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Strategic planning of bio-based supply chains: unlocking bottlenecks and incorporating social sustainability into biorefinery systems

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Abstract

The sourcing of renewable bio-resources and their conversion through novel biorefinery technology is being supported by several initiatives and policies worldwide involving the development of a circular bioeconomy. However, further questions remain unanswered such as how the strategic planning of new bio-based supply chains could contribute to sustainability targets given the common oversight for the social dimension in decision-making levels of biorefinery supply chains. Based on a systematic literature review of research papers on biorefineries, bottlenecks associated with the strategic planning of new supply chains from feedstocks originating from land and marine ecosystems were identified, along with the aspects currently representing the social dimension of sustainability. The results outline two main findings. First, the bottlenecks identified and portrayed by grass and seaweed-based supply chains can be summed into the following main categories: bio-resource availability, quality, logistic planning, economic, ecological, and social issues, policy, research and innovation. Second, current research at the strategic decision-making levels of biorefineries is substantially focused on techno-economic aspects. The inclusion of environmental aspects has been increasing with life cycle assessment methodologies in more recent years, while social elements remain widely disregarded. The results further uncover the social dimension, represented by aspects such as employment creation, participation of primary producers, food and energy security, stakeholders' engagement, societal acceptance, effects on local communities, workers' well-being, education, gender equality, cultural values, and potential conflicts. To overcome bottlenecks and incorporate social dimensions, new perspectives and interdisciplinarity are needed to extrapolate the boundaries of analytical frameworks currently adopted by biorefinery research. We suggest framing the planning of new bio-based supply chains within a socio-technical-ecological system to pursue integrated strategies toward more sustainable and socially relevant biorefinery systems.

Keywords
Circular Bioeconomy, Social Sustainability, Strategic Planning, Supply Chain Management, Seaweed, Grass

Abbreviation

Circular bioeconomy (CBE), Supply chains (SC), European Commission (EC), Supply Chain Management (SCM), Biorefinery Supply Chains (BSC), life-cycle assessment (LCA), social life cycle assessments (S-LCA) socio-technical-ecological system (STES)

1. Introduction

The sourcing of renewable bio-resources and their conversion through novel biorefinery technology is being supported by several initiatives and policies worldwide involving the development of a circular bioeconomy (CBE) (Global Bioeconomy Summit 2020; OECD 2018). The European Commission (EC), for example, is seeking to pursue a ‘sustainable and circular’ bioeconomy to meet climate mitigation targets and ecosystems restoration, while reviewing current unsustainable practices of production and consumption and systems (EC, 2018a). To achieve these aims, various initiatives are taking place for the research and development of novel biorefinery supply chains (BSC), where the processing of bio-resources originating from marine or terrestrial ecosystems could create a wide spectrum of bio-based supply chains (SC) such as food, feed, materials, chemicals, but also bioenergy in the forms of fuels, electricity and/or heat (Conteratto et al., 2021). Seeing a CBE as one constituent of great transformations to address global sustainability challenges (Urmetzer et al., 2020), profound changes and integrated strategies would be necessary for the development of new and sustainable SCs (Raimondo et al., 2021).

Supply Chain Management (SCM) has traditionally been focused on goals addressed to different and hierarchical decision-making levels named i) design or strategy (years in advance), ii) tactical (months up to a year) and iii) operational (days up to a month) (Zahraee et al., 2020). In a biorefinery, *strategic decisions* are, therefore, long-term resolutions, which might include feedstock availability and sourcing, possible suppliers, the optimal location, its capacity, and markets that can be accessed (Zahraee et al., 2020). This strategic planning often referred to as the SC design stage is complex due to its high level of uncertainty and multiple factors affecting decisions in the long run (Melnyk et al., 2014). Besides that, the inclusion of sustainability-related topics adds additional challenges, giving new directions and developments to the research field of SCM and BSC (Palmeros Parada *et al.* 2017; Alexander et al., 2014). Besides the potential contributions of biorefinery innovation toward sustainability targets, the deployment of new BSC does not inherently mean more sustainable SCs, particularly considering the current disregard for the social dimension of sustainability across disciplinary domains (Zahraee et al., 2020; Espinoza Pérez et al., 2017; Barbosa-Póvoa et al., 2018).

Despite the advancements in the fields of BSC and SCM, both areas are not fully integrated and the lack of understanding of the social dimension in the planning of BSC might induce the disregard of social sustainability aspects. This could entail, for example, overlooking aspects such as working conditions, employment opportunities, societal responses to new technologies, land rights conflicts, community engagement or cultural heritage (Cadena et al., 2019). The availability and management of bio-resources are further constrained by factors such as land availability, energy and labour inputs, cost factors, logistics and infrastructure aspects, biochemical properties and policy interventions (Grossauer and Stoeglehner, 2020; Ciria and Barro, 2016). Beyond that, it is imperative to respect the limits of Earth's ecosystems, where the use of bio-resources for the CBE (Rockström et al., 2009) or narrow sustainability criteria could open space for societal conflicts or unwanted environmental impacts (Janker and Mann, 2018; O'Brien et al., 2017).

