg of straw are produced per hectare (I), which can either remain in the field or be used for bioenergy production. Crambe rooted about 12 cm deep under shallow soil conditions (J), so only relatively low nitrogen replenishment from mineralization processes can be expected.

seed baring branch starts tanning (Samarappuli et al., 2020). Usually, the seed moisture level is decreased below 10% (Samarappuli et al., 2020). A combine harvester used for cereals can be used for crambe (FNR, 2001). Due to the heterogeneity of the crambe plants and stands, the harvesting costs are the highest costs in crambe cultivation (FNR, 2001). To avoid post-harvest seed losses, which are due to the small size and the low bulk density, transport and storage units must be lockable so that no seeds can fall out (Samarappuli et al., 2020).

3.2. Bioeconomic relevance of crambe

3.2.1. Historical data on crambe cultivation

Even though crambe is still not cultivated or used widely now, it is not the newest biomass for studying. Research on crambe started around the 1930s. Crambe has experienced cyclic interest from the scientific community, with peaks of research occurring in the 1960–70s, late 1990s, and early 2010s (Fig. 3). In the late 20th century, there were significant improvements in the oil yield of non-edible rapeseed, so called high erucic acid rapeseed (HEAR). HEAR became more economically competitive than crambe, and crambe research declined (Hebard,

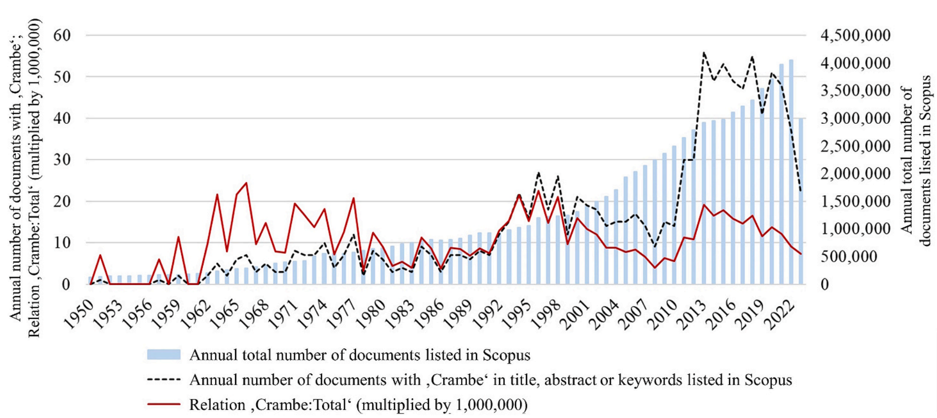

Fig. 3. Overview of documents listed in Scopus since 1950 until October 2023, featuring the annual total number of documents (blue bars), annual number of documents focused on crambe (black dotted line), and the relation of the annual number of documents focused on crambe to the annual total number of documents (multiplied by 10^6 for a better visualization) (red solid line). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2016). However, the high erucic acid content, the low-input characteristics and the high tolerance against environmental challenges such as droughts make crambe a compelling crop for social-ecologically more sustainable biobased value chains (Costa et al., 2019; Moura et al., 2018; Samarappuli et al., 2020). Nowadays, research on crambe is mainly done in the USA, Europe, and Brazil (Berzuini et al., 2021).

3.2.2. Valorization of crambe and its products

Crambe biomass can be used by several industries, however, each industrial product has different economic value. According to the report by Future Market Insights, the market size of crambe oil is 11 billion USD in 2022 and will grow to 28.4 billion USD by 2032 (Future Market Insights, 2022).

Fig. 4 depicts a common concept of the bioeconomy (Donner et al., 2020; Lange et al., 2012). The pyramid shows the different economic values of each type of biobased product. It shows the upward increasing economic value, which is combined by the pyramid shape with the amount of biomass needed for each industry. As shown in Fig. 4, the most valuable usage of biomass is for pharmaceutical use. The cosmetics industry gives the second highest value to biomass; transforming biomass into energy and heat is the lowest valorization.

Based on this principle, crambe can be valorized by determining what kind of products are possible from each crop fraction. The most valuable part of the crambe plant is the seed; as an oil crop, crambe seed is suitable for oil extraction (Cavalheiro et al., 2023). Crambe oil has a unique fatty acid composition, containing up to 65% erucic acid (Righini et al., 2016). The concentration of erucic acid in crambe oil is even higher than non-edible HEAR (High Erucic Acid Rapeseed), which has up to 50–55% erucic acid (Righini et al., 2016). The contents of oleic, linoleic, and linolenic acids are therefore much lower, between 5 and 17%, in crambe oil (Righini et al., 2016). The unsaponifiable matter content is about 2%. Having a high content of erucic acid makes crambe oil toxic for food or animal feed but useful for many other purposes such as cosmetics, lubricants, and biofuels (Alexopoulou et al., 2023; Cavalheiro et al., 2023).

Cosmetics companies use crambe oil in skin or hair care products like shampoo and face cream. In these products, pure crambe oil by cold-press is often used as an ingredient for anti-aging and skin-repairing purposes. These are the highest valued products from crambe, as indicated by the purchase cost of crambe seed oil products of around USD 50 kg^{-1} (Nature in Bottle, 2023). In Germany, most of the existing products with crambe oil on the market are natural cosmetics. For example, Lavera (Laverana Digital GmbH & Co. KG, Wennigsen, Germany), a natural cosmetic company, has several products containing crambe oil including moisturizer and serum (Lavera Naturkosmetik, 2023a, 2023b).

Crambe oil is thermostable; its chemical structure makes it suitable for use as an industrial lubricant, especially for chainsaws (Lazzeri et al., 1994). Erucic acid, which can be distilled from crambe oil, is used in various industries (Glaser, 1996; Leonard, 1992) (Table 2). However, since there is not much crambe cultivation on a commercial scale in the EU, erucic acid from crambe seeds is not the main resource for most of the applications yet. As with other bio-oils, crambe oil can also be used as biofuel.

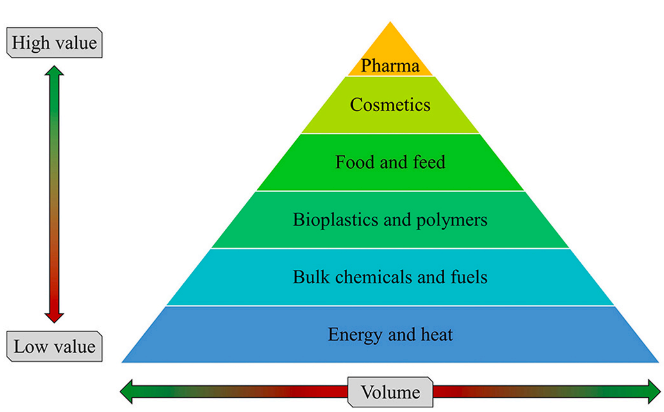

Fig. 4. Value pyramid for biobased products, adapted from Donner et al. (2020), and Lange et al. (2012).

After oil extraction, producers are left with a press cake, also called crambe meal. This meal contains a lot of protein and fiber. But it cannot be used as animal feed because single-stomached animals, such as swine and poultry, can develop toxicity problems from ingesting press cake from crambe seed oil extraction processing (Carlson and Tookey, 1983). Against, the protein could be used to produce biobased plastic materials (Newson et al., 2013). Following Walker (1996), the toxicity of the crambe seed cake could also be used for biobased plant protection measures such as nematicide and herbicide purposes. Negative effects on crop growth reported by Walker (1996) were not later confirmed (Tarini et al., 2020). On the contrary, Tarini et al. (2020) showed a positive effect of the application of seed cake extracts on crambe growth.

The residual parts of crambe, including stems (straw), leaves (part of the straw), and roots, are not valorized in the current bioeconomy. However, as with other crops, the crambe straw (lignocellulose biomass) could be used within the bioeconomy, for example, for bioenergy (Krzyżaniak et al., 2020) or left on the field as green mulch. It must be noted that these fibrous products have lower value than the oil products mentioned above. To sum up, crambe biomass could provide many types of valuable products at once, so that further research into practical applications would be very useful in order to better exploit the potential of this non-edible crop.

3.2.3. Ecosystem services

Besides economic value, crambe provides social and ecological value, too, such as provisioning, habitat, and regulating services to ecosystems. Regarding provisioning services, crambe provides oil for industry, feed for pollinators and increases the soil water infiltration rate (Zanetti et al., 2016). Moreover, it can act simultaneously as habitat for pollinators and other (beneficial) insects (Samarappuli et al., 2020). Most of crambe ecosystem services are regulating services; these include carbon sequestration, soil fertility improvement due to phytosanitary properties (FNR, 2001; Zanetti et al., 2016) and phytoextraction of heavy metals (e.g. Pb, Cd) from the soil (Gonçalves et al., 2020).

Nonetheless, there can be negative ecological impacts due to crambe cultivation such as erosion, nutrient leaching and greenhouse gas emissions from the production (Krzyżaniak and Stolarski, 2019; Samarappuli et al., 2020). However, in comparison to other oilseed crops, especially rapeseed, the negative environmental impacts are expected to be lower for crambe cultivation due to its low-demanding nature (Berzuini et al., 2021). Furthermore, the application of reduced tillage intensity could help reducing the greenhouse gas emissions from the soil (Krzyżaniak and Stolarski, 2019). However, to determine the overall ecosystem services (also including the nutrient use efficiencies) and environmental impacts of crambe in the Swabian Alb a true costs and benefits approach (Wagner et al., 2022) is recommended.

