Original Article

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# Social considerations for the cultivation of industrial crops on marginal agricultural land as feedstock for bioeconomy

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Abstract: Marginal agricultural land (MAL) has received much attention in research and policy formation as a potential resource for cultivating biomass for energy and biobased products. However, it is still unclear whether biomass from MAL meets the requirements of social sustainability. This study develops a conceptual linkage between value-chain analysis and social life-cycle analysis (S-LCA), and assesses both positive impacts (handprints) and negative impacts (footprints). A participatory approach including interviews and surveys was used to understand views and perceptions of the relevant stakeholders. A systemic strategy was applied to analyze value-chain activities, understand challenges, and identify competitive advantages and disadvantages. For S-LCA, the variety of impacts and indicators was met through a literature review and a consistent scoring system. The cultivation of perennial crops on MAL tends to cause skepticism among stakeholders, who are concerned about long-term commitment and biodiversity risks. Annual crops, on the other hand, are perceived by all stakeholder categories as very promising opportunities across all impact categories and indicators. They can facilitate income diversification and offer smart sustainable cropping options through crop rotation, agroforestry, etc. Most of the technological pathways examined are highly innovative, have a low technological readiness level, and are still at the early market development stage. As such they are ranked by stakeholders as

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medium opportunities for short-term implementation. In contrast, pyrolysis to industrial heat, ethanol from switchgrass, insulation material from hemp, and biogas/biomethane from sorghum are considered opportunities with good chances of being implemented in the short term. 

*Supporting information may be found in the online version of this article.*

Key words: bioeconomy; industrial crops; marginal agricultural land; rural development; S-LCA; social; sustainable development; perennial crops

## Introduction

The concept of restoring marginal agricultural land (MAL)[1,2] and simultaneously producing feedstock for biobased sectors[3,4] has gained attention through the years[5] as an attractive, low-input option[6,7] that can improve soil carbon[8] and provide renewable energy and raw materials.[9–12] Life-cycle analysis (LCA) has often been used as an approach to understand how such value chains can be established and operated with respect to safe planetary boundaries.[13–16] Research has focused primarily on environmental and economic issues[17,18] whereas the social implications[19] have so far received considerably less attention.[20] This is because social life-cycle analysis (S-LCA) is perceived most of the times as biased by subjective views of stakeholders for specific value chains. This restricts comparability of findings and potentially excludes regionally specific impacts.[21] Lack of suitable indicators has also been reported[22–24] as an additional limitation[25,26] which prohibits the connection of metrics to value-chain performance and stakeholder relevance, and thus reduces the transferability of results.[27,28]

Understanding the challenges that affect biobased value chains within the individual value-chain stages, and working directly with stakeholders to complement and focus life-cycle assessment, could reduce the uncertainties and deliver informed inputs for the socially relevant challenges related to their sustainable establishment and operation.[29] This study therefore combines value-chain analysis and stakeholder participatory methods with the UNEP/SETAC methodology[30] for SLCA and evaluates the social implications from specific biobased value chains that use as feedstock industrial crops[31] grown on MAL.[20]

The aim of this study is to focus on farming activities on MAL, providing evidence at individual value-chain stages. As such it complements other significant research on this topic, which examines the social implications for specific stakeholder categories,[32,33] levels of application (company, local, national and international), etc. It also captures the differentiated effects across three agro-ecological zones: Mediterranean, Atlantic, and Continental and Boreal, for ten value chains. The differentiation includes (i) crop type (annual[34] or perennial[35]) and (ii) technological readiness level (TRL) of the conversion pathways. The ten value chains form a representative matrix of biobased products, such as biotumen, organic acids, methyl decanoate, sebacic acid, insulation material, biogas/biomethane and adhesives, and services such as heat and electricity.

## Methods

This work establishes a conceptual, systemic[36] link among value-chain analysis (VCA), participatory methods, and S-LCA. It evaluates the positive impacts or handprints[37] (e.g., creation of jobs) and negative ones or footprints (e.g., land use). Social handprints[38] are the results of changes to 'business as usual' that create positive outcomes or impacts. They can be changes that reduce the social footprint or create additional/unrelated positive social impacts. Those changes can apply to the product or organization value chain or beyond its scope. Social footprints refer to adverse negative implications that result from the operation of a value chain or the use of a product or service. They can derive from the overall assessment or by impact category/subcategory.

### Value-chain analysis

Biobased value chains involve complex, cross sectoral interactions between their upstream and downstream stages. Moreover, their suitability, efficiency, and appropriate implementation scales depend on geographical and climate features, so their optimal performance tends to be region and case specific.[39] Decision making for their establishment and operation should therefore tackle the challenges and inform important decision matters for each value-chain stage, reflect their relevant merits and disadvantages, and use the evidence provided to optimize synergies and drive positive behaviors.

Value-chain analysis has been introduced by Porter[40] to represent internal activities involved with producing goods and services. The approach applies a systemic strategy[41] to analyze value-chain activities, understand challenges, and identify competitive advantages and disadvantages. Value-chain analysis fits well with the dynamic structure of the biobased value chains, which has interrelated stages for land use, biomass production, conversion, and end use (Fig. 1).

## Participatory methods

To understand the views and perceptions of relevant stakeholders[42] the work has also adapted a participatory approach[43–46] (Fig. 2). A series of interviews and surveys (Annex I in Appendix S1), has been undertaken through online webinar activities (i) to identify important challenges[47] that restrict the development and operation within and across the value-chain stages,[48,49] and (ii) to agree on S-LCA impact categories that relate to the challenges and select indicators that are relevant to the social implications of the value chains' performance but can also be associated to the stakeholder groups (farmers,[50] value-chain actors, and local communities).

## Social life-cycle analysis

Social life-cycle analysis is the social equivalent of environmental LCA.[51] It can operate 'from cradle to grave' and addresses social impacts within specified stages of a value chain at generic, local, and global scales.[52] Its systemic approach[53] accounts for social practices[54] and aligns well with the integration of biobased value chains[55] at territorial level or in specific sector-product systems.[56,57] Table 1 outlines the methodological challenges[58] in S-LCA and the respective approaches adopted in this paper to overcome them.

The work adopted the UNEP SETAC life-cycle initiative principles. This approach adds another dimension to social impacts, which is the stakeholders' role, so it has been considered more appropriate. The respective definition for social impact is: 'Consequences of social relations (interactions) weaved in the context of an activity (production, consumption or disposal) and/or stimulated by it and/or by preventive or reinforcing actions taken by stakeholders (ex. enforcing safety measures in a facility). Therefore, social impacts are dimensions of stakeholders relations affected positively or negatively by one of the stages in the life cycle of a product.'[59]

### Stakeholder categories

The following stakeholder categories are included in UNEP/SETAC: the local community, value-chain actors, consumers,

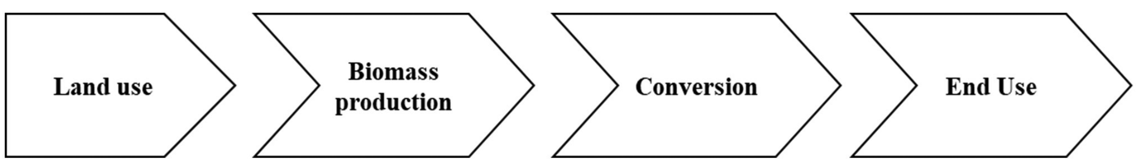


Figure 1. Value-chain stages in marginal agricultural land restoration with the cultivation of industrial crops for biobased products.

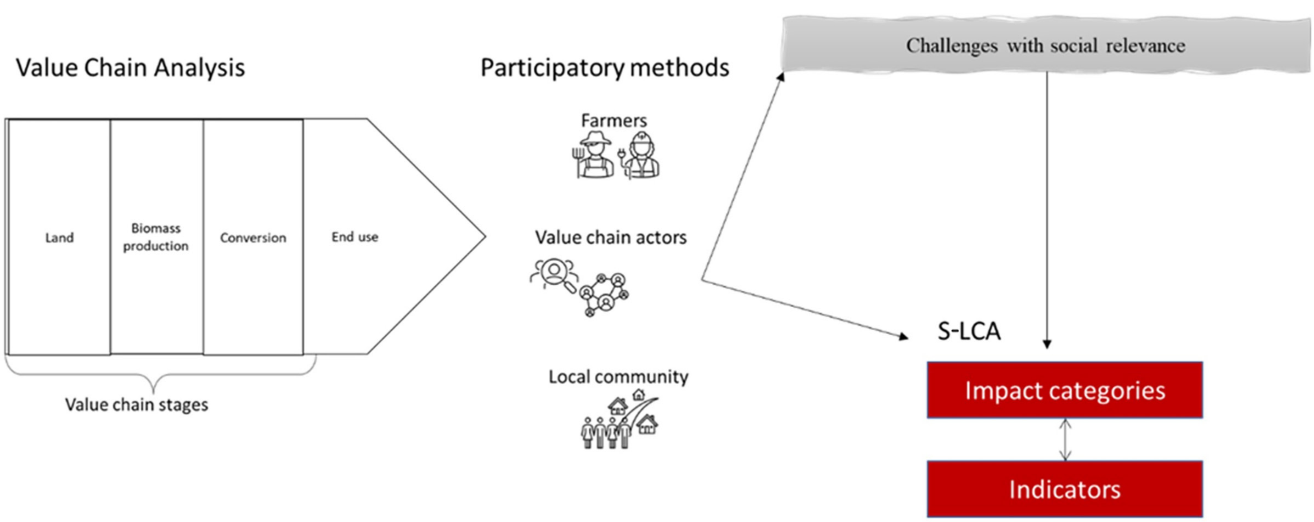


Figure 2. Conceptual link of the approaches used (S-LCA, social life cycle analysis).

workers, and society. In this work, we have focused on farmers in the category of workers, value-chain actors, and the local community. Their relevance to the value chain's stages is illustrated in Fig. 3 and described below.