Considering this knowledge gap, we argue that truly sustainable bio-based SCs will only be deployed once the human dimension is properly addressed in the planning process of BSC. Moreover, while bio-resources originating from terrestrial ecosystems have been more established in BSCs, recent research suggest marine-based bio-resources such as macroalgae as a promising alternative. Seaweed is often described as an enhanced feedstock because besides carbon sequestration potentials, it grows faster than land-based plants, and does not compete with arable land, freshwater or food production (Ali et al., 2022; Kumar et al., 2021). Hence, this study aims to identify bottlenecks from alternative bio-resources originating from marine or land-based ecosystems using as an example seaweed[1] and grass[2] feedstocks, as well as investigate the social elements covered by BSC research to explore more integrated planning of new BSC. To the authors' best knowledge, no review studies have been conducted on the investigation of the strategic planning of BSC aligning social sustainability and the uncertainties and constraints for its development (defined here as bottlenecks). Thus, the following research questions (RQ) lead the present work:

RQ1 What are the current bottlenecks for the establishment of new supply chains based on grass and seaweed for biorefining?

RQ2 What are the social aspects being considered in the strategical decision-making level of biorefinery supply chains?

RQ3 How strategies could address bottlenecks and include social aspects in integrated planning processes of emerging bio-based supply chains?

The integration of the fields of BSC and SCM from a system thinking perspective will help to better understand the synergies between the two areas for the planning and management of bio-based SCs, contributing to advancing the CBE discussion. This will provide essential new knowledge that can meaningfully impact the strategic planning of biorefineries systems and therefore avoid shortcomings in the actual deployment of bio-based SCs. Acknowledging that the emerging feedstocks under investigation comprise numerous plant species and distinctive biomes, for consistency purposes and considering strategic decision-making as the main emphasis of this study, we focus on 'grass' and 'seaweed' as the bio-resources. Furthermore, the scope of this paper is limited to national scales, where international trade does not play a role and farming systems are applied to temperate climates which have distinct season patterns affecting harvesting time, storage

[1] Example of new biorefinery concepts based on seaweed bio-resources see for example GENIALG https://genialgproject.eu/, Macro Cascade https://www.macrocascade.eu/, and MacroFuels https://www.macrofuels.eu/
[2] Example of new biorefinery concepts based on grass bio-resources: Biorefinery GLAS https://biorefineryglas.eu/, GO-GRASS https://www.go-grass.eu/, Far4More https://www.farm4more.ie/

and therefore the whole logistic planning and embedded socio-cultural context where such bio-resources are sourced from.

The paper is structured as follows. The background and literature review are presented in section 2 followed by material and methods in section 3, which described the research design and process. In section 4, the results provide a descriptive overview of the sample, the bottlenecks and the social aspects identified. Section 5 provides a discussion and examination of the implications of those findings, exploring the development of more integrated planning of BSCs. Finally, the conclusion outlines the main findings in section 6, indicating future research directions.

2. Literature Review

The deployment of new SCs based on the sourcing of alternative bio-resources targeting feedstocks from marine or terrestrial ecosystems is being discussed by the current literature on biorefinery development. For example, new BSC based on grasses or seaweeds biomass is being supported by the premise that grasslands (see Thers and Eriksen, 2022; Ravindran et al., 2021; and Cossel *et al.* 2019) or seaweed (see Nilsson et al., 2022; Larsen et al., 2021; and Olsson *et al.* 2020) present greater potentials in meeting sustainability targets. Sustainability, as derived from the World Commission on Environment and Development (WCED) definition is defined as the capacity '*to ensure that [humanity] meets the needs of the present without compromising the ability of future generations to meet their own needs*' (WCED 1987, p.16). This definition is followed by the broadly adopted framework of sustainability in SCM: the triple bottle line approach, which addresses sustainability as the division and intersection of social, environmental and economic pillars (Bouchery et al., 2017). Other theoretical approaches and frameworks in sustainability science also exist, aiming to embrace more systemic perspectives. One example is based on socio-technical-ecological systems, which are notably relevant to addressing the complexity of human-environment interactions (Ahlborg *et al.* 2019). Hence, social sustainability can be also grounded as a social process concerned with society's interactions with nature and transformation activities (Wohlfahrt *et al.* 2019; Littig and Grießler, 2005).

Previous studies on BSC as well as in SCM indicate, however, a lack of social observations and alignment between the two research fields. In the field of SCM, Barbosa-Póvoa *et al.* (2018) reviewed 220 papers to identify different decision levels regarding sustainability practices, indicating the preponderance of optimisation models with economic and environmental objectives. In the review conducted by Rebs *et al.* (2019) on system dynamics modelling for sustainable SCM, it is further suggested that the inclusion of social aspects is challenging and that a better understanding of production systems and stakeholders' interactions could help to address this shortcoming. Concerning BSCs, Ubando *et al.* (2019) indicate that very few studies on biorefineries consider the role of stakeholders, policy frameworks, economic incentives or strategies for sustainable biomass sourcing. Similarly, Zahraee *et al.* (2020) reviewed 300 papers to assess biomass SC modelling and optimization, concluding that future research should focus more on social and environmental objectives. Although there is a common agreement on the lack of the social dimension and its relevance for the sustainability of production and consumption systems, no studies have been conducted to investigate this dimension in a comprehensively way for BSCs. Considering the controversies arising in this transition process (Starke et al., 2022) and the different interests and perceptions of stakeholders (Dieken et al., 2021), social aspects should be properly addressed in the planning of BSC as well as to ensure sustainable sourcing of bio-resources in the long term (Salvador et al., 2022; Sillero et al., 2021). Therefore, a critical review of the current knowledge and careful examination of emerging bio-based systems is reasoned by direct impacting the strategic decision-making of BSCs and reassuring the relevance of inter-transdisciplinary efforts (Knierim et al., 2017) in the transition to a CBE.