Table 2
Derivatives of high-erucic-acid oils for industrial applications, adapted from Glaser, 1996; Leonard, 1992.

Derivative	Application
Erucamide	Slip agent
Erucyl alcohol	Emollient
Various fatty nitrogen derivatives	Hair care and textile softening
Behenyl alcohol	Pour point depressant
Esters and others	Lubricants
Glyceryl tribehenate	Food emulsifier
Silver behenate	Photography

3.3. The Swabian Alb

In this section, some details about the target region are given in terms of general location characteristics, predominant industries, and agricultural land use.

3.3.1. Site description

The Swabian Alb is a low mountain range located in the German federal state of Baden-Württemberg, stretching approximately 220 km in length and up to 40 km in width (Biosphärengebiet Schwäbische Alb, 2023). It is the largest contiguous karst region in Germany and is characterized by a diverse landscape consisting of several natural geographic regions (DFG Research Unit, 2017).

The Swabian Alb is known for its deep karstification, resulting from the presence of in-situ unlayered reef limestones and dolomites. The land's soil type varies, with clayey loams and calcareous rendzina being found on some land, and shallow calcareous black soils on others. In the dry valleys, decalcified loams can also be found. With about 38% of the total area covered by trees, a large part of the Swabian Alb is forested (DFG Research Unit, 2017).

The specific implementation site for the strip-intercropping trial from the MIDAS project is a marginal (shallow stony soil) area at the Upper Lindenhof. It is a central research location for livestock sciences, bioenergy, and agronomy associated with the UHOH. Some of the research focuses are the improvement of crops and crop-growing systems as well as sustainability aspects of agriculturally produced biomass. The Upper Lindenhof is located next to Reutlingen and lies 720 m above sea level (University of Hohenheim, 2020). The average annual temperature of the past 8 years was 8.6 °C and the average precipitation 816.2 mm. There have been an average of 2112 h of sunshine per year in this period. This resulted in an average of 241 growing days per year, which means that on these days, the average temperature was above 5 °C (Agrarmeteorologie Baden-Württemberg).

3.3.2. Main industries and agricultural land use

The region of the Swabian Alb is recognized for its diversified and strong industrial base, which is dominated by mid-size companies. Various clusters of industries, especially within mechanical engineering, dot the landscape. Automotive and engineering companies are dominant; the most well-known companies (or their suppliers) within mechanical engineering are Bosch, Daimler, Porsche, and Trumpf. In addition, aerospace, textile manufacturing, medical, and biotechnology companies are based in the Swabian Alb. The textile industry, which has been established for many years, is a microcosm of the Swabian Alb's business culture. Textile manufacturing in the Swabian Alb markets to both businesses and consumers; their inventive products range from protective and functional athletic fabrics to materials for the medical and automotive industries. Besides regional fashion labels like Hugo Boss, Marc Cain, Sanetta, and Erima, many highly innovative companies in the field of technical textiles have established in the Swabian Alb (Neckaralb).

Many development and research institutions network on both regional and international scales. Manufacturers in the region often partner with local research institutions. Relevant in this context are the Natural and Medical Sciences Institute (NMI) at the University of Tübingen as well as the University Hospital Tübingen (UKT) and the network Medical Valley Hechingen. In biotechnology, the universities of Reutlingen and Albstadt-Sigmaringen play an important role. It is further worth mentioning that there are four Max-Plank-Institutes and the German Institute of Textile and Fiber Research (https://www.ditf.de/de/) in the Neckar-Alb region.

Besides the strong engineering and research clusters, agriculture plays a significant role in the Swabian Alb, with 52% of its land being used for arable farming, grassland, or orchards. The crops grown in the area include spring barley, winter wheat, and winter barley (DFG Research Unit, 2017). However old wheat and spelt varieties, malting barley, lentils, oil flax, buckwheat, camelina, and caraway have been cultivated again in the region for some years. Extensive use of meadows and pastures, especially by sheep, also plays a significant role (Biosphärengebiet Schwäbische Alb, 2023). The Swabian Alb has many strong businesses with strong ties to research and innovation, but at the same time adheres to traditions.

3.4. Value web for crambe in the Swabian Alb

With all the information from the previous sections, a potential value web for crambe is developed (Fig. 5). The farmer, the primary biomass producer, grows crambe and separates the distinct parts of crop. Seeds can be sent to an oil mill, while the stem and any leaves remaining on it could be processed for industry or biogas. Alternatively, these residues can be left on the field as green mulch. The seeds yield two products after pressing in an oil mill, the seed oil and the residue ('seed cake' or 'seed meal'). Some industries value the whole crambe seed oil, while others look for the more refined pure erucic acid. After the valuable oil has been removed, the seed meal is left. It is not recommended to use the seed meal residue as feed for animals because of the toxic glucosinolates. If removed, these compounds have potential in the pharmaceutical industry.

As far as the stems and leaves are concerned, it is not yet clear whether these lignocellulosic parts of the crambe can be processed by the fiber industry into paper and packaging, biopolymers, and textiles. If they are not used in industry, the stalks and leaves could be converted into biogas and heat in a biogas plant. Due to the high degree of ripeness, it would probably be necessary to pre-treat the biomass so that it can be better decomposed in anaerobic digestion (Wang et al., 2023). The digestate, a residue of biogas production, can be used as a fertilizer, closing the loop back to the farmer. The roots and the seed cake of crambe have been shown to have a strong anti-nematode effect and therefore could eventually be converted into a bio-pesticide (Coltro-Roncato et al., 2016; Tarini et al., 2020; Walker, 1996). But taking out the roots from the soil is very work-intense and is assumed to have negative effects in terms of soil fertility and biodiversity.

Farmers and industrial stakeholders play specific roles in creating and transforming crambe into valuable products. In contrast to this, regional and governmental institutions, as well as research institutions and universities, exert more diffuse influence. These stakeholders serve as information bridges, advocates, and networkers, adding value in a different way. Academic stakeholders are essential, as they develop and improve the knowledge base for agricultural and industrial stakeholders. As mentioned, academia is especially important because of their cooperation activities with the industry. Besides this, regional and governmental institutions can build a beneficial environment for the value web, supporting valuation with large-scale investments and legislation, but also with small-scale project management, marketing, and networking activities. Farmers, industry, and other stakeholders also have social networks that help spread subject matter expertise and best practices about agriculture and biobased value chains. Together, these stakeholders bolster the value web and lift it to new heights.

3.5. SWOT analysis of the potential value web

The designed value web is evaluated using a SWOT framework. Analyzing strengths, weaknesses, opportunities, and threats of the potential value web from a system perspective provides insights about external and internal forces affecting crambe's prospects in the Swabian Alb. To better integrate the social dimension of value webs, selected answers from the interviewed stakeholders are incorporated; the entire questionnaire (in German) will be made available on request.

Table 3 summarizes the major findings of the SWOT analysis; all aspects will be elaborated in the following sections, and the complete SWOT analysis can be found in Figs. 6–9.

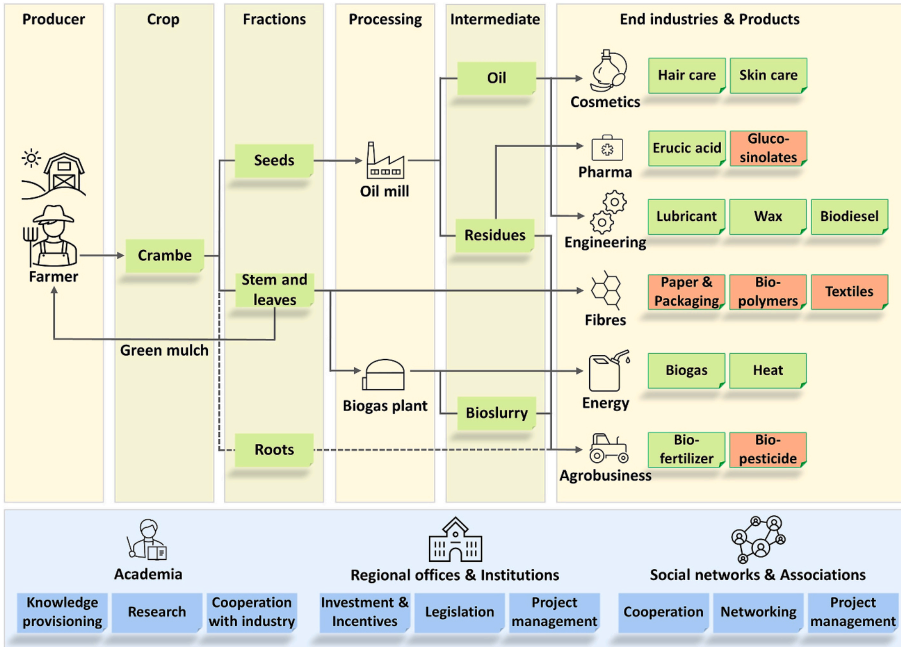

Fig. 5. Potential value web of crambe in the Swabian Alb. Major stakeholders are represented by icons, while products are shown in rectangles. Green rectangles represent currently possible products, while red rectangles stand for products requiring additional research for implementation. Solid lines show established product valorization pathways, while dotted lines show potential products. Stakeholders, processors, and industries are in yellow columns, while biomass is depicted in green columns. The blue row along the bottom stands for stakeholders that influence the entire process from seeding to sales. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 3
SWOT analysis of the potential value web of crambe in the Swabian Alb.