## Goal and scope

The goal of the S-LCA has been to investigate the potential social impacts from the restoration of MAL with industrial crops for biobased materials and energy. The analysis (based on available information and access to regional stakeholders) captured the differentiated impacts across three agro-ecological zones: Mediterranean, Atlantic, and Continental and Boreal for ten value chains including (i) annual and perennial crop types and (ii) conversion pathways with different TRLs and market development stages.

**Table 1. Methodological challenges in S-LCA and approaches adopted to overcome them.**

| S-LCA methodological challenges[58] | Approaches adopted to overcome challenges |
|---|---|
| Relating existing quantitatively indicators | Literature review, value-chain analysis to focus on specific challenges in each value-chain stage and surveying to validate findings |
| Obtaining specific data for regionalized S-LCA | Literature review and interviews with crop and technology experts |
| Quantifying all impacts properly | Consistent scoring system |
| Evaluating the results | Surveying and interviews to validated findings |

The results can be used firstly to understand the social implications of such value chains and secondly to identify possibilities for improvements.

The work adopted the attributional model, which evaluates social impacts associated with the question of 'how the product is being made' (Fig. 4). This has been regarded as the most relevant and fit to be combined with the VCA concept and used to assess the selected value chains. Ten value chains have been selected for in-depth analysis within the sustainability assessment in the framework of an internal project workshop on selection of value chains and interlinkages (Table 2). The reference unit of 1 ha of occupied land for 1 year for biomass production systems is applied within this article.

## Indicators

The analysis considered only indicators that are relevant to the specific value-chain stages (Fig. 5). Table 3 presents the stakeholder and impact categories, indicators, and their relevance to the value-chain stages.

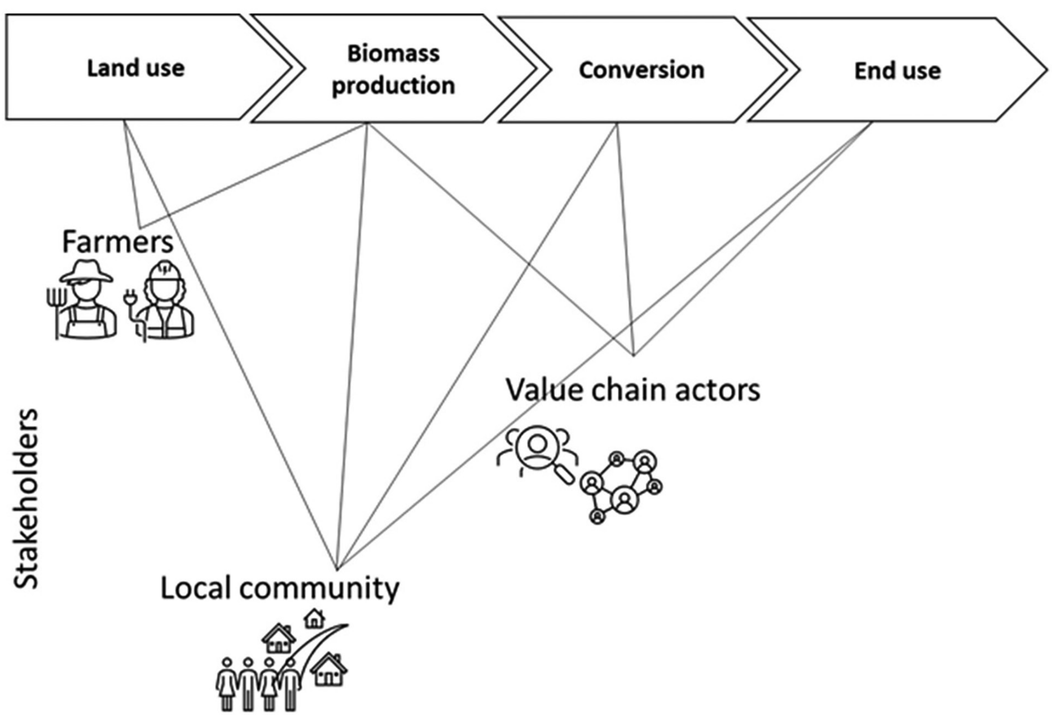


Figure 3. Stakeholder's relevance across value-chain stages.





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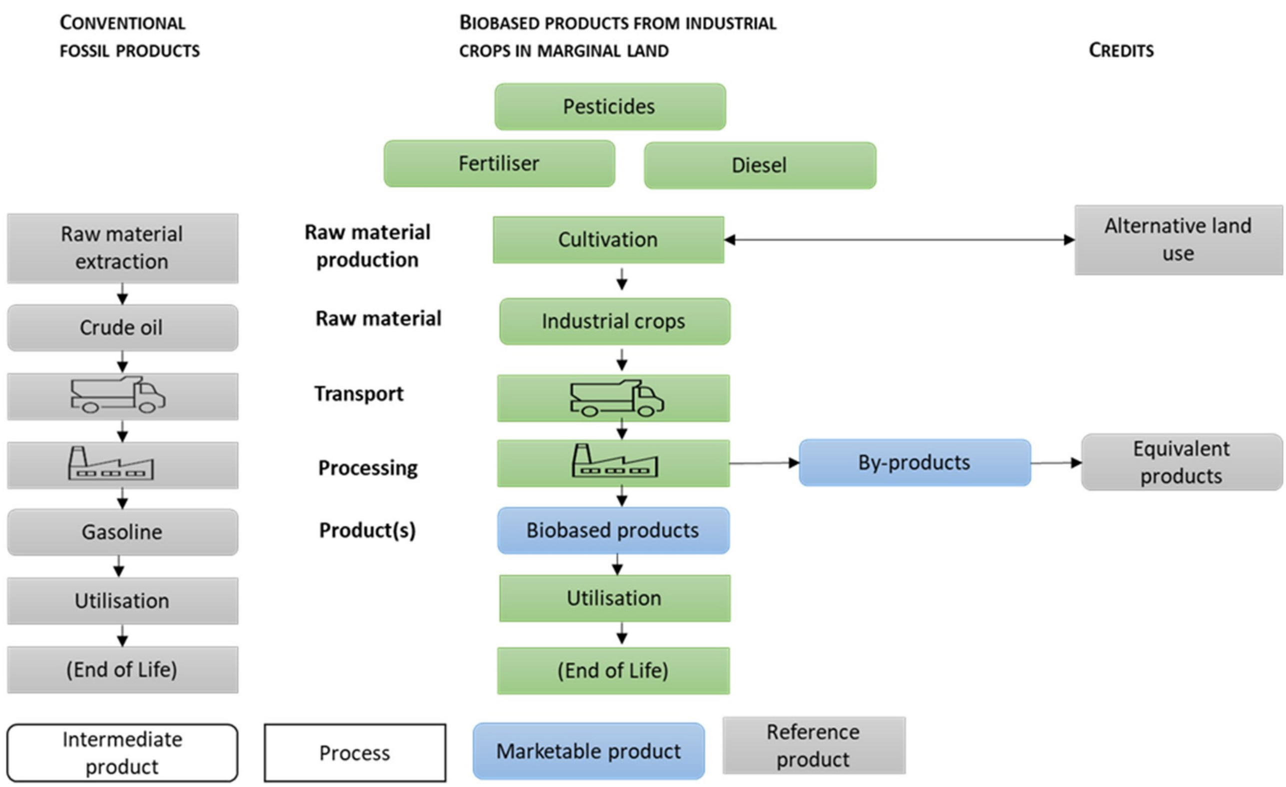


Figure 4. Sustainability assessment within the MAGIC project (Magic: Marginal lands for growing industrial crops: Turning a burden into an opportunity. European Union's horizon 2020 research and innovation program under grant agreement no. 727698.). The MAGIC bio-based products are compared with conventional reference products, both along the entire life cycle.