3. Material and methods

The methodological approach is based on a systematic literature review (Denyer and Tranfield 2009) and qualitative content analysis (Mayring 2014). The research process follows five-main steps including i) question formulation, ii) studies location, iii) studies selection, iv) analysis and synthesis, v) results and implications as displayed in Figure 1 and described in detail in the following subsections.

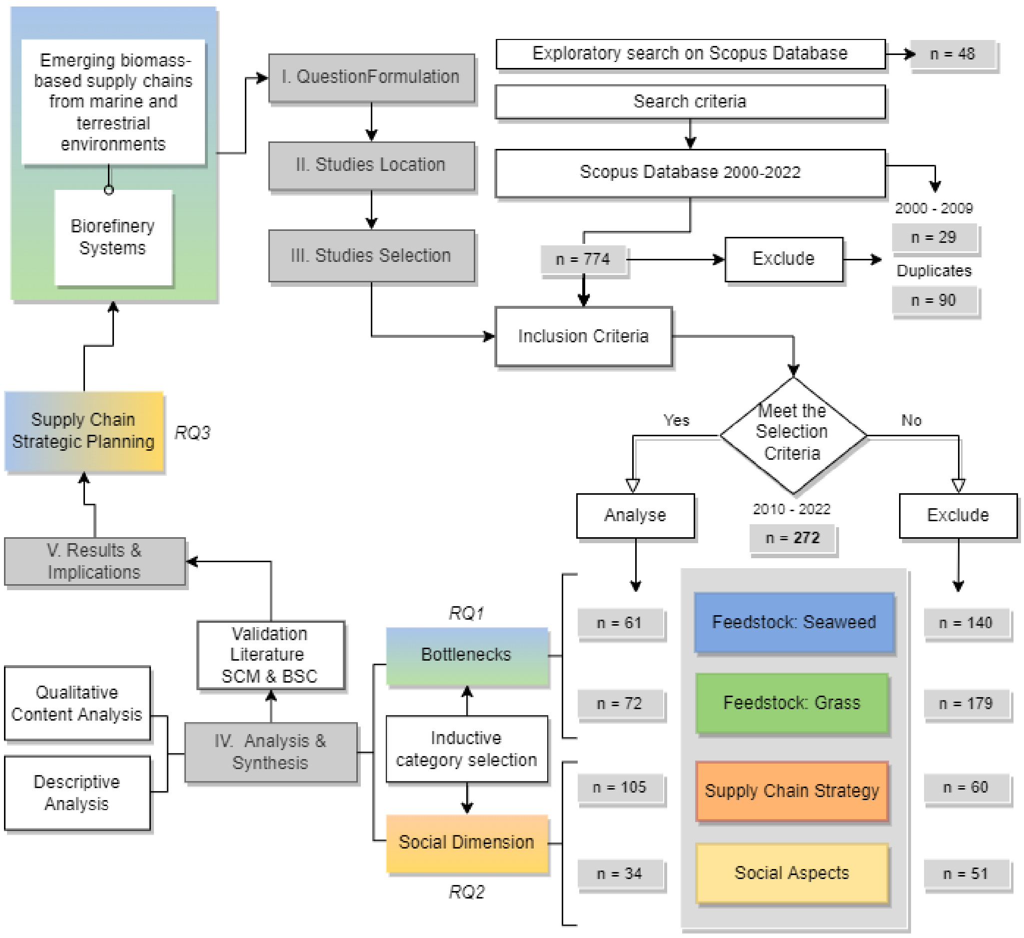


Figure 1 - Overview of the research process following Denyer and Tranfield (2009) and Mayring (2012)

3.1 Focus: question formulation

The acronym *CIMO* (Context, Intervention, Mechanism, and Outcome) is used to formulate the question guiding the research process (Denyer and Tranfield, 2009). Hence, the review focuses on identifying what are the current bottlenecks for the establishment of emerging bio-based SCs, as well as social aspects *(C),* for the strategic planning of BSC *(I),* critically reviewing their relevance and meaning *(M)* in the CBE context *(O).*

3.2 Search: studies location and screening

For searching the articles, an exploratory search on Scopus, the most comprehensive database of peer-reviewed literature (Ballew, 2009), was conducted. The terms included “seaweed” OR “grass” AND “biorefinery” AND “supply”, which resulted in 48 results, from those 34 being original research articles and only 7 of them approaching SC strategy. No studies on seaweed from a SCM perspective were found and only a few studies focused on grass. This was an indication that BSC based on the bio-resources under analysis fits the assumption of “emerging SCs” i.e. not yet commercially established. To locate the studies, a list of keyword equations was applied as well as inclusion criteria in the screening process (Table 1). This aimed to avoid studies outside of the scope, and to analyse the core of literature within different groups i.e. grass (1), seaweed (2); and strategic decision-making of BSC (3). Assuming that group 3 would have a limited approach to social aspects based on previous research, keywords were added in an attempt to yield more articles that included words related to social sustainability, following the UNEP-SETAC guidelines for social life cycle assessments (S-LCA) (Benoît Norris et al., 2013) and aspects covered by voluntary certification schemes of already established biorefinery systems (German and Schoneveld, 2012).