Strengths	Weaknesses
- Resilient and low-input crop with a short life cycle (can be both cover or catch crop) - Multiple products from crop fractions - Financial and institutional support for industrial crops	- Non-native, novel crop - Unknown quality, quantity, and yield stability - Underdeveloped market infrastructure
Opportunities	**Threats**
- Growing market for natural cosmetics or biofuels - Regional innovation culture - Regional sustainability infrastructure	- Instability from climate change - Regional and crop-specific competition - Technological innovations

3.5.1. *Strengths*

Due to the drought-tolerance (Moura et al., 2018) and low demand for nutrients (Costa et al., 2019), crambe grows in a variety of rainfed conditions and requires little fertilization. These core biophysical characteristics of crambe are a strength because they mean lower risks for farmers; less investment on inputs and more tolerance to various climatic conditions reduces farmers' financial and operational risks (Fig. 6). Farmer 2 mentioned "the effort [of growing crambe] is not as high as with rapeseed" and "the cultivation of crambe would fit very well on the soils of the Swabian Alb." As a low-input crop, crambe could be grown on marginal land in the Swabian Alb.

Additionally, various parts of the crambe plant can be valorized by existing stakeholders in the Swabian Alb. The crambe plant has fractions that fit distinct parts of the biomass value pyramid (see Fig. 4). The seeds, containing valuable erucic acid, can be used by cosmetics, chemical, and engineering companies; they are of high value even at low quantities. The stem and remaining leaves (if any), though less valuable, can be used by fiber and textile companies. Even crambe roots and the seed cake (from oil extraction process) have potential value, as they have natural pesticides. Stakeholders from the fiber industry particularly referenced this idea, core to the bioeconomy, saying "With a view to the bioeconomy, we are keen on any plant that allows a regional cascade use (as in this case, first food/feed products such as oils, flour), then processing into cellulose and lignin material flows" (Fibers365 GmbH). Another fiber company was concerned with waste, saying "we are only interested in one part of the plant; what happens to the rest?" (Fiber industry stakeholder 1). The concentration of economic value in the seeds and the cascading uses of crambe residues help to diversify the outputs and incomes of the crambe value web. Diversification is a strength of the crambe value web.

In addition, significant financial and institutional investments from the EU underpin the crambe value web. This research supports the MIDAS project, which seeks to bolster regional biobased value webs for industrial crops. Secure funding and institutional alignment supply structure to the crambe value web.

3.5.2. *Weaknesses*

Despite these strengths, crambe cultivation in the Swabian Alb has many unknowns and weaknesses (Fig. 7). First, crambe is a novel, non-native crop. Farmers have little to no experience with crambe; one farmer mentioned "I can't say what the yield potential, quality and quantity of the ingredient is from [crambe] to rapeseed" (Farmer 1). This may create inefficiencies and friction in the value web. Stakeholders from the cosmetics industry specifically mentioned concerns about quality, saying "The oil has to meet our quality requirements" (Dr.

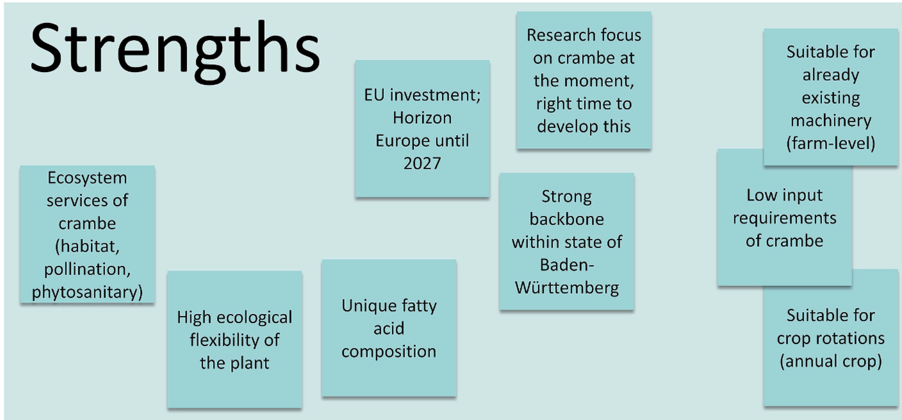

Fig. 6. Estimated strengths of crambe cultivation on marginal land in the Swabian Alb (results from the questionnaires and their elaboration by the authors of this study).

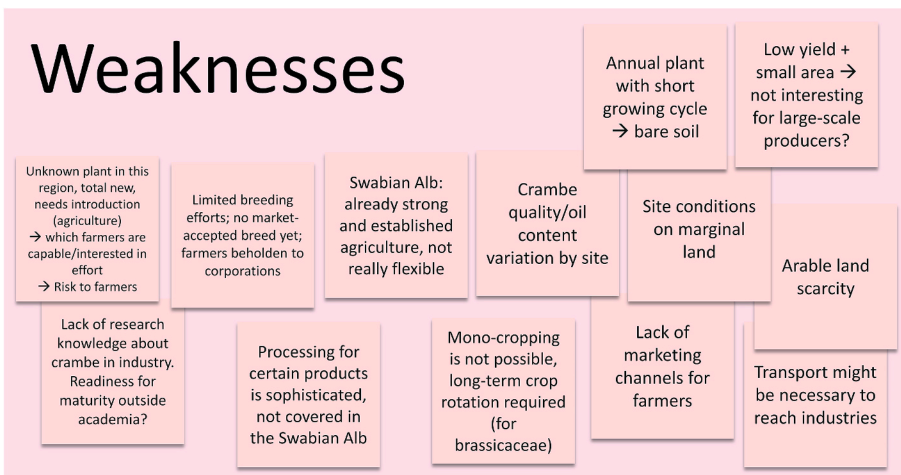

Fig. 7. Estimated weaknesses of crambe cultivation on marginal land in the Swabian Alb (results from the questionnaires and their elaboration by the authors of this study).

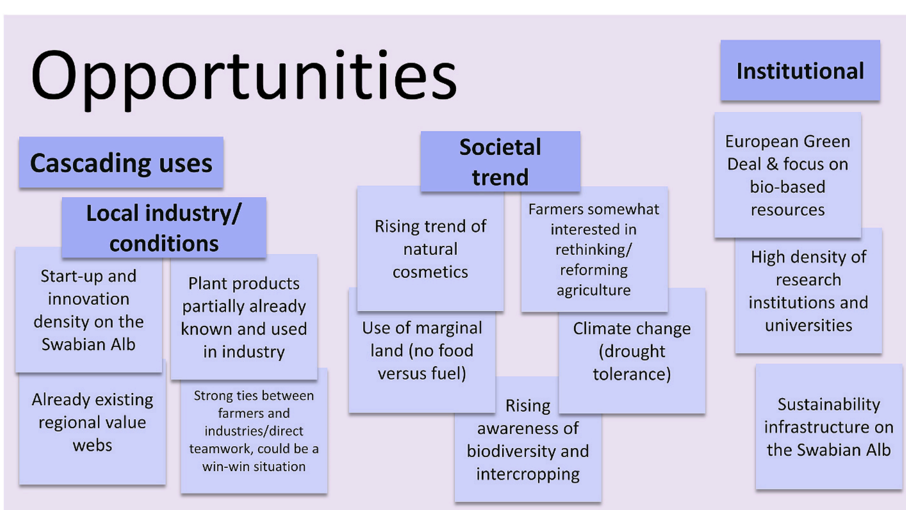

Fig. 8. Estimated opportunities of crambe cultivation on marginal land in the Swabian Alb (results from the questionnaires and their elaboration by the authors of this study).

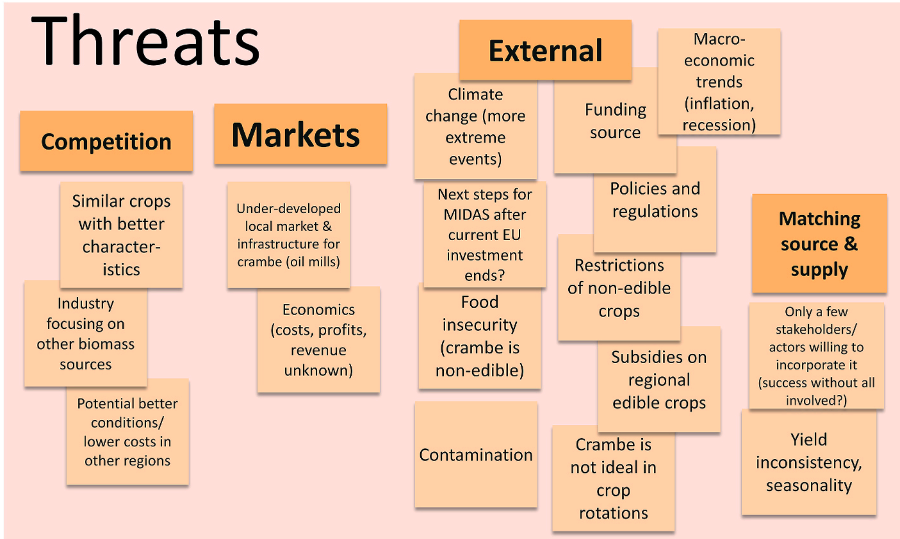

Fig. 9. Estimated threats of crambe cultivation on marginal land in the Swabian Alb (results from the questionnaires and their elaboration by the authors of this study).