**Table 2. Overview of the ten analyzed value chains.**

| Crop (A: Annual; P: Perennial) | Conversion technology | Main product |
|---|---|---|
| Miscanthus (P) | Pyrolysis | Industrial heat |
| Poplar (P) | Gasification | SNG |
| Switchgrass (P) | Fermentation | Ethanol |
| Willow (P) | Pyrolysis | Biochemicals (biothumen) |
| Safflower (high oleic) (A) | Oxidative cleavage | Azelaic and pelargonic acid |
| Camelina (high oleic) (A) | Metathesis | Methyl decenoate |
| Castor (P) | Alkaline cleavage | Sebacic acid |
| Industrial hemp (P) | Mechanical processing | Insulation material |
| Sorghum (A) | Anaerobic digestion | Heat and power Biomethane |
| Lupin (A) | Extraction | Adhesives |

For land use, the impact category applied in this study is natural resources and the category indicators are (i) land use and development, and (ii) access to natural resources. The respective inventory indicators are (i) land occupancy, which reflects annual or perennial nature of the crops, and (ii) crop yield/ha, which can measure the productivity of the MAL type.

For biomass production, the category indicators applied in this study for the working conditions impact category are: (i) wages, which can illustrate opportunities for income diversification, (ii) social benefits, and (iii) health and safety. For the natural resources impact category, the respective indicator for this stage is biodiversity. The respective inventory indicators are (i) income and profitability per crop, (ii) incentives at farm level, (iii) compliance with health-and-safety regulations, and (iv) crop traits relevant to biodiversity.

For the conversion stage, the impact category applied in this study is innovation and the category indicators are (i) technology development, and (ii) system versatility. The respective inventory indicators are: (i) TRL, and (ii) scale and relationship to logistics.

For the end-use stage, the impact category applied in this study is innovation and the category indicator is market prospects. The respective inventory indicator is the market size and trends. The rural development impact category has been applied across all value-chain stages. It has been

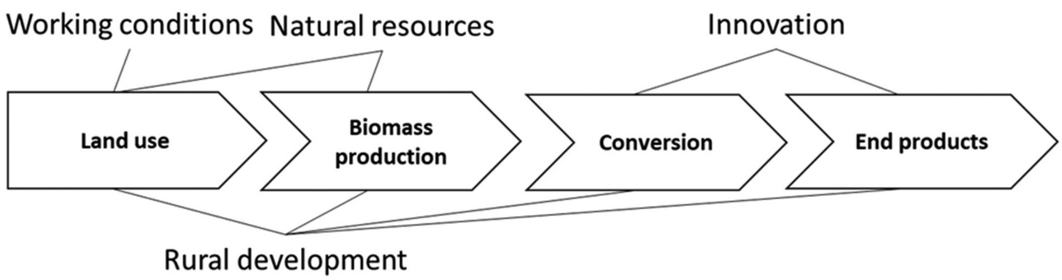


Figure 5. Relevance of impact categories to value-chain stages.

**Table 3. Stakeholder and impact categories, indicators, and relevance to challenges within and across the value-chain stages.**

| Stakeholder category | Impact category | Category indicators | VC stage[a] | Inventory indicators |
|---|---|---|---|---|
| Farmers | Working conditions | Wages | BP | Income and profitability per crop |
| | | Social benefits (diversification of income) | BP | Incentives at farm level |
| | | Health and safety | BP, EU | Compliance with health and safety regulations, end users' health and safety[b] |
| Value-chain actors | Innovation | Technology development | C | Technological readiness level (TRL) |
| | | System flexibility | C | Scale & logistics |
| | | Market prospects | EU | Market size and trends |
| Local community | Natural resources | Biodiversity | BP | Crop traits relevant to biodiversity |
| | | Land use | LU | Annual/perennial |
| | | Access to natural resources | LU | Crop yields/ha |
| | Rural development | Local employment | All | Jobs |
| | | Contribution to rural economy | All | Gross value added (GVA) |

[a]Land Use (LU); Biomass Production (BP); Conversion (C); End Use (EU).
[b]See.[82]

addressed with the following category indicators: (i) local employment, (ii) contribution to rural economy, and (iii) public commitment to sustainability. The respective inventory indicators are: (i) jobs, (ii) gross value added (GVA), and (iii) policies.

## Inventory

Data collection has been based on a combination of literature, interviews, and online surveying.

The UNEP/SETAC approach (Fig. 6) clarifies that 'subjective data is sometimes in S-LCA the most appropriate information to use. Bypassing subjective data in favour of more 'objective' data would introduce greater uncertainty in the results, not less. "and that a" clear difference lies in the fact that inventory data and impact assessment are specified in relation to different stakeholders defined. In S-LCA, stakeholder involvement/participation is also emphasized.'[59]

In this study we used a mix of subjective data through interviews and surveying and a set of more objective cross-referenced values derived from a systematic literature review. The balance between quantitative, qualitative, and semi-quantitative data differs across value chains and mostly depends on the TRL both for the upstream (land use, biomass production) and the downstream (conversion, end use) stages. The data sources for each value chain also differ (Tables 4 and 5).

# Results

## Challenges in value-chain stages and the role of stakeholders

The work followed a bottom-up approach[60,61] to ensure that the S-LCA addressed important issues that impact the establishment and operation of the value chains. Stakeholders have been engaged to facilitate

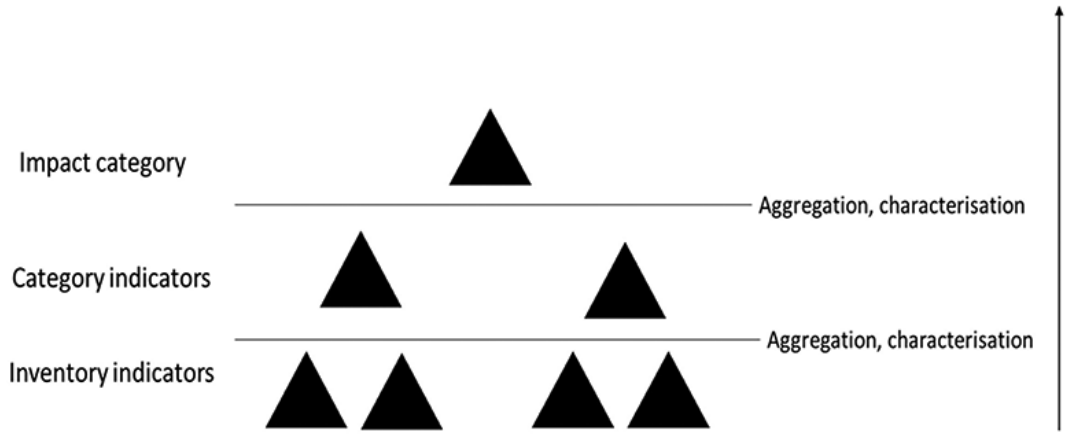


Figure 6. Concept of interlink between impact category, inventory, and category indicators. Source: UNEP/SETAC- inspired by ISO 14044 (2006).

**Table 4. Stakeholder groups contacted during the life-cycle inventory and their relevance to the value-chain stages.**

| Value-chain stage | Stakeholders contacted | Number | Country |
|---|---|---|---|
| Land use, biomass production | *Farmers* | 40 | |
| | Farmers (including representatives from cooperatives) | 29 | UK, BE, S, I, RO, BG, HUN, SI, DE, FIN, HR, BG |
| | Landowners (including associations) | 11 | BE, UK, FR, FIN |
| Biomass production, conversion, end use | *Value-chain actors* | 27 | |
| | Biobased industries | 12 | DE, I, S, FIN, ES, FR, HUN, HR |
| | Advanced biofuels | 8 | FI, UK, FR, ES, DE |
| | Steel industry | 2 | DE, UK |
| | Logistics companies | 5 | FR, DE, I, UK, RO |
| | *Local community* | 13 | |
| | Innovation clusters | 3 | NL, DE, UK |
| | Local government | 4 | |
| | Local business owners | 2 | UK, FR |
| | NGOs | 4 | BE, DE, UK, BG |

the understanding challenges, potential opportunities, and impacts along the value chains.[62,63] The challenges at each stage of the value chain were identified from the literature.[64,65] Then they were validated through selected interviews and online surveys. The main ones are summarized below and in Table 6.

Restoration of MAL with industrial crops may risk displacement of other land-based activities.[17,66,67] Moreover, it must ensure sustainable, yet profitable[68,69] practices that can use water efficiently,[70,71] prevent soil erosion,[72] support biodiversity,[73] improve soil and nutrient management,[74,75] and facilitate carbon sequestration.[76–80]

In a similar way to arable land, the cultivation of industrial crops on MAL includes soil preparation, crop establishment, plant protection and fertilization management, harvesting practices, post-harvest measures, storage, and transport81 and may require site-specific design.[82] Cropping practices must value and improve biodiversity, enable low-input regenerative agriculture, and minimize intensity of activities.[83] Storage facilities must accommodate multiple feedstocks with variant quality and forms. Low-carbon transport options and efficient routes must be designed and adopted.