The search was conducted for the period 2000-2022, yielding a total of 774 articles by applying the keyword equations, including only research articles in the document type. Of those, only 29 articles were published in the time frame 2000 to 2009 indicating the newness of this research field. Considering that biorefinery technology advancements can change greatly over time, the articles analysed incorporated the last twelve years of academic results, with the last search conducted in August 2022 (published or “in press”). To ensure the relevance of studies, the inclusion criteria filtered the results from the search and with the exclusion of 90 duplicates, a total of 272 articles comprised the sample for analysis.

Table 1 - Keywork equations used to locate studies in the Scopus database and screening process

Group	Keyword Equation	Inclusion Criteria
1 Grass	(grass-silage OR grass) AND (biorefinery)	Only articles focus on temperate climates, which have distinct seasonal patterns affecting bio-resource supply. Grasses are categorised here as lignocellulosic herbaceous, i.e. non-woody (Elbersen et al., 2017) and exclude articles with only descriptive information of the biochemical analysis.
2 Seaweed	(seaweed OR macroalgae) AND (biorefinery)	Exclude articles with only descriptive information on biochemical analysis.
3 Supply Chain Strategy	(supply chain design) AND (biorefinery) (supply chain strategy) AND (biorefinery)	Only original articles on the strategic/design decision level (Espinoza Pérez et al., 2019) of BSCs.
4 Social Aspects	(supply chain) AND (biorefinery) AND (socio-economic OR social) (biomass supply) AND (grass OR seaweed) AND (social OR socio-economic) (biorefinery OR biomass supply) AND (employment OR health OR training OR education OR social OR socio-economic OR human OR rights OR jobs OR community)	Only articles with at least one social aspect are directly mentioned.

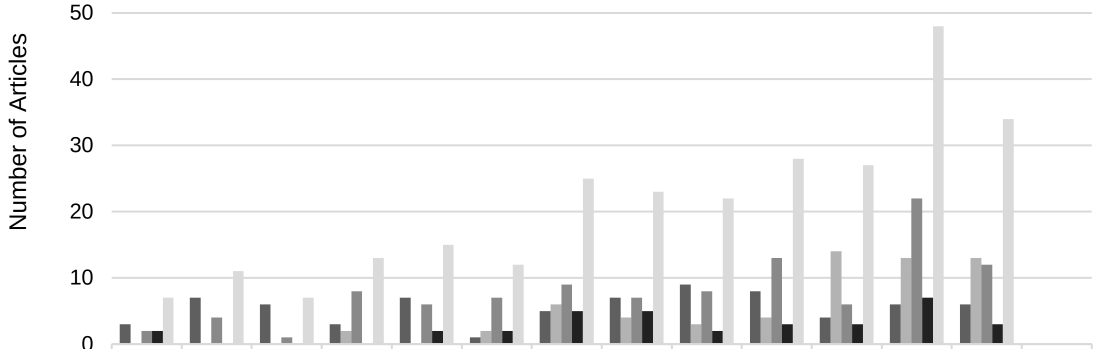
3.3 Rigour and quality: a*nalysis and synthesis*

The sample was analysed following two main procedures a) descriptive analysis and b) content analysis. The descriptive analysis (a) was used to access the distribution of the studies over time, journals, key-works, the coverage of SC phases (source and cultivation; harvesting and collection; processing and conversion) or the entire system and design; as well as the aimed products. For bottlenecks and social aspects identification (b), the studies were coded for categories following Mayring (2014) for content analysis using inductive coding in NVivo software. First, the inductive coding framework searched for topics related to the barriers or challenges identified or described in the studies analysed referent to groups 1 and 2 (RQ1). Those topics broadly represent the “bottlenecks” categories, which were refined and validated by comparing to current literature related to BSC, specifically, Sajid (2021), Wohlfahrt et al. (2019), Zahraee *et al.* (2020) and Fanali (2016). Second, the inductive coding framework searched for topics related to the description of social or human-impacted elements in the studies analysed referent to groups 3 and 4 (RQ2), whether they are directly or indirectly assessed by the studies in the sample. Those topics broadly represent the “social aspects” categories, which were validated by comparing current literature on SCMs, social criteria of S-LCA and certification schemes, specifically Desiderio et al. (2021), Benoît Norris et al., (2013) and German and Schoneveld (2012). To improve internal validity, the resulting categories were corroborated among the researchers and the coding results were validated by the above-mentioned studies related to BSC and SCM to support external validity (Gibson, 2006). The results are presented in section 3 with the outcomes from RQ1 and RQ2, which are explored in the discussion section with implications for the development of more integrated strategies for BSC planning (RQ3).

4. Results

4.1 Descriptive analysis

The 272 articles analysed were published over the period of twelve years on a steady rise in the number of studies (*Figure 2*). This trend is evident in the number of publications related to the strategic stage of the SC and the feedstocks under investigation, particularly seaweed, in more recent years.