Hauschka by WALA Heilmittel GmbH) and asking for "certified quality for cosmetic use" (Seifenreich Naturkosmetik Manufaktur).

Second, grain yields were rather low (0.85 ± 0.15 Mg ha^{-1}) in the Swabian Alb in year 2023 compared with findings from Samarappuli et al. (2020). Even though this can be explained by significant harvest losses due to a thunderstorm event (daily precipitation sum: 45 mm d^{-1}) that happened a few days before harvest was planned, insecurities remain on the grain yield level and grain yield stability of crambe. This further complicates value web implementation, as both producers and consumers want some assurance about quantity and prices. Farmers are looking for a purchase guarantee from industry ("If the purchase by an industry is guaranteed, I see no problem", Farmer 1), while industry wants more information before committing ("crambe could be interesting - depending on questions such as economic viability, storability, what quantities are available" Fibers365 GmbH).

Third, no infrastructure currently exists for processing, transporting, and marketing crambe. Logistical challenges may impair crambe acceptance and success in the Swabian Alb. All interview groups (regional administration, industry, academia, and farmers) mentioned the lack of information about logistics as a barrier to crambe cultivation.

3.5.3. Opportunities

Looking externally, several opportunities are available for a value web for crambe in the Swabian Alb (Fig. 8). Notably, crambe cultivation could be buoyed by the rising market share of natural cosmetics. Sales of natural cosmetics in Germany have roughly doubled in the past decade - to a level of around 1.48 billion euros in 2021 (BioFach, 2022). Crambe, primarily because of its unique fatty acid composition, is an appealing ingredient in natural cosmetics, from deodorants to hair care. Stakeholders in the regional cosmetics industry mentioned "the composition sounds extraordinary" (Dr. Hauschka by WALA Heilmittel GmbH). One cosmetic company already produced crambe products in the past ("We have already successfully used crambe oil for a private label project", Seifenreich Naturkosmetik Manufaktur), though it was not locally sourced.

Regional infrastructure for both innovation and sustainability could help crambe's value web to expand and thrive. The Swabian Alb is home to many research institutions. Its innovation culture, supported by a high density of start-ups and research centers, makes it a hub for new ideas. The Swabian Alb is also committed to sustainability (DFG Research Unit, 2017). As a UNESCO biosphere, the links between nature and culture are ever-present in the Swabian Alb (DFG Research Unit, 2017). Regional institutions, such as bioeconomy district offices, offer project management and networking opportunities to scale up and scale out sustainable solutions such as biobased products. Regional administrators mentioned that "companies also want to get more and more involved in the topic of sustainability" (BIOPRO Baden-Württemberg GmbH) and stressed the essentiality of "cooperation with existing local contacts" (BIOPRO Baden-Württemberg GmbH). Several stakeholders mentioned the importance of the Swabian Alb in their product sourcing; all four interviewed cosmetics companies said it was important to have regional inputs in their products. Local sustainable solutions integrated into the cultural and social fabric of the Swabian Alb are promising areas into which crambe production can grow. Overall, this sustainability infrastructure can therefore be seen as an opportunity for crambe value chain development in the Swabian Alb.

3.5.4. Threats

The value web for crambe in the Swabian Alb also faces external challenges (Fig. 9). First, as with any biobased resource, crambe cultivation and valuation is affected by climate change. Extreme weather events and variable temperatures could significantly diminish crambe yields. For example, crambe can only be considered drought-tolerant if the biophysical site conditions allow the development of physiological and morphological adaptation processes as described by Moura et al. (2018). At a bulk density of more than 1.4 Mg m^{-3} (Oliveira et al., 2023), the root architecture of crambe cannot properly adapt to drought, so yields are higher when more precipitation falls. Therefore, drier European summers (Ferdini et al., 2023; Pörtner et al., 2022; Von Cossel et al., 2019a) could affect the availability of crambe products in regions where soil compaction, i.e. high bulk densities, is common.

The value web envisions regional businesses using locally produced crambe, but competition exists across geographic and agricultural dimensions. The Swabian Alb competes with agricultural regions all over the world. Indeed, some German companies were sourcing crambe oil from South Africa (Alexmo cosmetics, 2023; Manske, 2023). Moreover, Farmer 3 reported that in the Swabian Alb, the demand for land for crop cultivation is high ("the problem is a generally high demand for agricultural land"). High demand for land means low excess supply for novel crops like crambe.

While the Swabian Alb has innovation and sustainability entrenched in its institutions, other regions may provide institutional and financial support for crambe cultivation. Crambe itself primarily competes with HEAR in providing industrial lubricants. Since the 1980s, crambe has been outcompeted by HEAR; HEAR has higher oil content per seed (Hebard, 2016). However, crambe typically has higher erucic acid content. This competition between crambe and HEAR is ongoing, and the markets will determine the valuation of each crop, especially regarding the differences of growth suitability between crambe and HEAR. One farmer questioned why even change from HEAR to another crop, responding to the questionnaire with "We wonder why the high erucic rape should be replaced at all" (Lauteracher Alb-Feld-Früchte). Other farmers were concerned about the competitiveness, saying "crambe is only interesting when crambe can compete with other crops" (Farmer 3).

3.6. Currently possible value chain in the Swabian Alb

After combining the potential value web, the SWOT analysis, and stakeholder perspectives with the existing industries and companies in or near the Swabian Alb, a currently possible value chain emerges (Fig. 10). For crambe products, the fiber and cosmetics industries are the most important sectors in the region. The cosmetics industry is no predominant industry in the Swabian Alb, but nevertheless there is a high company density within this field. The SWOT analysis revealed two positive trends: first, the cosmetics industry is already using crambe oil for its products, and second, the natural cosmetics are on the rise. Furthermore, the interviewed natural cosmetics industry, especially the small start-ups (Duschbrocken GmbH & Seifenreich Naturkosmetik Manufaktur), seemed to be open-minded and innovation focused. Moreover, they already address sustainability issues by producing solid body and hair care alternatives, as well as plastic free packaging to reduce environmental impacts. Crambe's status as a low-input crop could have additional value for these environmentally focused companies. Though the fiber industry showed interest in crambe, further research and laboratory analyses would first be necessary to determine the exact components of the fibers and to be able to align on possible uses. For these reasons, the adapted value chain focusses on the use of crambe seeds and oil by the natural cosmetics industry as well as on the energy generation from the residues of the seed pressing. Nutrients are recycled back to the farmer via bioslurry or green mulch.

Just as in the potential value web (Fig. 5), valuable products resulting from these pathways are the pure crambe seed oil, hair and skin care products, biogas, heat, and bioslurry. While the fiber companies learn about crambe and its value, it might be most valuable for the farmer to utilize the leaves and stems of crambe as a green mulch on the field. Indirectly involved stakeholders like academia, regional institutions, and social networks are equally essential in this value chain (Fig. 10). Indeed, these actors play key roles in stabilizing the proposed value chain and expanding it into the envisioned value web highlighted in Fig. 5.

4. General discussion

A huge gap exists between the potential value web (Fig. 5) and the implementable (final) value chain (Fig. 10). To evaluate the prospects of crambe, per the research question of this study, it is important to know about the limitations of this work and the requirements of stakeholders.

4.1. Research limitations

This manuscript is written prior to the completion of the MIDAS field trials in the Swabian Alb (Alexopoulou et al., 2023). This leaves many open questions, including crambe yields, quality, and composition.

Another important limitation is the method used to contact stakeholders. The questions asked in the questionnaires were very open, giving the stakeholders the option to answer with as much detail as they wanted. This was done to increase the answering rate; nevertheless, this method resulted in a high variance of answer quality. Furthermore, the open questions could have led to a convenience bias, usually receiving the most detailed and rather positive answers from interested and innovation-focused companies. In addition, no follow-up has been carried out with the stakeholders after receiving their answers.

In addition to these aspects, there was a lack of literature on various aspects of possible biorefinery processes (e.g. use of crambe straw in the fiber industry). This is a common problem when considering the prospects of introducing new crops and their respecitve value-chains which was also observed by Marraccini et al., 2020. This could have resulted in a confirmation bias, concentrating on the use of crambe seed oil in the cosmetics industry, which was easiest to conceptualize.