Oil crops examined in this study are mostly annuals and generally occupy less land than perennials. For successful maturity and acceptable yield levels, some oil crops, such as safflower (*Carthamus tinctorium* L.)[84] and castor (*Ricinus communis* L.)[18] require relatively high temperatures in comparison with camelina (*Camelina sativa* L.), for example. This makes safflower and castor unsuitable for cultivation on MAL across the cooler Atlantic climate (AEZ 2). Furthermore, annual oil crops require a crop rotation in which they can be grown alternately with other plant species, as monoculture cultivation is generally prohibited for phytosanitary reasons. Wherever oil crops are to be cultivated, it must therefore be possible to find at least as many other plant species as the plant species-specific

**Table 5. Social life-cycle analysis impact category indicators and their relevance to challenges within value-chain stages.**

| VC stage | Inventory indicators | Relevant challenges |
|---|---|---|
| BP | Income and profitability per crop | Unemployment in rural areasLack of crop diversification |
| BP | Incentives at farm level | Social and economic resilience in rural areas |
| BP, EU | Compliance with health and safety regulations, end users' health and safety[a] | Safe, low impact practices, consumer's health and safetyFlexible storage facilities; low carbon transport |
| C | Technological readiness level (TRL) | Low technological readiness level (TRL) of innovative conversion pathways |
| C | Scale and relationship to logistics | Flexible feedstock capacity and low emissions operation |
| EU | Market size and trends | Early market development stage and high-risk financing |
| BP | Crop traits relevant to biodiversity | Improve biodiversity, enable low input, regenerative agriculture, and minimize intensity of activities. |
| LU | Land occupancy (annual/perennial) | Access to neglected natural resources without displacement of other land-based activities |
| LU | Crop yields/ha | Apply sustainable practices to prevent soil erosion and improve soil management |
| All | Jobs | Unemployment, lack of job opportunities |
| All | Gross value added (GVA) | Rural development |

[a]See.[82]

phytosanitary properties require. For a most efficient harvest, a combined harvester may be required. These have not yet been developed for all of the oil crops investigated here.[85]

Carbohydrate and fibercrops examined in this study, such as sorghum (*Sorghum bicolor* L. Moench) and hemp (*Cannabis sativa* L.), are also annual species and require appropriate crop rotation and a suitable climate to achieve acceptable biomass yield and appropriate quality. Further challenges include the need for specialized harvesting practices, such as allowing for a separate harvest of seeds and stems in hemp cultivation. The transportation costs may also be a decisive factor, especially for carbohydrate crops, as their high-moisture content (depending on the biomass use, of course) may require short field–storage distances.

The lignocellulosic crops examined in this study provide the best opportunities to protect the soil and the groundwater because they are perennials. After being successfully established, they can be grown on the same area for long periods, of 15 years or more. This long-term land occupation can be viewed as negative because the area would not available for other land uses during this time.

Activities for biomass conversion to biobased products include construction and operation of biorefineries. Challenges with regard to construction include low TRL of innovative conversion pathways, early market development stage, and high-risk financing. Challenges for operation include resource efficiency, low emissions performance, handling mixed volumes of feedstocks and improving synergies for valorization of residues and co-products.

End use of biobased products and services includes activities related to their distribution and use by consumers. Products should be compatible with existing infrastructure, standards, and distribution channels. Furthermore, both consumer acceptance and successful market uptake will be subject to their fitness to substitute existing products and commodities in sectors such as chemicals, food, energy, and fuels. Singh *et al.* (2020)[79] reported that consumer acceptance remained a challenge with underdeveloped standards/certification procedures and unfamiliarity with bio-based products.[86]

The sections below describe the relevance of stakeholders to the value-chain stages and their role in overcoming the challenges that prohibit successful establishment and sustainable operation.

## Land use

Farmers, value-chain actors, and local communities can inform the selection of suitable MAL and help understanding the respective improvements required to return it to productivity. Decision making for innovative cropping solutions can be efficient only if these are embedded to the existing planning process and the daily activities in farms and the surrounding countryside.[87] Further issues for potential stakeholders' involvement include:

- Farmers and local community can advise if the suggested land use systems can improve biodiversity, preserve water, and lead to overall net zero carbon solutions that are well integrated to current land use patterns.
- The local community can organize awareness campaigns and training and on-field tours to inform the public about regenerative agricultural practices for industrial crops in MAL.

**Table 6. Overall challenges across value-chain stages and stakeholders' role.**

| Value-chain stages | Challenges (as defined through interviews and surveying) | Farmers | Value-chain actors | Local community |
|---|---|---|---|---|
| Land use | Access to neglected natural resources without displacement of other land-based activities | Guide decision making for site selection | Safeguard displacement of other activities | Foster carbon conservation and sequestration |
| | Sustainable practices to prevent soil erosion and improve soil management | Stay informed about new cropping methods and opportunities for carbon farming and other support. | Contribute (to the extent possible) to carbon farming and net zero agriculture initiatives | Awareness and training campaigns for regenerative agriculture, incl. Carbon farming |
| Biomass production | Improve biodiversity, enable low input, regenerative agriculture, and minimize intensity of activities. | Adopt sustainable cropping practices<br>Advise on financial support required to improve infrastructure | Facilitate the provision of industrial crops, produced under sustainable practices | Rural communities can improve their awareness and endorse new developments for bioeconomy in their regions.<br>Local consumers can demand the adoption of standards and labelling systems for the biobased goods/services they select. |
| | Flexible storage facilities | Sometimes the farmers must take part in storage activities. In such cases they have to comply to requirements of value chain actors in this area. This compliance should be assisted by relevant decision making from VCA. | Adopt new storage processes and seek funding for innovative components | |
| | Low carbon transport | Rent/purchase efficient machinery and equipment | Develop/join low carbon transport schemes and initiatives | |
| Conversion | Low technological readiness level (TRL) of innovative conversion pathways, early market development stage and high-risk financing | n/a | Establish communication and robust contractual agreements with farmersImprove synergies for valorization of residues and co-products | |
| | Low emissions operation | n/a | Monitor emissions and establish energy efficient machinery compatible to the most recent environmental standards | |
| End use | Consumers' acceptance | Increase visibility of sustainable crop production in marginal land through joint initiatives with other farms/farmers' cooperatives | Ensure biobased products are compatible with existing infrastructure, standards and distribution channelsImprove labelling | Enhance social inclusion |
| Across all stages | Lack of awareness; lack of clarity for strategic decision making | Improve knowledge transfer – strengthen communication and networking | | |
| | Lack of crop diversification and job opportunities | New jobs | | |
| | Rural development | Invest in farms and farm generation renewal | Economic diversification | Local rural development |

## Biomass production

During this stage, all the stakeholder categories have a significant role. Industrial crop cultivation will form part of the farming activities and can be considered successful only if the crops are well adapted to the respective ecosystems,[88] if their cultivation complies with the local sustainability regulations, and if it is carefully integrated to the annual farming activities with minimal distortions and displacement of other activities that take place in the respective regions.

Value-chain actors such as agricultural material suppliers, and workers can also contribute by understanding the potential added value from the bioeconomy related biomass production, endorse it and integrate it to their daily work.[89] Planning for efficient storage spaces and improving low carbon transport for goods in the region will also benefit biomass logistics.

The local community should be consulted at the initial planning stages for biomass production in each region. They can assist with the crop selection, contribute knowledge for existing machinery and infrastructure and advise on what needs to be improved to ensure a sustainable, efficient workflow. Further issues for the potential involvement of relevant stakeholders include:

- Farmers and value-chain actors can adopt resource-efficient practices in crop cultivation, harvesting and handling, and share their experiences with each other.
- Value-chain actors should support resource-efficient cropping practices and facilitate the respective agricultural activities.
- Farmers, the local community, and value-chain actors can advise on limitations in terms of infrastructure and policy-relevant needs, and guide targeted financial support.

### Conversion

Value-chain actors and the local community are the most relevant stakeholders for the conversion stage. The former include industrial actors and workers in the conversion plant.

Industrial actors should establish connections with farmers to ensure they have the appropriate contractual arrangements for year-round biomass supply in the required specifications in terms of quality and quantity. They also need to communicate and network with the local community to ensure their industrial facilities are accepted and well-integrated in the region and the planned daily activities do not disturb the quality of life of the local population.

Local community should be engaged from the planning stage and tailored capacity building events and public awareness campaigns must be organized to improve local people's knowledge for the benefits of the new developments and the overall bioeconomy. Further issues for the potential involvement of relevant stakeholders include:

- Value-chain actors should ensure circularity by making provisions to optimize the use of co-products and any waste streams.
- The local community, with support from public and private funds, should invest in knowledge distribution, capacity building, and networking.
- Value-chain actors and the local community with the support from government and funding institutions can provide financial support to industry and businesses to help the initial high investment cost of transition from fossil-based technologies to bio-based technologies.

### End use

Value-chain actors and the local community are the most relevant stakeholders for the end-use stage. The first include industrial actors and people involved in the distribution of the biobased products and/or services[90] (e.g., heat, electricity).