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total
Grass (Group 1)	3	7	6	3	7	1	5	7	9	8	4	6	6	72
Seaweed (Group 2)	0	0	0	2	0	2	6	4	3	4	14	13	13	61
Strategy (Group 3)	2	4	1	8	6	7	9	7	8	13	6	22	12	105
Social (Group 4)	2	0	0	0	2	2	5	5	2	3	3	7	3	34
Total	7	11	7	13	15	12	25	23	22	28	27	48	34	272

Figure 2 - Number of articles across years (2010-2022) at the four main groups assessed

The articles reviewed suggest a strong disciplinary focus related to the fields of technology, chemistry, and energy research. It further indicates that interfaces with disciplines from social sciences, for example, may not be integrated as part of the strategic planning of BSC. Additionally, the network map of keywords across the 272 scientific publications was generated using the full counting in the software VOSViewer. The resulting overlay visualisation (Figure 3) displays developments over time, where it is possible to observe with the yellow colours that the latest research is more focused on environmental aspects such as greenhouse gas (GHG) emissions and the use of life-cycle assessment (LCA) methods.

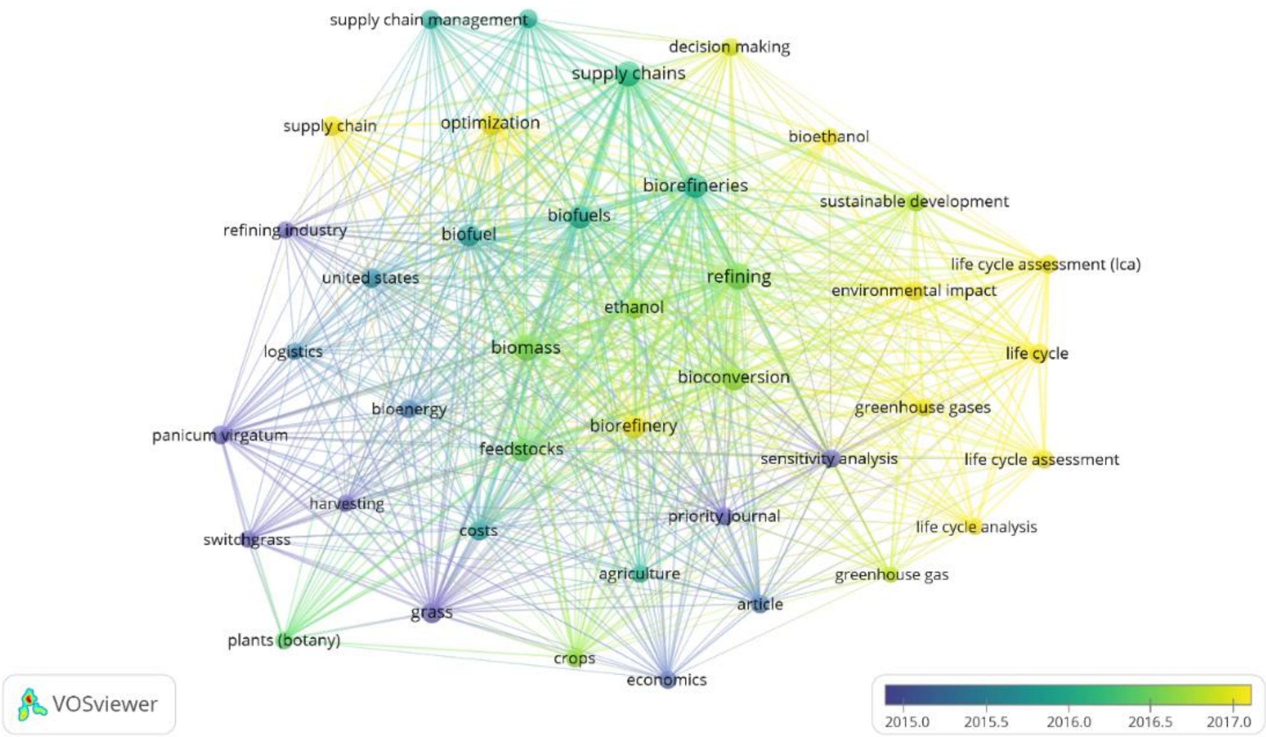


Figure 3 - The keyword network of the sample (n=272)

4.2 Bottlenecks with bio-resources originated from marine and terrestrial ecosystems

4.2.1 Grass-based supply chains

The stable supply of grassland bio-resources is one of the main bottlenecks identified (Figure 4) and argued to be related to grass availability both in terms of securing a stable input volume, as well as concerning land availability as a major constraining factor, aligned to optimal plant location and storage (Sallustio et al., 2022; Sesmero et al., 2021) In addition to input practices and cutting regimes, water availability, weather effects and storage conditions are further key bottlenecks affecting the quality, logistic system and viability of the entire SC (Boob *et al.*, 2019; Griffith *et al.* 2014). It is indicated by several authors that bio-resources sourcing is directly related to the economic feasibility of the biorefinery, which imposes also trade-offs between transportation costs and the catchment area for the processing capacity, particularly when further than 50km from the biorefinery plant (Ou *et al.*, 2018; Perrin *et al.*, 2017; Bomberg *et al.* 2014). Environmental impacts on ecosystems would also differ depending on the types of grasses and farm management practices. For example, regarding the use and type of fertilisation methods as well as depending on harvest practices (Corona *et al.*, 2018; Parajuli *et al.* 2018; Schmer *et al.*, 2012). Harvesting time and frequency are pointed to as the major determinant of feedstock quality for biorefining as well as concerning GHG emissions performance (Larsen *et al.*, 2019; Zanetti *et al.*, 2019).