Further, the literature lacks data on other issues to be considered regarding the land-water-energy-food nexus of crambe-based crop rotations on marginal agricultural land. Besides the water demand (which is considered low for crambe because it is considered as drought tolerant and low demanding), another very important factor is the potential effect of crambe-based crop rotations on the groundwater quality. Usually, the groundwater quality is endangered due to nutrient leaching from agriculture, especially in view of the macronutrient nitrogen, particularily in form of ammonium or nitrate (collectively referred to as ‚N' in the following). It can be expected that there is a low risk of N leaching

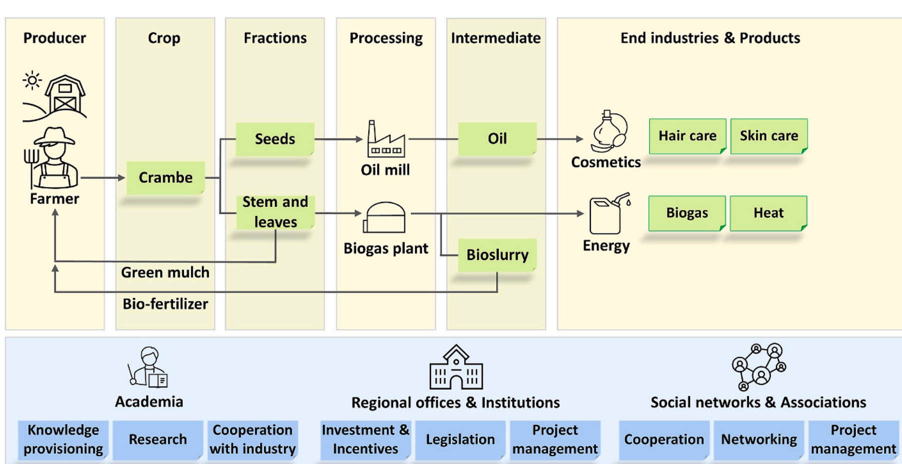

Fig. 10. Currently possible value chain in the Swabian Alb. Major stakeholders are represented by icons, while products are shown in rectangles. Green rectangles represent currently possible products. Solid lines show established product valorization pathways. Stakeholders, processors, and industries are in yellow columns, while biomass is depicted in green columns. The blue row along the bottom stands for stakeholders that influence the entire process from seeding to sales. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

due to crambe cultivation because it usually only requires low fertilization rates (about 50-120 kg N ha^{-1}) (Berzuini et al., 2021). Combined with an early harvest in August there would be enough time to either sow a winter annual crop (e.g., *Melilotus officinalis* L.) or a catch crop (e.g., *Phacelia tanacetifolia* Benth.). This could further reduce the risk of leaching due to any excess N in the soil but this has yet to be researched.

4.2. Marginal land in the Swabian Alb

As mentioned in the introduction, the EU project MIDAS aims at cultivating industrial crops on marginal agricultural land. On the marginal agricultural land of the Upper Lindenhof, where some field trials of MIDAS are occurring (Fig. 1), the conditions are not optimal for crop cultivation because of loamy, stony soil. According to Rieke and Wöllper (2018), the share of marginal land in the Swabian Alb, defined as land neither used for agricultural production purposes nor as forest area, only amounts to 0.1% in the main districts. Other stakeholders describe all shallow soils in the Swabian Alb, which are not optimal for cultivation but are nevertheless used by the farmers, as marginal land. These different definitions of marginal land affect the prospects for crambe grown in the Swabian Alb because the value web assumes crambe will only be cultivated on marginal land (in accordance with MIDAS) so not to compete with food crop cultivation. Taking these circumstances into consideration, it may be a challenge to achieve profitable yields which would reduce the economic sustainability of the crambe-based bioeconomy sector in the Swabian Alb. Even though marginal land could be suitable for cultivating crambe (Von Cossel et al., 2019b), farmers are unlikely to plant crambe if incomes are insufficient. Below, requirements of a successful crambe value web, including economic viability, described by stakeholders are discussed in more detail.

4.3. Requirements of stakeholders for a successful crambe value web

Several requirements for a successful establishment of a value web of crambe in the Swabian Alb have been noted by different stakeholders. They are shown in Table 4. General terms are used to group similar sentiments from multiple stakeholders.

The economic viability of crambe products was a major necessity for most stakeholder groups. Besides this, farmers seem to have a strong need for security, stating the importance of price, purchase guarantees, and policy support (Table 4). This demonstrates the key role of public institutions and the academic sector in supporting technological change as part of assessing the prospects of system innovations (Oylar-an-Oyyinka, 2006) like the crambe-based bioeconomy in the Swabian Alb. According to Geels (2004), a great opportunity for the success of system innovation generally lies in the fact that public institutions can also be used to conceptualize the dynamic interplay between actors and structures. In the case of crambe-based value chains, this would be in particular the actors from agriculture and industry (the actors) on the one hand and the regional offices and institutions on the other.

Furthermore, the farmers care about practical matters like the storability of crambe and its adverse effects in crop rotation with food crops. For the fiber and cosmetics industry, the exact chemical composition of the purchased parts needs to be known in advance, therefore initial chemical analytics play a key role for them. In contrast to the fiber industry, which needs large quantities, the rather small cosmetics companies seek lower purchase quantities of oil. Both industries require supply security; they need good storability, availability, and a working logistics system to allow for year-round production. In terms of economic sustainability, it was stated that an equal demand of all parts of the crop is crucial to (i) ensure minimal waste within the value web, and (ii) to enable additional revenue through the cascading use of crambe biomass. As the cosmetics industry can create high value from the oil, a strong focus is on quality aspects, mentioning quality certifications and controlled organic cultivation as core requirements (Table 4). Academic stakeholders furthermore call attention to the need for technical qualification and existing infrastructure for the value web. In addition, public institutions point out the necessity to meet the resource needs of the industry and the need to have enough agricultural land available in the region.

It was shown that a more holistic view makes sense to evaluate the prospects of crambe-based bioeconomy approaches in the Swabian Alb. This phenomenon of considering more than just one actor or just one technical aspect is consistent with the findings of Schut et al. (2014), who investigated an agricultural system innovation in the field of crop protection. In the future, however, it should be investigated more thoroughly which private and public goods would be influenced by this bioeconomy approach in the region (Lewandowski et al., 2024) (e.g. the promotion of biodiversity or the phytosanitary effect in crop rotation were mentioned in the survey) in order to enable a holistic evaluation.

5. Conclusion and outlook

After evaluating the industrial, agricultural, and institutional landscape of the Swabian Alb, the potential value web of crambe was narrowed down to a value chain with cosmetics as the prime target sector. This result incorporates results from both SWOT and stakeholder analysis. The smaller chain does not imply that crambe has few prospects in the Swabian Alb. It merely depicts the currently possible status, which, as indicated by the potential value web, has immense growth potential. Many stakeholders will be involved helping crambe production, from seeding to sales, thrive in the Swabian Alb. To help crambe reach its potential, several factors need to be addressed.

First of all, there is a lack of data on crambe cultivation in the Swabian Alb. There is no analysis of the long-term yield stability and biomass quality of crambe grown in the Swabian Alb. Yield stability,

Table 4
Requirements stated by stakeholders for crambe value web in the Swabian Alb.

Stakeholder category	Key requirements			
	Economic	Quality	Infrastructure	Other
Regional offices and institutions	- Economic viability - Meeting industrial resource needs		- Logistics	- Land availability
Industry – Fibers	- Economic viability - Supply security	- Chemical analytics	- Logistics	- Equal demand for all parts of the crop (i.e., no waste)
Industry – Cosmetics	- Supply security	- Chemical analytics - Oil quality certification - Controlled organic cultivation	- Regionality	- Small purchase quantities
Academia	- Economic viability	- Technical qualifications	- Logistics	
Farmers	- Economic viability - Price guarantee - Purchase guarantee	- Storability	- Logistics - Supporting agricultural policies	- No adverse effects in crop rotation

storability, and quality were principal factors for all stakeholders in crambe valorization (Table 4), especially with regard to concerns on the economic sustainability.

However, the fact that stakeholders, even those unfamiliar with crambe, showed positive interest in crambe and its fractions is promising. Thus, further trials and assessments on the field- and farm-level will help capitalize on the interest from local cosmetics and fiber industries. Farmers will become more familiar with this unique crop, and cultivation guidelines shared among farmers' associations could provide the foundation to grow the value chain into a more sustainable value web. Looking beyond the Swabian Alb, regional stakeholders could engage in knowledge transfer with other crambe-producing or -consuming regions. Other German companies and subject-matter experts may use crambe and might supply advice to help these products succeed in the Swabian Alb. Future research focusing on bioprocessing and production plants, leveraging diverse partners, would inform the more technical prospects of crambe in the Swabian Alb. This knowledge sharing would reinforce crambe's value for the region. However, it is vital to address both the specific concerns of local stakeholders and the social, economic, and environmental sustainability of crambe's value web. Solutions must be context-specific, and the concept of a sustainable bioeconomy should be at the centre of novel agricultural projects.

Sustainability requires more than just meeting market needs. To ensure the social-ecological sustainability of a crambe value web, further research and practical application is required. It is necessary to address these exact facets of sustainability by assessing environmental outcomes, such as biodiversity impact, nutrient leaching, erosion mitigation, and engaging social concerns in regional advisory groups. An integrated sustainability assessment, including environmental assessment, Life Cycle Costing, and Social Life-Cycle-Analysis for different biobased products will help giving clear scores across all dimensions of sustainability (MIDAS, 2023). While this study is narrowly scoped, designing a regional value web for one industrial biomass crop, the outcome and methodology of this research can also be transferred to other product systems to ensure sustainability is at the core of production.

CRediT authorship contribution statement

Lena-Sophie Loew: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Data curation, Conceptualization, Visualization. **Laura-Marie Fiedelak:** Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Mary Catherine Duff:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Yo Uetsuki:** Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Valentin Schlecht:** Writing – review & editing, Validation, Methodology. **Iris Lewandowski:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Federica Zanetti:** Writing – review & editing, Validation. **Efthymia Alexopoulou:** Funding acquisition, Conceptualization, Project administration, Writing – review & editing. **Moritz von Cossel:** Writing – review & editing, Visualization, Validation, Data curation, Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

Agrarmeteorologie Baden-Württemberg. Wetterstation oberer Lindenhof - langjährige mittelwerte. https://www.wetter-bw.de/Internet/AM/NotesBwAM.nsf/bwweb/909632485a7411e3c1257db20026831b?OpenDocument&TableRow=3.1.1.

Alexmo cosmetics, 2023. Abyssinian (krambe) öl, raff [WWW Document]. URL. https://www.alexmo-cosmetics.de/Abyssinian-Krambe-Oel-raff. (Accessed 11 June 2023).