Further issues for the potential involvement of relevant stakeholders include:

- Farmers can increase the visibility of sustainable crop production in MAL through joint initiatives with other farms/farmers' cooperatives.
- Value-chain actors can adopt standards, which can regulate the quality of biobased products/services.
- Value-chain actors can implement labeling mechanisms, which can help in the quality monitoring.
- Value-chain actors and the local community should contribute to increasing consumers' awareness and facilitate change in consumers' behavior.

## Social life-cycle analysis of biobased value chains

### Value-chain assessment

According to UNEP/SETAC 'S-LCA encounters both positive and negative impacts of the product/service life cycle and includes these 1) because beneficial impacts are often of importance and 2) to encourage performance beyond compliance (with laws, international agreements, certification standards, etc.).'[59]

To assess the results of the study, a scoring system is used to aggregate the data and information in a more quantitative and visual manner and to provide the possibility of comparison between them. Detailed process schemes can be found in the MAGIC project Deliverable 6.2: System description of selected value chains[91] and the MAGIC project Deliverable 6.1: Definitions and settings.[92]

This study has introduced a scoring system where any social risks (footprints) and/or opportunities (handprints) regarding each of the category indicators have been graded for each stage (Fig. 7), and social risks result in a higher score.

The section below presents a comparative overview of the impact assessment for the value chains (see Table 2) per impact category (working conditions, innovation,

| | | |
|---|---|---|
| Low risk/ high opportunity | -3 | ↑ |
| Medium risk/ medium opportunity | -1 | ↗ |
| High risk/ Low opportunity | 1 | ↘ |
| Very High risk/ Very Low opportunity | 3 | ↓ |

Figure 7. Scoring system for social risks and opportunities.

natural resources, and rural development) and discusses the performance for the respective indicators and value chains. Detailed performance of individual value chains is included in Annexes II and III in Appendix S1.

Overall, social risks for access to natural resources, income diversification, and biodiversity are higher for not marginal land than marginal land. Land acquisition is the main hotspot in all value chains primarily because the crops are non-food ones that entail risks for competition with food and feed cropping especially in the case of perennials due to long-term commitment for land use. All the crops can offer opportunities for MAL restoration, but perennials are considered to be a very high social risk for conventional arable land in terms of biodiversity and high risk for access to natural resources and income diversification for competition with other food and feed crops. All the value chains, when implemented sustainably, can offer good opportunities for biodiversity, social benefits, income diversification, local employment, and rural development.

### *Working conditions (income diversification, incentives at farm level, health, and safety)*

The working conditions impact category in this study focuses on farmers and the cultivation of industrial crops in MAL. The analysis focused on understanding and evaluating how the new activity can impact opportunities for income diversification, and if there are any social benefits and any issues regarding health and safety (Fig. 8).

Perennial crops like miscanthus (*Miscanthus* Andersson), switchgrass (*Panicum virgatum* L.), willow (*Salix* L.), poplar (*Populus* L.), and castor (*Ricinus communis* L.) offer opportunities for income diversification to farmers[66,93] and landowners[78,94] as they can provide raw materials for several biobased markets. Annual crops have been considered good opportunities because they can form part of sustainable crop production systems, as winter cover crops, etc. The various cropping practice options can offer crop and income diversification in European regions. The working conditions in the farm would be similar to the ones for traditional crops with the exception of perennials for which the first year when the plantations are established, intense activities will occur. The inclusion of such crops in the Common Agricultural Policy and other related strategic documents is expected to provide social benefits for farmers. Health and safety impacts are the same as in other agricultural activities and include injuries from the use of equipment and machinery, skin diseases associated with chemical use and prolonged sun exposure, hearing problems from continuous exposure to heavy machinery, etc. Appropriate standards and regulations must be in place to prevent accidents and minimize such impacts. The main results in this impact category among the value chains are:

- Cultivation of the crops on MAL offers better opportunities whilst their cultivation in conventional land always entails the risk of competition and displacement unless they are cultivated with the principles of best management practices, as part of rotation, intercropping, etc. The opportunities are better for annual crops and conversion technologies with high TRL, which are already commercial or close to commercialization.
- All the value chains are subject to incentives at farm level through the Common Agricultural Policy and other regional funds (ERDF, ESIF, etc.). There are, however, gaps in prioritization and tailoring the available financing opportunities to funding packages that can be easily accessed by farmers and landowners at local level.
- Health and safety issues present risks both at the upstream and downstream so attention must be paid during planning and implementation.

### *Innovation (Technology development, System versatility, Market prospects)*

Most of the examined technological pathways are highly innovative, have low TRL, and are still at the early market development stage. As such they are ranked by stakeholders as medium opportunities for short-term implementation (Fig. 9). Only pyrolysis to industrial heat, ethanol from switchgrass, insulation material from hemp and biogas/ biomethane from sorghum are considered opportunities with high chances of being implemented in the short term. The main results in this impact category among the value chains are:

- All value chains offer opportunities for technology development. The highly innovative pathways with low TRL, however, present slightly lower opportunities than the ones that are already commercial.
- All value chains present strong opportunities for system versatility as they allow co-product valorization.
- The market size for all value chains has very strong opportunities with the exception of industrial heat, SNG, biotumen, and sebacic acid, which offer slightly lower opportunities either because there are other lower cost



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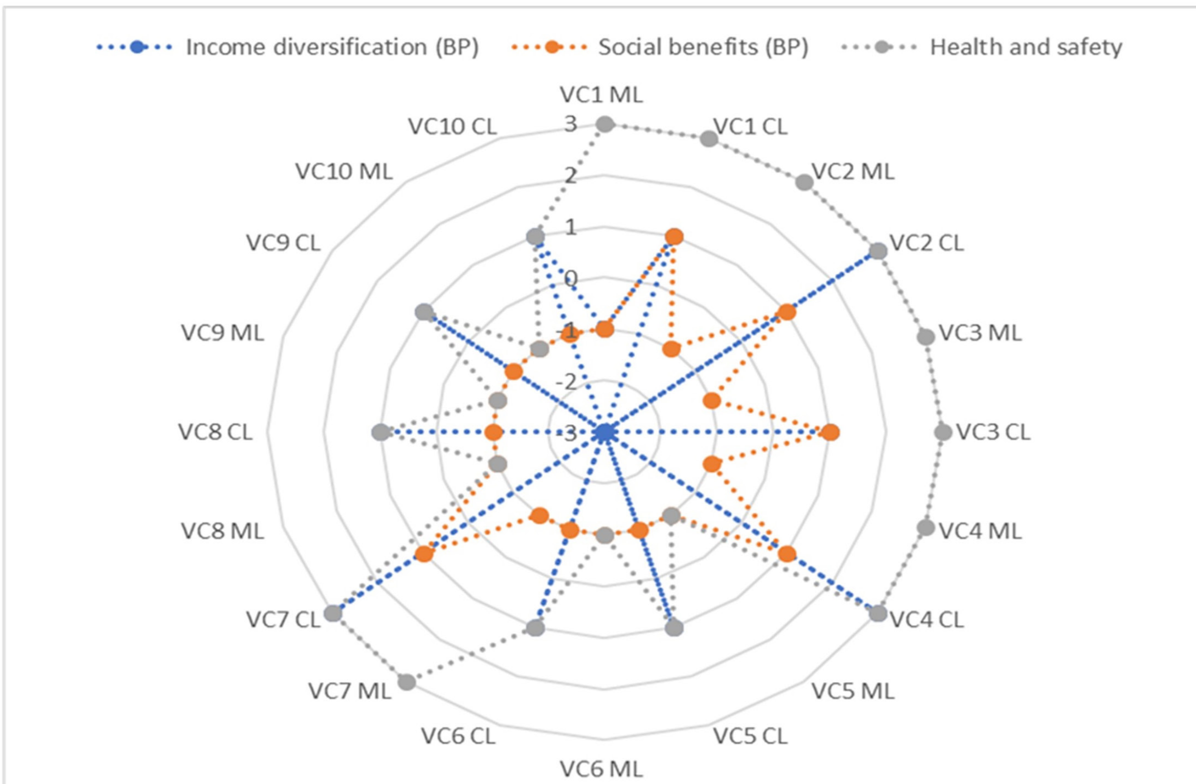



| | |
|---|---|
| VC1:Miscanthus, Pyrolysis, Industrial Heat | VC6: Methyl decenoate from camelina |
| VC2: SNG from poplar (via gasification) | VC7: Sebacic acid from castor oil |
| VC3: Ethanol from switchgrass (via hydrolysis & fermentation) | VC8: Insulation material from hemp |
| VC4: Biotumen from willow (via pyrolysis) | VC9: Biogas/biomethane from sorghum |
| VC5: Organic acids from safflower | VC10: Adhesives from lupin |

Figure 8. Comparison of social risks for the 'working conditions' category indicators and value-chain stages in marginal agricultural land (ML) and conventional land (CL).