Several bottlenecks are also still related to research and development of biochemical properties of different grasses for biorefining and the best conversion technology for commercial applications aligned to an optimal product range according to the quality or composition required and the desired final products (Corona *et al.*, 2018). This further indicates the experimental character of grass-based biorefinery systems, with feasible designs, optimal pathways and prospective by-product valorisation with coupled biogas systems still under investigation (Van Dael et al., 2014). As a potential improvement of the SC planning, grass-silage as a feedstock conservation process is indicated for allowing storage and therefore more stable sourcing all year around (He-Lambert *et al.*, 2018). However, considering the diverse modes of ensiling and a wide variation of storage practices depending on the farm, weather conditions and quality requirements depending on the final product application still require further research (Sakarika et al., 2022; Santamaria-Fernandez *et al.*, 2019; O'Keeffe *et al.*, 2011). Finally, SC planning is dependent on the local infrastructure, transportation modes available, biorefinery location, GHG emissions assessments and coordination with feedstock suppliers (He-Lambert *et al.*, 2018; Bomberg *et al.* 2014). Farmer's participation and decision-making are reported as a key issue affecting SC planning, once farm practices would not only affect the quality and ecological impacts, but also the volume available and determination of price. This rationale determines a common practice of adopting long-term contractual relations between farmers and biorefineries as a sourcing strategy to ensure a stable feedstock supply (Cundiff et al., 2020; Eranki and Dale, 2011; Zhu and Yao, 2011).

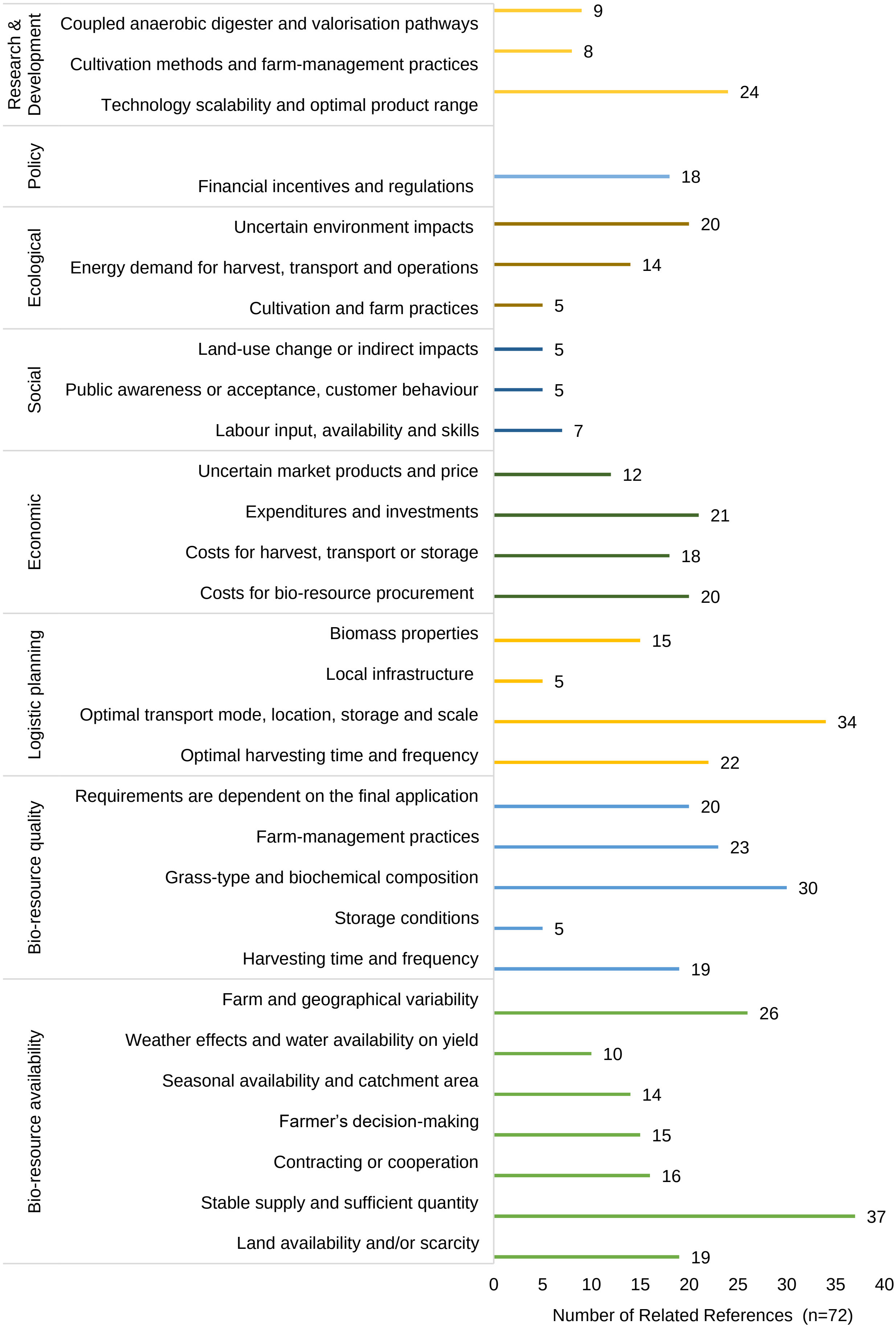


Figure 4 - Bottlenecks for the strategical planning of grass-based supply chains according to the literature analysed