Alexopoulou, E., Elbersen, B., Trindade, L., Cosentino, S.L., Monti, A., Carmona, M., Lewandowski, I., Kyritsis, S., Cocchi, M., Papazoglou, E.G.. The MIDAS project: utilization of marginal lands for growing sustainable industrial crops and developing innovative bio-based products. https://www.scopus.com/record/display.uri?eid=2-s2.0-85174599914&origin=resultslist.

Altieri, M.A., 1999. The ecological role of biodiversity in agroecosystems. Agric. Ecosyst. Environ. 74, 19–31. https://doi.org/10.1016/S0167-8809(99)00028-6.

Anderson, M.D., Peng, C., Weissl, M.J., 1992. Crambe, Crambe abyssinica Hochst., as a flea beetle resistant crop (Coleoptera: chrysomelidae). J. Econ. Entomol. 85, 594–600. https://doi.org/10.1093/jee/85.2.594.

BECOOL, 2023. Brazil-EU cooperation for development of advanced lignocellulosic biofuels [WWW document]. URL. https://cordis.europa.eu/project/id/744821. (Accessed 10 August 2023).

BeonNAT, 2023. Innovative value chains from tree & shrub species grown on marginal lands as a source of biomass for biobased industries. BeonNAT project. . https://beonnat.eu/ (Accessed 10 August 2023).

Berzuini, S., Zanetti, F., Christou, M., Alexopoulou, E., Krzyżaniak, M., Stolarski, M.J., Ferioli, F., Monti, A., 2021. Optimization of agricultural practices for crambe in Europe. Ind. Crop. Prod. 171, 113880 https://doi.org/10.1016/j.indcrop.2021.113880.

BIKE, 2023. Biofuels production at low – ILUC risk for European sustainable bioeconomy [WWW document]. The project URL. https://www.bike-biofuels.eu/the-project/ (Accessed 10 August 2023).

Biosphärengebiet Schwäbische Alb, 2023. Biosphärengebiet Schwäbische Alb: Landwirtschaft im Biosphärengebiet Schwäbische Alb [WWW Document]. URL. https://www.biosphaerengebiet-alb.de/schuetzen-entwickeln/landwirtschaft. (Accessed 11 June 2023).

Boulestreau, Y., Peyras, C.-L., Casagrande, M., Navarrete, M., 2022. Tracking down coupled innovations supporting agroecological vegetable crop protection to foster sustainability transition of agrifood systems. Agric. Syst. 196, 103354 https://doi.org/10.1016/j.agsy.2021.103354.

Carlson, K.D., Tookey, H.L., 1983. Crambe meal as a protein source for feeds. JAOCS (J. Am. Oil Chem. Soc.) 60, 1979–1985. https://doi.org/10.1007/BF02669969.

Cavalheiro, L.F., Prado, E.R.L., de Freitas, O.N., Nazário, C.E.D., Rial, R.C., Viana, L.H., 2023. Biofuels obtained from the crambe (Crambe abyssinica) oil. J. Anal. Appl. Pyrol. 175, 106214 https://doi.org/10.1016/j.jaap.2023.106214.

Chui, M., Evers, M., Manyika, J., Zheng, A., Nisbel, T., 2020. The Bio Revolution Innovations Transforming Economies, Societies, and Our Lives. https://www.mckinsey.com/industries/life-sciences/our-insights/the-bio-revolution-innovations-transforming-economies-societies-and-our-lives.

Clifton-Brown, J., Hastings, A., von Cossel, M., Murphy-Bokern, D., McCalmont, J., Whitaker, J., Alexopoulou, E., Amaducci, S., Andronic, L., Ashman, C., Awty-Carroll, D., Bhatia, R., Breuer, L., Cosentino, S., Cracroft-Eley, W., Donnison, I., Elbersen, B., Ferrarini, A., Ford, J., Greef, J., Ingram, J., Lewandowski, I., Magenau, E., Mos, M., Petrick, M., Pogrzeba, M., Robson, P., Rowe, R.L., Sandu, A., Schwarz, K.-U., Scordia, D., Scurlock, J., Shepherd, A., Thornton, J., Trindade, L.M., Vetter, S., Wagner, M., Wu, P.-C., Yamada, T., Kiesel, A., 2023. Perennial biomass cropping and use: shaping the policy ecosystem in European countries. GCB Bioenergy 15, 538–558. https://doi.org/10.1111/gcbb.13038.

Coltro-Roncato, S., Stangarlin, J.R., Júnior, A.C.G., Kuhn, O.J., Gonçalves, E.D.V., Dildey, O.D.F., De Moraes Flores, É.L., 2016. Nematicidal activity of crambe extracts on Meloidogyne spp. Semina. Ciencias Agrarias 37, 1857–1870. https://doi.org/10.5433/1679-0359.2016v37n4p1857.

Costa, E.F., Almeida, M., Alvim-Ferraz, C., Dias, J.M., 2019. Cultivation of Crambe abyssinica non-food crop in Portugal for bioenergy purposes: agronomic and environmental assessment. Ind. Crop. Prod. 139, 111501 https://doi.org/10.1016/j.indcrop.2019.111501.

de Groot, R., Brander, L., van der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christie, M., Crossman, N., Ghermandi, A., Hein, L., Hussain, S., Kumar, P., McVittie, A., Portela, R., Rodriguez, L.C., ten Brink, P., van Beukering, P., 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosyst. Serv. 1, 50–61. https://doi.org/10.1016/j.ecoser.2012.07.005.

Dentoni, D., Cucchi, C., Roglic, M., Lubberink, R., Bender-Salazar, R., Manyise, T., 2022. Systems thinking, mapping and change in food and agriculture. Bio base Appl. Econ. 11, 277–301. https://doi.org/10.36253/bae-13930.

European Commission Directorate-General for Research and Innovation, 2023. Horizon Europe. https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en.

DFG Research Unit, 2017. Mittlere Schwäbische Alb: DFG research unit 1695 "regional climate change". URL. https://klimawandel.uni-hohenheim.de/en/alb0 (Accessed 11 June 2023).

Donner, M., Gohier, R., de Vries, H., 2020. A new circular business model typology for creating value from agro-waste. Sci. Total Environ. 716, 137065 https://doi.org/10.1016/j.scitotenv.2020.137065.

European Commission, Directorate-General for Research and Innovation, 2019. Bioeconomy : the European Way to Use Our Natural Resources : Action Plan 2018. Publications Office. https://doi.org/10.2777/79401.

Ferdini, S., von Cossel, M., Wulfmeyer, V., Warrach-Sagi, K., 2023. Climate-based identification of suitable cropping areas for giant reed and reed canary grass on marginal land in Central and Southern Europe under climate change. GCB Bioenergy 15 (4), 424–443. https://doi.org/10.1111/gcbb.13033.

FIBRA, 2015. Fiber crops as a sustainable source of bio-based materials for industrial products in Europe and China. URL. (Accessed 10 August 2023).

FIRST2RUN, 2019. Flagship demonstration of an integrated biorefinery for dry crops sustainable exploitation towards biobased materials production. URL. (Accessed 10 August 2023).

FNR, 2001. Krambe - eine alternative Sommerölfrucht (translation: Crambe - an alternative summer oil fruit). Landwirtschaftsverlag, Münster, Germany. URL. https://idw-online.de/de/news42786.

FORBIO, 2018. Fostering sustainable feedstock production for advanced biofuels on underutilised land in Europe. URL. In: . https://cordis.europa.eu/project/id/691846 (Accessed 10 August 2023).

Fritsche, U., Brunori, G., Chiaramonti, D., Galanakis, C., Hellweg, S., Matthews, R., Panoutsou, C., 2020. In: Future Transitions for the Bioeconomy towards Sustainable Development and a Climate-Neutral Economy—Knowledge Synthesis Final Report, 10. Publications Office of the European Union, Luxembourg, p. 667966. URL. https://publications.jrc.ec.europa.eu/repository/handle/JRC121212.

European Commission, 2022. Utilization of Marginal lands for growing sustainable industrial crops and developing innovative bio-based products | MIDAS | Project | Fact sheet | HORIZON. CORDIS - EU research results. URL. https://cordis.europa.eu/project/id/101082070.

Future Market Insights, 2022. Crambe Abyssinica Seed Oil Market Outlook (2022 to 2032) [WWW Document]. URL (Accessed 13 May 2024).

Gascuel-Odoux, C., Lescourret, F., Dedieu, B., Detang-Dessendre, C., Faverdin, P., Hazard, L., Litrico-Chiarelli, I., Petit, S., Roques, L., Reboud, X., Tixier-Boichard, M., de Vries, H., Caquet, T., 2022. A research agenda for scaling up agroecology in European countries. Agron. Sustain. Dev. 42, 53. https://doi.org/10.1007/s13593-022-00786-4.

Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory. Res. Pol. 33, 897–920. https://doi.org/10.1016/j.respol.2004.01.015.

Glaser, L.K., 1996. Crambe: an Economic Assessment of the Feasibility of Providing Multiple-Peril Crop Insurance. Economic Research Service for the Risk Management. https://legacy.rma.usda.gov/pilots/feasible/PDF/crambe.pdf.

GOLD, 2023. Growing energy crops on contaminated land for biofuels and soil remediation. Growing energy crops on contaminated land for biofuels and soil remediation. URL. https://www.gold-h2020.eu/.