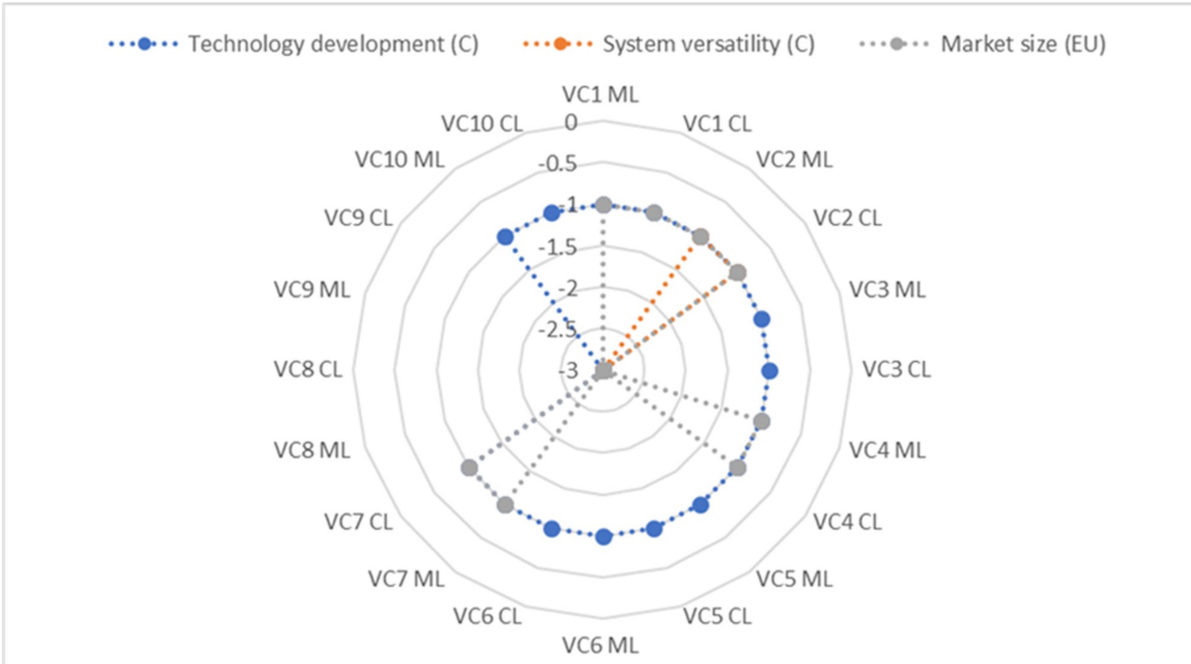
alternatives and/or they are still at precommercial level (which is the case for the last three).

## Natural resources (biodiversity, land acquisition, delocalization and migration, access to natural resources, biodiversity)

Perennial industrial crops are considered a resource-efficient option for European countries[95–97] because they are established once, have dense rooting systems, use low water and nutrient inputs, and have high drought resistance.[98] Land-use change is considered limited in case of MALs that are not suited for arable crops requiring higher quality soils. Perennial cropping reduces tillage and erosion risks[99] and increases soil carbon. As the site is only cultivated once, at establishment, reductions in soil disturbance and erosion can also be achieved compared with conventional arable crops.[100,101]

Most of the annual plants in the study can offer opportunities for land use and development and can also improve biodiversity as part of crop rotation, agroforestry, and other carbon farming-related practices (Fig. 10). They are drought and high-temperature tolerant, and can therefore be grown without irrigation even under dry agroecological conditions. They can be grown on MALs and/or lands with heavy metals. The main results in this impact category among the value chains are:

- Perennial crops present risks for long-term land use both on MAL and conventional land. The annual crops are considered to be good opportunities for cultivation

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| VC1:Miscanthus, Pyrolysis, Industrial Heat | VC6: Methyl decenoate from camelina |
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| VC5: Organic acids from safflower | VC10: Adhesives from lupin |

Figure 9. Comparison of social risks for the 'innovation' category indicators and value-chain stages in marginal agricultural land (ML) and conventional land (CL).

on marginal land but when cultivated on conventional land they are ranked as lower risk compared to perennials.

- Similar results are obtained for biodiversity; perennial species – especially when cultivated on conventional land – are considered high risk if they are not integrated in sustainable land-use planning procedures. Annual crops offer opportunities for biodiversity improvements when integrated in sustainable cropping, and they are ranked as lower risk compared to perennials.
- All crops offer opportunities to restore land with biophysical marginality and improve soil quality of MAL with safflower, camelina, hemp, sorghum, and lupin being ranked as better options.

## *Rural development (local employment, contribution to rural economy)*

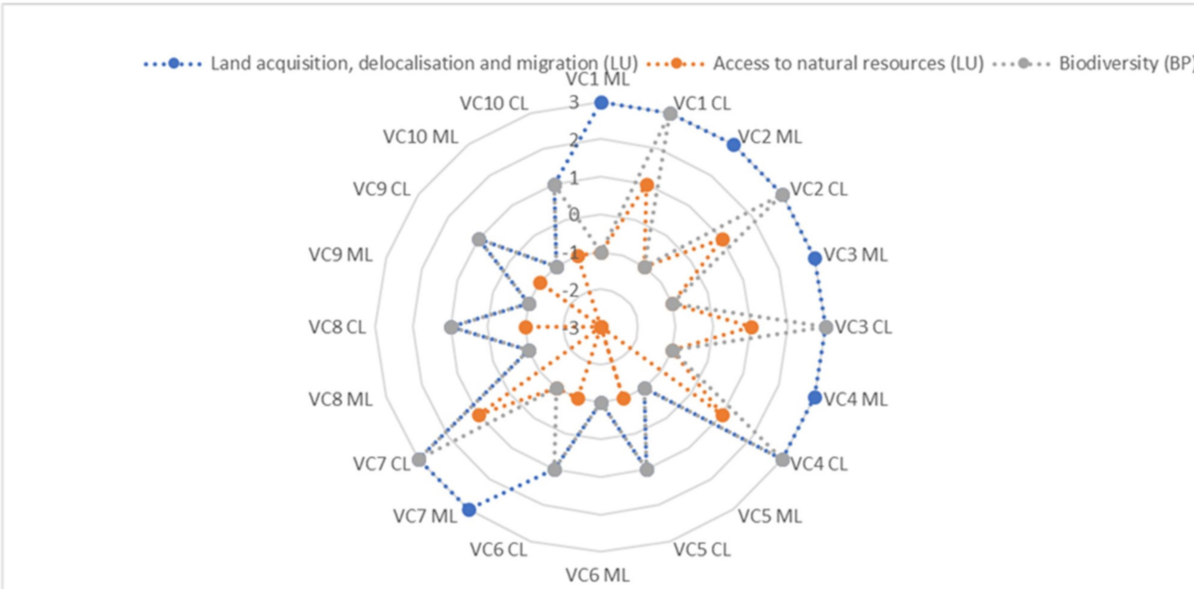
All the crops offer significant opportunities for local employment, can contribute to the rural economy,[102] and are attractive options for low-quality land, which remains unused or is abandoned due to low profitability prospects (Fig. 11). The annual crop species in this study are short season crops and can be grown successfully with rotation with legumes and/or cereals. This offers significant opportunities to farmers for income diversification as they can have two crops within a year with different markets.

The main results related to the value chains in this impact category are:

- All the value chains present opportunities for the creation of local employment both in marginal and in conventional land with the annual species ranked as offering higher than perennial.
- Similarly, all the value chains are considered as good opportunities for rural development in European regions.

## Interpretation

This identifies significant, socially relevant issues of the analyzed life cycles per value chain, agro-ecological zone and stakeholder category.




| | |
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| VC4: Biotumen from willow (via pyrolysis) | VC9: Biogas/biomethane from sorghum |
| VC5: Organic acids from safflower | VC10: Adhesives from lupin |

Figure 10. Comparison of social risks for natural resources category indicators and value-chain stages in marginal agricultural land (ML) and conventional land (CL).

### *Value chains*

Stakeholders considered land use as a risk for perennial grasses and as a high risk for willow and poplar due to the long-term commitment and intense labor activities required for such cultivation, especially during the grubbing up stage (field clearance and preparation for the next activity). On the contrary all other crops being mostly annual and some of them being suitable for agroforestry, crop rotations, etc. are considered as opportunities for land use with castor, camelina, lupin and safflower being ranked higher than sorghum and hemp.

In the biomass production stage lupin, hemp, and castor are considered crops whose cultivation is familiar to farmers and they are evaluated as strong opportunities while the rest of the crops are still relatively new, and they are considered as medium opportunities from the farmers' and local community's point of view.

Most of the conversion technologies in the value chains involve significant innovations as they are at low TRL. As such they are considered medium opportunities for short-term implementation. Only pyrolysis to industrial heat, ethanol from switchgrass, insulation material from hemp, and biogas/biomethane from sorghum are considered opportunities with high chances of being implemented in the short term.