4.2.2 Seaweed-based supply chains

One of the main bottlenecks and a common consensus across the literature analysed (

Figure 5) is argued to be the viability of scaling-up seaweed biorefineries beyond pilot projects considering the optimal range of products given the current financial (un)feasibility of seaweed-based biorefineries. The high costs are often associated with feedstock sourcing and its processing technology (Emblemsvåg et al., 2020; Konda et al., 2015). Besides being theoretically proven that it might already be economically feasible in some markets (Parsons et al., 2019), in practice, it represents a high-risk investment with uncertain conversion routes and feasible final products range (Deng et al., 2022; van den Burg et al., 2016). Cost factors might prevent commercial applications in addition to the shortage of large volumes of seaweed which would require scaling up seaweed aquaculture (Fasahati et al., 2022). However, knowledge of different species' life-cycle for commercial applications is still premature and uncertainties regarding the impacts of large-scale macroalgae cultivation or biorefinery processing also exist (Nilsson et al., 2022; Seghetta *et al.* 2016). Thus, the still highly critical bottlenecks in the areas of research and development.

There is also a lack of knowledge in understanding suitable design scales and different cultivation techniques considering different regions, which are related to the dynamic and complex settings of marine ecosystems (Parsons et al., 2019; Saqib et al., 2013). This connects to a high degree of context sensitivity in bio-resources availability. Several authors have reported that the impacts, choice of species, and yield are highly dependent on site selection, weather events, and local environmental conditions (Rajak, Jacob and Kim, 2020; Raikova *et al.*, 2020; Prabhu *et al.*, 2020). This results in variability in feedstock composition, associated with different quality requirements for biorefining depending on the desired product range. Even within a single species, the compositions can be substantially influenced by environmental conditions such as differences in salinity, nutrient availability, temperature and light, as well as cultivation period and harvesting time (Baghel *et al.*, 2020; Olsson, Toth and Albers, 2020; Tedesco and Daniels, 2018). Furthermore, seaweed has a bioaccumulation property and might gather pollutants available in the water such as heavy metals or iodine, which will influence its intended final use and applications (Adams et al., 2021). Additional bottlenecks are inherent to the seaweed's biochemical properties. For example, due to its high water content, salt, ash, and possibly also harmful chemical inputs are required for component extraction (Olsson *et al.* 2020; Ögmundarson *et al.*, 2020; Gallagher *et al.*, 2018). These particularities often impose energy and labour-intensive pre-processing operations, aligned to still unestablished infrastructure and equipment for the handling, transportation and processing of large volumes of this kind of biological resource (Jones *et al.*, 2020; Prabhu *et al.*, 2020; Giwa, 2017).

Finally, uncertain market uptake and product prices related to the downstream stages are influenced by consumer demand, perceptions, and trade conditions that differ depending on location and policies (Emblemsvåg et al., 2020; Prabhu et al. 2020). Some studies claim that a lack of financial incentives, as well as long-term policies, may be hindering the sector's development (Rajak *et al.*

2020; Buschmann *et al.*, 2017). Social awareness or regulatory requirements such as licencing difficulties are further bottlenecks, aligned to conflict potentials regarding the use of marine areas or market share between seaweed-based products (Rajak *et al.* 2020; Beacham *et al.*, 2019; Gallagher *et al.*, 2018).