Gonçalves, A.C., Schwantes, D., Braga de Sousa, R.F., Benetoli da Silva, T.R., Guimarães, V.F., Campagnolo, M.A., Soares de Vasconcelos, E., Zimmermann, J., 2020. Phytoremediation capacity, growth and physiological responses of Crambe abyssinica Hochst on soil contaminated with Cd and Pb. J. Environ. Manag. 262, 110342 https://doi.org/10.1016/j.jenvman.2020.110342.

GRACE, 2023. GRowing Advanced industrial Crops on marginal lands for biorEfineries. URL. . https://www.grace-bbi.eu/project/ (Accessed 10 August 2023).

Hebard, A., 2016. Successful commercialization of industrial oil crops. Ind.Oil Crop. 343–358. https://doi.org/10.1016/B978-1-893997-98-1.00012-9.

Hempoint, 2022. 2022 Hemp seed catalogue - EU registered varieties. In: Hempoint, s.r.o., Hruškové Dvory 116, 586 01 Jihlava, Czech Republic. URL. In: . https://hempoint.cz/wp-content/uploads/2022/01/Hemp-seeds-2022.pdf.

Ionov, M., Yuldasheva, N., Ulchenko, N., Glushenkova, A.I., Heuer, B., 2013. Growth, development and yield of crambe abyssinica under saline irrigation in the greenhouse. J. Agron. Crop Sci. 199, 331–339. https://doi.org/10.1111/JAC.12027.

Jakob, K., Bramm, A., Ochrimenko, N., 1999. Effect of water and nitrogen on yield and quality parameters of crambe. Crambe abyssinica Hochst. ex. R.E. Fries). Pflanzenbauwissenschaften 3, 40–51.

Jankowski, K.J., Sokólski, M., Szatkowski, A., Kozak, M., 2022. Crambe – energy efficiency of biomass production and mineral fertilization. A case study in Poland. Ind. Crop. Prod. 182, 114918 https://doi.org/10.1016/j.indcrop.2022.114918.

Kaplinsky, R., Morris, M., 2001. A Handbook for Value Chain Research. Brighton.

Keegan, D., Kretschmer, B., Elbersen, B., Panoutsou, C., 2013. Cascading use: a systematic approach to biomass beyond the energy sector. Biofuels.Bioprod. Biorefining 7, 193–206. https://doi.org/10.1002/bbb.1351.

Klaus, M., Makowski, N., 1996. Untersuchungen zur N-dungung bei krambe (Crambe abyssinica hochst. EX R.E. fries). Arch. Agron Soil Sci. 40, 197–204. https://doi.org/10.1080/03650349609365947.

Kleine, A., von Hauff, M., 2009. Sustainability-driven implementation of corporate social responsibility: application of the integrative sustainability triangle. J. Bus. Ethics 85, 517–533. https://doi.org/10.1007/s10551-009-0212-z.

Krzyżaniak, M., Stolarski, M.J., 2019. Life cycle assessment of camelina and crambe production for biorefinery and energy purposes. J. Clean. Prod. 237, 117755 https://doi.org/10.1016/j.jclepro.2019.117755.

Krzyżaniak, M., Stolarski, M.J., Graban, Ł., Lajszner, W., Kuriata, T., 2020. Camelina and crambe oil crops for bioeconomy—straw utilisation for energy. Energies 13, 1503. https://doi.org/10.3390/en13061503.

Lange, L., Bech, L., Busk, P.K., Grell, M.N., Huang, Y., Lange, M., Linde, T., Pilgaard, B., Roth, D., Tong, X., 2012. The importance of fungi and of mycology for a global development of the bioeconomy. IMA Fungus 3, 87–92. https://doi.org/10.5598/IMAFUNGUS.2012.03.01.09.

Lavera Naturkosmetik, 2023a. Basis sensitiv Feuchtigkeitscreme [WWW Document]. URL https://www.lavera.de/basis-sensitiv-feuchtigkeitscreme-4021457649945. .

Lavera Naturkosmetik, 2023b. Lavera glow by nature serum [WWW Document]. URL https://www.lavera.de/glow-by-nature-serum-4021457650217. . (Accessed 11 June 2023).

Lazzeri, L., Leoni, O., Conte, L.S., Palmieri, S., 1994. Some technological characteristics and potential uses of Crambe abyssinica products. Ind. Crop. Prod. 3, 103–112. https://doi.org/10.1016/0926-6690(94)90083-3.

Lewandowski, I., Von Cossel, M., Winkler, B., Bauerle, A., Gaudet, N., Kiesel, A., Lewin, E., Magenau, E., Marting Vidaurre, N.A., Müller, B., Schlecht, V., Thumm, U., Trenkner, M., Vargas-Carpintero, R., Weickert, S., Weik, J., Reinmuth, E., 2024. An adapted indicator framework for evaluating the potential contribution of bioeconomy approaches to agricultural systems resilience. Adv. Sustain. Syst. https://doi.org/10.1002/adsu.202300518.

Lewandowski, I. (Ed.), 2018. Bioeconomy: Shaping the Transition to a Sustainable, Biobased Economy. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-68152-8.

Leonard, E.C., 1992. High-erucic vegetable oils. Ind. Crop. Prod. 1 (2), 119–123. https://doi.org/10.1016/0926-6690(92)90009-K.

Lewandowski, I., 2017. Increasing biomass production to sustain the bioeconomy. In: Knowledge-Driven Developments in the Bioeconomy. Springer, Cham, pp. 179–203. https://doi.org/10.1007/978-3-319-58374-7_10.

LIBBIO, 2021. Lupinus mutabilis for Increased Biomass from marginal lands and value for BIOrefineries [WWW Document]. Lupinus mutabilis for Increased Biomass from marginal lands and value for BIOrefineries. URL. https://cordis.europa.eu/project/id/720726. (Accessed 10 August 2023).

MAGIC, 2021. Marginal lands for growing industrial crops: turning a burden into an opportunity [WWW document]. Marginal lands for growing industrial crops: turning a burden into an opportunity. URL. https://cordis.europa.eu/project/id/727698. (Accessed 10 August 2023).

Manske products for cosmetics, 2023. Abyssinianöl Raffiniert 100 Ml. https://www.manske-shop.com/Oele-Butter-Wachs-konventionell/Oele/Abyssinianoel/Abyssinianoel-raffiniert-100-ml.html.

Marraccini, E., Gotor, A.A., Scheurer, O., Leclercq, C., 2020. An Innovative Land Suitability Method to Assess the Potential for the Introduction of a New Crop at a Regional Level. Agronomy 10 (3). Article 3. https://doi.org/10.3390/agronomy10030330.

Marting Vidaurre, N.A., Vargas-Carpintero, R., Wagner, M., Lask, J., Lewandowski, I., 2020. Social aspects in the assessment of biobased value chains. Sustainability 12, 9843. https://doi.org/10.3390/su12239843.

MIDAS, 2023. MIDAS – Marginal Lands and Industrial Crops for the European Bioeconomy. Website. https://www.midas-bioeconomy.eu/.

Moura, L.M.F., Costa, A.C., Müller, C., Filho, R.O.S., Almeida, G.M., Vital, R.G., de Castro, J.N., Teixeira, M.B., 2018. Drought tolerance in potential oilseed plants for biofuel production. Aust. J. Crop. Sci. 12, 289–298. https://doi.org/10.21475/ajcs.18.12.02.pne836.

MULTIHEMP, 2017. Multipurpose hemp for industrial bioproducts and biomass. https://cordis.europa.eu/project/id/311849.

Nature in Bottle, 2023. Abyssinian (crambe) seed oil. https://www.natureinbottle.com/product/abyssinian_crambe_oil.

Neckaralb. Industries & Clusters. URL. https://www.neckaralb.de/en/business-location-investor-service/industries-cluster.

Newson, W.R., Kuktaite, R., Hedenqvist, M.S., Gällstedt, M., Johansson, E., 2013. Oilseed meal based plastics from plasticized, hot pressed crambe abyssinica and Brassica carinata residuals. JAOCS (J. Am. Oil Chem. Soc.) 90, 1229–1237. https://doi.org/10.1007/s11746-013-2261-9.

Oliveira, C.E.S., Zoz, T., Castagnara, D.D., Zoz, A., Mortinho, E.S., Fernandes, G.C., Sobrinho, R.L., Faria, G.A., 2023. Growth of crambe under different soil bulk densities and water restriction. Russ. J. Plant Physiol. 70, 63. https://doi.org/10.1134/S1021443722602592.

OPTIMISC, 2016. Optimizing Miscanthus Biomass Production - OPTIMISC. [WWW Document]. Optimizing Miscanthus Biomass Production - OPTIMISC. URL. https://cordis.europa.eu/project/id/289159. (Accessed 10 August 2023).

Oyelaran-Oyeyinka, B., 2006. Systems of innovation and underdevelopment: an institutional perspective. Sci. Technol. Soc. 11, 239–269. https://doi.org/10.1177/097172180601100201.

PANACEA, 2021. Panacea - a thematic network to design the penetration PAth of non-food agricultural crops into European agriculture. URL. . https://ec.europa.eu/eip/agriculture/en/find-connect/projects/panacea-thematic-network-design-penetration-path.html (Accessed 10 August 2023).

Panoutsou, C., Germer, S., Karka, P., Papadokostantakis, S., Kroyan, Y., Wojcieszyk, M., Maniatis, K., Marchand, P., Landalv, I., 2021. Advanced biofuels to decarbonise European transport by 2030: markets, challenges, and policies that impact their successful market uptake. Energy Strategy Rev. 34, 100633 https://doi.org/10.1016/j.esr.2021.100633.