End use presents similar scoring. All products/services are considered opportunities that can pave the way to a carbon-neutral bioeconomy but only pyrolysis to industrial heat, ethanol from switchgrass, insulation material from hemp and biogas/biomethane from sorghum are considered as having high chances of being implemented in the short term (Fig. 12).

Value chains with willow and poplar are considered high risk in terms of land use because they are perennial tree plantations. Perennial grasses miscanthus and switchgrass are ranked similarly but at a less risky level.

Apart from these, all the value chains are considered as moderate to high opportunities. More specifically, value chains with high TRL (biogas/biomethane, insulation material, ethanol, and pyrolysis for industrial heat) are also



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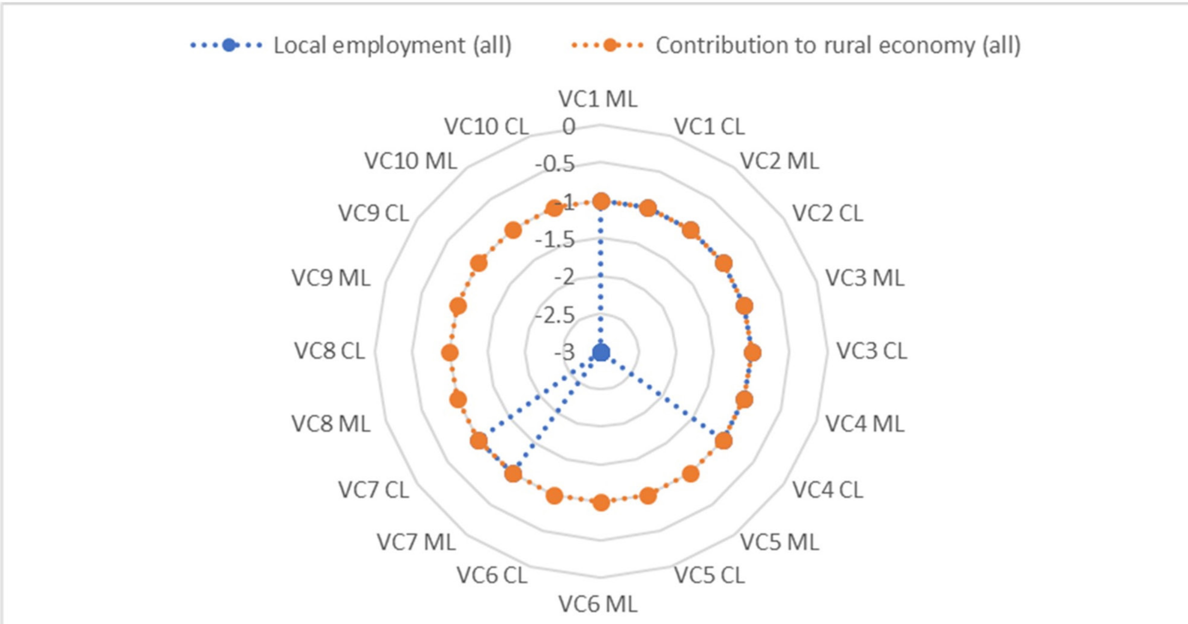


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|---|---|
| VC1:Miscanthus, Pyrolysis, Industrial Heat | VC6: Methyl decenoate from camelina |
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| VC3: Ethanol from switchgrass (via hydrolysis & fermentation) | VC8: Insulation material from hemp |
| VC4: Biotumen from willow (via pyrolysis) | VC9: Biogas/biomethane from sorghum |
| VC5: Organic acids from safflower | VC10: Adhesives from lupin |

Figure 11. Comparison of social risks for rural development category indicators and value-chain stages in marginal agricultural land (ML) and conventional land (CL).

considered better opportunities than the those with low TRL levels because they are more likely to be implemented in the short term.

## *Agro-ecological zones*

The following three aggregated agro-ecological zones (AEZ) are used in this study: (i) AEZ 1 – Mediterranean (MED), (ii) AEZ 2 – Atlantic (ATL), and (iii) AEZ 3 – Continental and Boreal (CON).[103] Within these zones, different biophysical constraints prevail, which may restrict the growth of industrial crops and the biophysical marginality conditions. The two most important constraints in each zone have been identified by von Cossel et al.,[78] and corresponding yields were set by the partners.

## *Crop performance in agro-ecological zones*

The information in the subsection for agro-ecological zones focuses on the crop-specific performance and any risks that have been considered of social relevance by the various stakeholders that participated in the analysis.

AEZ 1 – Mediterranean (MED): Miscanthus. Miscanthus is suitable for the Mediterranean agroclimatic zone. It exhibits high yields and resists water stress by decreasing photorespiration – i.e., by reducing leaf area and increasing root growth.[104]

Poplar. Poplar has shown a positive energy balance and high energy efficiency[105] when grown in the Mediterranean agroclimatic zone.

Switchgrass. Switchgrass is considered a suitable crop for less fertile, erosive lands, and requires low inputs (fertilization and water). Due to its deep rooting system, switchgrass survives in Mediterranean conditions and has higher water-use efficiency than carbohydrate crops like maize (*Zea mays* L.).[106]

Willow. Willow is a short rotation woody crop which exhibits good yield under high temperatures, marginal soil, and climatic conditions, and thus is considered suitable for the Mediterranean zone.[107]

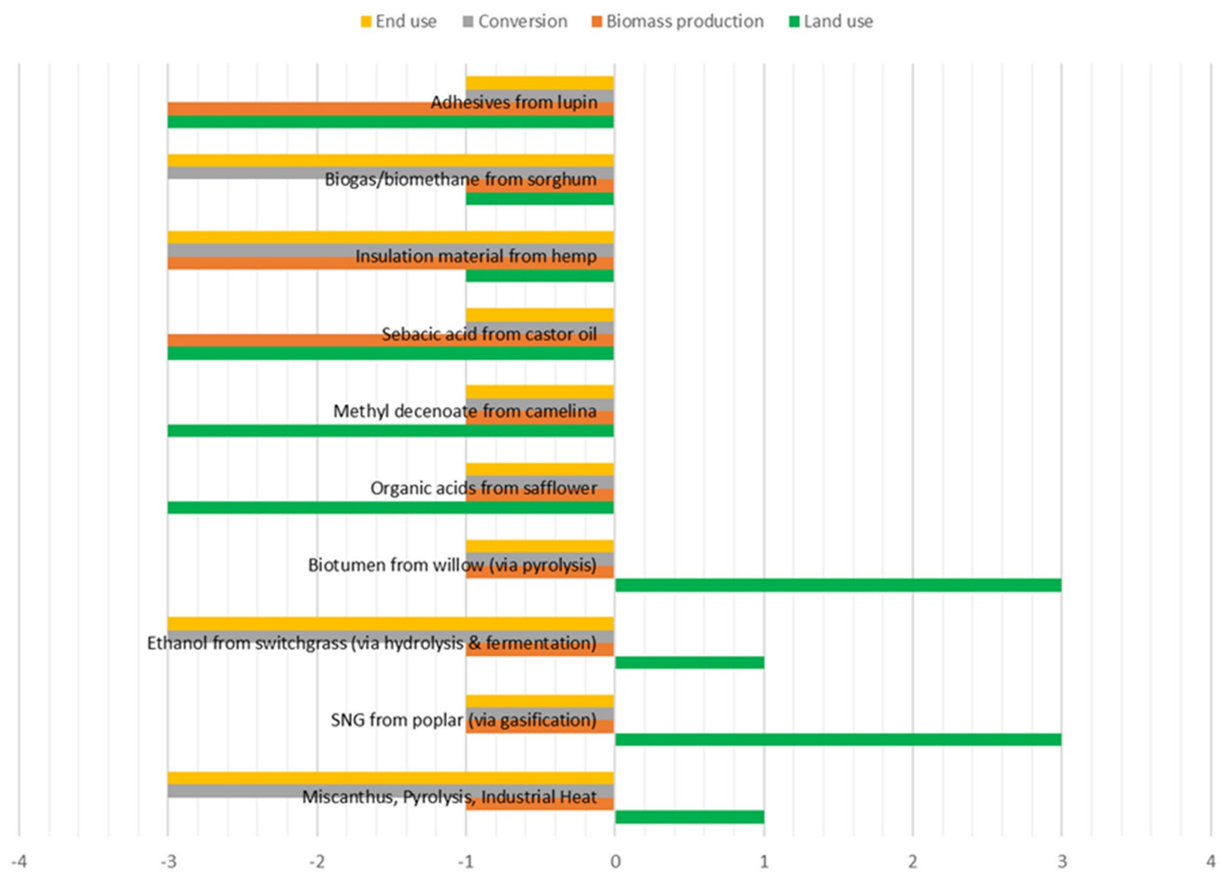


Figure 12. Overall scoring of risks/opportunities within value-chain stages in the biobased value chains (negative values represent 'handprints' – opportunities).

Safflower. Safflower grows well in Mediterranean conditions as it is best suited to a hot, dry climate. This is because of its deep rooting system, which can take up moisture and nutrients (like N) from deeper soil layers. The crop is suitable for rotational cropping and it has been reported that it can reduce N leaching into the ground water.[108]

Camelina. Literature reports that camelina has highest seed yields when grown in the Mediterranean zone.[109]

Castor. Castor is well suited for the Mediterranean zone. It has been reported that, with favorable temperatures and regular irrigation, productivity increases significantly.[110]

Industrial hemp. Hemp has shown good productivity in semi-arid Mediterranean but its productivity is affected by water shortages and high air temperatures. Manipulation of the sowing date is therefore recommended to avoid these unfavorable climatic conditions.[111]

Sorghum. Sorghum is a drought-tolerant crop which has the ability to extract water from deep-soil and give high yields under rain-fed, water-scarce Mediterranean conditions.[110]

Lupin (*Lupinus mutabilis* Sweet). Lupin is well adapted to the Mediterranean zone and is also considered a profitable crop.[112]

The main risks with social relevance in the Mediterranean agro-climatic zone concern the crops' adaptability to long dry periods, especially during years with limited rainfall, as well as deterioration of soil quality due to desertification.[3] These can lead to gradual land abandonment due to low yield and limited profitable crop opportunities for farmers.

The main opportunities in this agro-climatic zone include farmers' willingness to diversify their crop production and to seek low input farming opportunities because desertification, soil erosion, and lack of water force them to find new alternative crops and cropping methods that are resilient to the adverse climate-change situations.

AEZ 2 – Atlantic (ATL): Miscanthus. Miscanthus is a C4 crop with high radiation, water and nitrogen use efficiency that prefers warm temperate climatic conditions. They grow from dormant winter rhizome when the soil temperature reaches 10–12 °C.[113]

Poplar. Poplar is a low-input woody crop, which can be grown on MALs in warm-temperate climatic zones because warm temperature supports the rapid growth of plant, and they have high photosynthetic capacity aided by their large leaf area. All this makes them suitable for Atlantic North and South.[114]

Willow. Willow is considered a suitable crop in the Atlantic zone.

Safflower. Safflower has both winter and spring varieties, and it can grow on marginal soil and under very low rainfall conditions. It is suitable in Atlantic agroclimatic conditions.

Industrial hemp. Hemp is suitable in a wide range of climatic conditions and a study shows that hemp yield was found to be slightly lower for the countries in Atlantic zone (Netherlands and the UK) compared to Italy, which is in the Mediterranean zone.[115]

Lupin. Lupin is found to be suitable for the Atlantic zone and has the potential to replace food oil crop soybean.

The main risks with social relevance in the Atlantic agro-climatic zone relate to changes in temperature, which may affect the crop selection and respective growing cycles, rotations, etc.[3] Biodiversity risks also ranked very high in the group of stakeholders from the region as well as possibilities for organic farming and low input, climate smart agriculture.

Respective opportunities in the agro-climatic region include the high awareness of farmers and their high level of networking and involvement in bioeconomy and circular economy clusters and relevant initiatives.

AEZ 3 – Continental and Boreal (CON): Miscanthus. Miscanthus grows well in the Continental and Boreal region of Europe and the production level is good even in lower quality soil with little fertilization and protection from pests and diseases.[116,117]

Poplar. Poplar is considered suitable for short rotation coppice in the Boreal zone because of the fast growth rate in summer (when the air temperature is above 20 °C). The biomass yield from the boreal climatic system is not very different from the warm-temperate regions, if appropriate crop management practices are applied.[118]

Switchgrass. Switchgrass is suitable in the Continental zone within Europe.

Willow. Like poplar, willow is considered suitable for short-rotation coppice in the Boreal zone because of its fast growth rate in summer (when the air temperature is above 20 °C). The biomass yield of willow under the Boreal climate is not very different from the warm-temperate regions, if adequate cultivation practices are applied.[119]

Safflower. Safflower can also be grown in the Continental and Boreal climate but it does not mature until late autumn.

Camelina. Camelina is well adapted to Continental and Boreal conditions because there are both summer- and winter-annual varieties available.[120]

Castor. Castor is a spring crop and is very sensitive to temperature but can grow in low water available conditions. It is a suitable crop in the Continental and Boreal zones.

Industrial hemp. Hemp is adapted to wide variety of environment and is multipurpose crops – fiber and oil.[121]

Lupin. Lupin is a legume that is suitable for cultivation in most Continental European regions, and it provides the capability to fix atmospheric nitrogen.

The main socially relevant risks in the Continental and Boreal agro-climatic zone concern competition for land, ecological concerns, and the landscape. Biodiversity concerns also ranked very high in this region, as in the Atlantic region, with most stakeholders rating it as the most important concern for future agriculture.

Opportunities in the agro-climatic zone include the farmers' high awareness and their high level of networking and involvement in bioeconomy and circular economy clusters and initiatives.

## *Stakeholder groups*

Farmers consider the higher risks associated with the value chains to be the lack of governance and their highly innovative nature (Table 7). They do, however, see strong opportunities for rural development and the restoration of MAL that is left abandoned and unused. Improvements to working conditions

**Table 7. Overall risk scoring of the impact categories by the three stakeholder groups for the biobased value chains (deep red = high overall risk, light red = medium overall risk, light green = low overall risk).**

| Value chains | Farmers | Value-chain actors | Local community |
|---|---|---|---|
| Miscanthus, pyrolysis, industrial heat | Medium | Low | Low |
| SNG from poplar | High | High | Medium |
| Ethanol from switchgrass (via hydrolysis and fermentation) | Medium | Medium | Low |
| Biotumen from willow (via pyrolysis) | High | High | High |
| Organic acids from safflower | Medium | Medium | Medium |
| Methyl decenoate from camelina | Low | High | Medium |
| Sebacic acid from castor oil | Medium | High | High |
| Insulation material from hemp | Low | Low | Low |
| Biogas/biomethane from sorghum | Low | Low | Low |
| Adhesives from lupin | Low | Medium | Medium |

and income diversification are also ranked as opportunities if the selection of crops and the respective cropping practices follow sustainability principles and regulations.

Value-chain actors consider the higher risks associated with the value chains to be access to and resource efficient use of natural resources and the working conditions, including health and safety and job skills. The local community considers the higher risks associated with the value chains to be the lack of governance, their highly innovative nature, and the working conditions, including income and job creation.

## Conclusions

During the last decade, the concept of MAL has received much attention both in research and policy formation as a potential resource for the cultivation of biomass for the biobased economy. This work applied the S-LCA methodology in combination with VCA and evaluated the positive impacts (handprints) in addition to the negative ones (footprints) for a set of ten biobased value chains that use industrial crops cultivated on MAL as feedstock.

### What is the most important, socially relevant implication for the cultivation of industrial crops in MAL?

Land use has been considered the most important implication across the value-chain stages. It has been ranked as a high risk (footprint) for perennial grasses and as a very high risk for willow and poplar due to the long-term commitment and intense labor activities required for such cultivation, especially during the grubbing up stage (field clearance and preparation for the next activity). On the other hand, most other crops were annual and some of them were suitable for agroforestry. Crop rotation, etc., was considered as presenting an opportunity (handprints) for land use, with castor, camelina, lupin, and safflower being ranked higher than sorghum and hemp.

Across stakeholder categories both farmers and the local community consider higher risks associated with the value chains to include the lack of governance and their highly innovative nature. They do, however, see good opportunities for rural development and the restoration of MAL that is left abandoned and unused.

### How have the industrial crops performed in this S-LCA analysis?

Results indicate that perennial crops cultivated in MAL rank high in terms of governance (due to high priority in Renewable Energy Directive II) but they cause skepticism among the stakeholders interviewed when it comes to long-term commitment for land use and biodiversity risks. Annual crops on the other hand are perceived by all stakeholder categories as high or very opportunities across all impact categories and indicators. They can facilitate income diversification and offer smart, sustainable cropping options through crop rotation, agroforestry, etc.

### How have the conversion technologies performed in this S-LCA analysis?

Most of the technological pathways examined are highly innovative, have low TRL, and are still at the early market development stage. As such they are ranked by stakeholders as medium opportunities for short term implementation. Only pyrolysis to industrial heat, ethanol from switchgrass, insulation material from hemp, and biogas/biomethane from sorghum are considered opportunities with good chances of being implemented in the short term.

## Author contributions

Calliope Panoutsou: Conceptualization, Methodology, Validation, Resources, Writing – Review and Editing, Supervision. Moritz von Cossel: Resources, Writing – Review and Editing, Visualization and Investigation. Pilar Ciria: Validation, Investigation, Resources, Review and Editing. Carlos Ciria: Validation, Investigation, Resources, Review and Editing. Andrea Monti: Validation, Investigation, Resources, Review and Editing. Federica Zanetti: Validation, Investigation, Resources, Review and Editing. Jean-Luc Dubois: Validation, Investigation, Resources, Review and Editing.

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