Panoutsou, C., von Cossel, M., Ciria, P., Ciria, C.S., Baraniecki, P., Monti, A., Zanetti, F., Dubois, J.-L., 2022. Social considerations for the cultivation of industrial crops on marginal agricultural land as feedstock for bioeconomy. Biofuels.Bioprod. Biorefining 16, 1319–1341. https://doi.org/10.1002/bbb.2376.
Pawar, R.V., Hulwan, D.B., Mandale, M.B., 2022. Recent advancements in synthesis, rheological characterization, and tribological performance of vegetable oil-based lubricants enhanced with nanoparticles for sustainable lubrication. J. Clean. Prod. 378, 134454 https://doi.org/10.1016/j.jclepro.2022.134454.
Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., 2022. IPCC 2022: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC. https://www.ipcc.ch/report/ar6/wg2/.
Power, A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies. Phil. Trans. Biol. Sci. 365, 2959–2971. https://doi.org/10.1098/rstb.2010.0143.
Pushkarova, N., Yemets, A., 2022. Biotechnological approach for improvement of Crambe species as valuable oilseed plants for industrial purposes. RSC Adv. 12, 7168–7178. https://doi.org/10.1039/D2RA00422D.
Reinhardt, J., Hilgert, P., Von Cossel, M., 2022. Yield performance of dedicated industrial crops on low-temperature characterized marginal agricultural land in Europe – a review. Biofuels.Bioprod.Biorefining 16, 609–622. https://doi.org/10.1002/bbb.2314.
Ricciotti, F., 2020. From value chain to value network: a systematic literature review. Manag. Rev.Q. 70, 191–212. https://doi.org/10.1007/s11301-019-00164-7.
Rieke, J., Wöllper, F., 2018. Flächen für Landwirtschaft in den Kreisen Baden-Württembergs. Statistisches Monatsheft Baden-Württemberg 9, 55–59. https://www.statistik-bw.de/Service/Veroeff/Monatshefte/PDF/Beitrag18_09_11.pdf.
Righini, D., Zanetti, F., Monti, A., 2016. The bio-based economy can serve as the springboard for camelina and crambe to quit the limbo. Oilseeds.Fats.Crops.Lipids. 23 https://doi.org/10.1051/OCL/2016021.
Romero-Perdomo, F., Carvajalino-Umaña, J.D., Moreno-Gallego, J.L., Ardila, N., González-Curbelo, M.Á., 2022. Research trends on climate change and circular economy from a knowledge mapping perspective. Sustainability 14, 521. https://doi.org/10.3390/su14010521.
Samarappuli, D., Zanetti, F., Berzuini, S., Berti, M.T., 2020. Crambe (crambe abyssinica hochst): a non-food oilseed crop with great potential: a review. Page 1380 10, 1380 Agronomy 10 (2020). https://doi.org/10.3390/AGRONOMY10091380.
Scheiterle, L., Ulmer, A., Birner, R., Pyka, A., 2018. From commodity-based value chains to biomass-based value webs: the case of sugarcane in Brazil's bioeconomy. J. Clean. Prod. 172, 3851–3863. https://doi.org/10.1016/j.jclepro.2017.05.150.
Schut, M., Rodenburg, J., Klerkx, L., van Ast, A., Bastiaans, L., 2014. Systems approaches to innovation in crop protection. A systematic literature review. Crop Protect. 56, 98–108. https://doi.org/10.1016/j.cropro.2013.11.017.
SEEMLA, 2018. Sustainable exploitation of biomass for bioenergy from marginal lands in Europe. URL. . https://cordis.europa.eu/project/id/691874 (Accessed 10 August 2023).
Stahel, W.R., 2016. The circular economy. Nature 531, 435–438. https://doi.org/10.1038/531435a.
SUNLIBB, 2014. Sustainable liquid biofuels from biomass biorefining. (Accessed 10 August 2023).
Tarini, G., Melo, A.S., Fontana, L.F., da Silva, E., Bolanho, B.C., Moreno, B.P., Sarragiotto, M.H., Dias-Arieira, C.R., 2020. Aqueous extracts of Crambe abyssinica seed cake: chemical composition and potential for nematode control. Ind. Crop. Prod. 156, 112860 https://doi.org/10.1016/j.indcrop.2020.112860.
Teitelbaum, L., Boldt, C., Patermann, C., 2020. Global Bioeconomy Policy Report (IV): a decade of bioeconomy policy development around the world. In: Secretariat of the Global Bioeconomy Summit 2020 C/o BIOCOM AG, Berlin, Germany, p. 9. https://gbs2020.net/wp-content/uploads/2021/04/GBS-2020_Global-Bioeconomy-Policy-Report_IV_web-2.pdf, 30.3.24.
Tscharntke, T., Klein, A.M., Kruess, A., Steffan-Dewenter, I., Thies, C., 2005. Landscape perspectives on agricultural intensification and biodiversity – ecosystem service management. Ecol. Lett. 8, 857–874. https://doi.org/10.1111/j.1461-0248.2005.00782.x.
UHOH, 2023. Department biobased resources in the bioeconomy, Institute of Crops Science. University of Hohenheim (Accessed 10 August 2023).
United Nations Department of Economic and Social Affairs. World population prospects 2022: summary of results. UN DESA/POP/2021/TR/NO. 3. URL. https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/wpp2022_summary_of_results.pdf.
University of Hohenheim, 2020. Lindenhöfe: agricultural experiment station. URL. https://versuchsstation.uni-hohenheim.de/en/lindenhoefe-en.
Virchow, D., Beuchelt, T.D., Kuhn, A., Denich, M., 2016. Biomass-based value webs: a novel perspective for emerging bioeconomies in Sub-Saharan Africa. Technol.Inst. Innovat.Marginalized Smallholders.Agric.Dev. 225–238. https://doi.org/10.1007/978-3-319-25718-1_14/FIGURES/2.
Von Cossel, M., Lewandowski, I., Elbersen, B., Staritsky, I., Van Eupen, M., Iqbal, Y., Mantel, S., Scordia, D., Testa, G., Cosentino, S.L., Maliarenko, O., Eleftheriadis, I., Zanetti, F., Monti, A., Lazdina, D., Neimane, S., Lamy, I., Ciadamiro, L., Sanz, M., Carrasco, J.E., Ciria, P., McCallum, I., Trindade, L.M., Van Loo, E.N., Elbersen, W., Fernando, A.L., Papazoglou, E.G., Alexopoulou, E., 2019b. Marginal agricultural land low-input systems for biomass production. Energies 12, 3123. https://doi.org/10.3390/en12163123.
Von Cossel, M., Wagner, M., Lask, J., Magenau, E., Bauerle, A., Von Cossel, V., Warrach-Sagi, K., Elbersen, B., Staritsky, I., Van Eupen, M., Iqbal, Y., Jablonowski, N.D., Happe, S., Fernando, A.L., Scordia, D., Cosentino, S.L., Wulfmeyer, V., Lewandowski, I., Winkler, B., 2019a. Prospects of bioenergy cropping systems for a more social-ecologically sound bioeconomy. Agronomy 9, 605. https://doi.org/10.3390/agronomy9100605.
Von Cossel, M., Winkler, B., Mangold, A., Lask, J., Wagner, M., Lewandowski, I., Elbersen, B., van Eupen, M., Mantel, S., Kiesel, A., 2020. Bridging the gap between biofuels and biodiversity through monetizing environmental services of miscanthus cultivation. Earth's Future 8, e2020EF001478. https://doi.org/10.1029/2020EF001478.
Wagner, M., Winkler, B., Lask, J., Weik, J., Kiesel, A., Koch, M., Clifton-Brown, J., von Cossel, M., 2022. The true costs and benefits of miscanthus cultivation. Agronomy 12, 3071. https://doi.org/10.3390/agronomy12123071.
Walker, J.T., 1996. Crambe and rapeseed meal as soil amendments: nematicidal potential and phytotoxic effects. Crop Protect. 15, 433–437. https://doi.org/10.1016/0261-2194(96)00001-4.
Wang, J., Ma, D., Lou, Y., Ma, J., Xing, D., 2023. Optimization of biogas production from straw wastes by different pretreatments: progress, challenges, and prospects. Sci. Total Environ. 905, 166992 https://doi.org/10.1016/j.scitotenv.2023.166992.
Wohlfahrt, J., Ferchaud, F., Gabrielle, B., Godard, C., Kurek, B., Loyce, C., Therond, O., 2019. Characteristics of bioeconomy systems and sustainability issues at the territorial scale. A review. J. Clean. Prod. 232, 898–909. https://doi.org/10.1016/j.jclepro.2019.05.385.
World Commission on Environment and Development, 1987. Our Common Future, from One Earth to One World.URL. https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf.
Zanetti, F., Scordia, D., Vamerali, T., Copani, V., Cortivo, C.D., Mosca, G., 2016. Crambe abyssinica a non-food crop with potential for the Mediterranean climate: insights on productive performances and root growth. Ind. Crop. Prod. 90, 152–160. https://doi.org/10.1016/J.INDCROP.2016.06.023.
Zhu, L.H., 2016. Crambe (crambe abyssinica). Ind.Oil Crop. 195–205. https://doi.org/10.1016/B978-1-893997-98-1.00007-5.