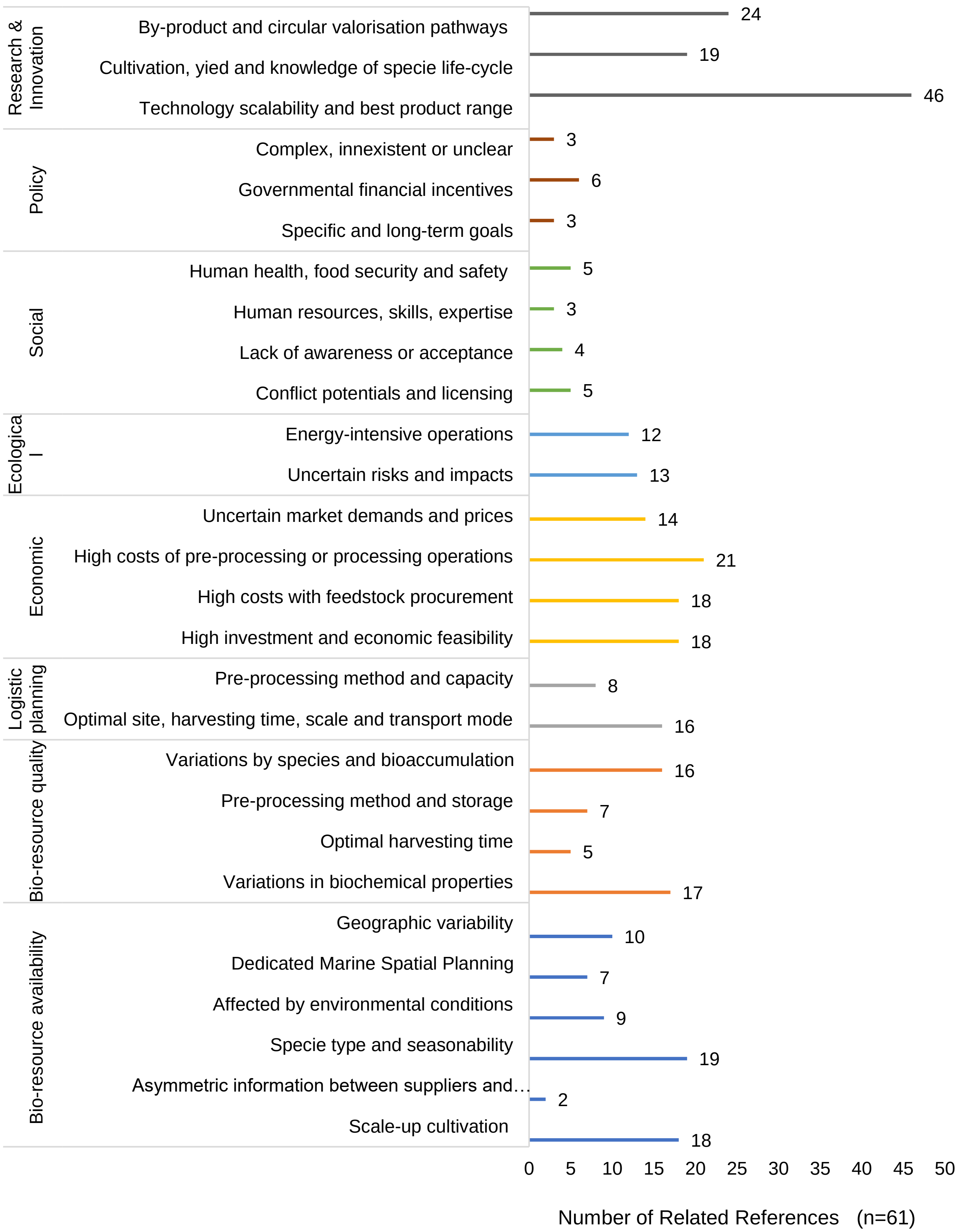


Figure 5 - Bottlenecks for the strategical planning of seaweed-based supply chains according to the literature analysed

4.3 Social sustainability in biorefinery supply chain strategy

The results related to the strategical decision-making level of BSC (Group 3 and 4, n = 139) reveal predominant research approaches using mathematical programming methods. In 43% of the articles analysed, either profit maximisation or cost minimisation was pursued as a single objective. The use of optimization models such as Mixed-Integer Linear Programming Models (MILP) is present in 31% of the cases and often associated with geographic information system (GIS) and LCA analysis to assess environmental impacts. Most strategies are still largely focused on biofuel SCs as the main biorefinery product in 65% of the aimed outcomes at the design level. At this level, 35% of the studies analysed included at least one environmental aspect, with the notable rising number of environmental LCAs, which indicate increasing concerns regarding the avoidance of ecological impacts in the deployment of new BSCs (Khounani et al., 2021). Concerning the social dimension, only 32% of the studies analysed at the strategical decision-making level mentioned social aspects, which is reduced to 17% when considering the whole sample (n = 272).

In most cases, social aspects are only mentioned or indirectly addressed. Although with significantly minor representation, these elements were aggregated in Figure 6, which currently represents the social dimension as portrayed by the literature analysed. Job creation is the most common one and accounts for 19% of the social aspects directly indicated and assessed. Indirect social aspects comprised, for example, the social benefits provided by the minimisation of GHG emissions (Saleem et al., 2021). These two aspects are rather related to positive outcomes of the deployment of BSCs, whereas issues related to food security or potential conflicts over natural resources depict a negative connotation and the limits of Earth's ecosystems related to the availability and supply of bio-resources in the CBE context. This further connects to societal concerns around land-use change and controversial debates about food versus fuel and therefore current preferences for biorefining second-generation (or non-food) feedstocks (Rehman et al., 2021). In addition, the feedstock supply is further dependent on variables such as primary producers' willingness to participate in the SC. This is argued to directly affect feedstock availability, and sourcing strategies (Zupko, 2021).

Stakeholder's participation and collaboration are indicated as challenging aspects in the implementation of new SC. This is because the decision-making process must include distinct groups such as primary producers, biorefinery operators, transportation providers, policy makers and local communities where the biorefinery might be located (Alcocer-Garcia et al., 2022; Martinkus et al., 2019). Moreover, quality of work and consumer preferences or societal awareness are further aspects comprising the social dimension (Wheeler *et al.*, 2018). Along the same lines, Parish et al. (2016) indicate the importance of social well-being and acceptability in BSCs, which includes not only quality of work but also societal responses being directly related to public perceptions, effective participation of stakeholders, transparency, and risk of natural disasters. Despite the results help to unveil how social aspects have been considered in the strategic decision-making levels of BSCs, there is an overwhelming lack of the social dimension beyond the quantification of social aspects such as number of jobs generated or indirect societal benefits by replacing fossil-based by bio-based SCs. The relevance and implication of these findings are discussed in the section below while exploring how strategies could encompass more integrated planning processes to overcome the bottlenecks identified and address the social dimension which widely interwind with techno-economic and environmental dimensions.

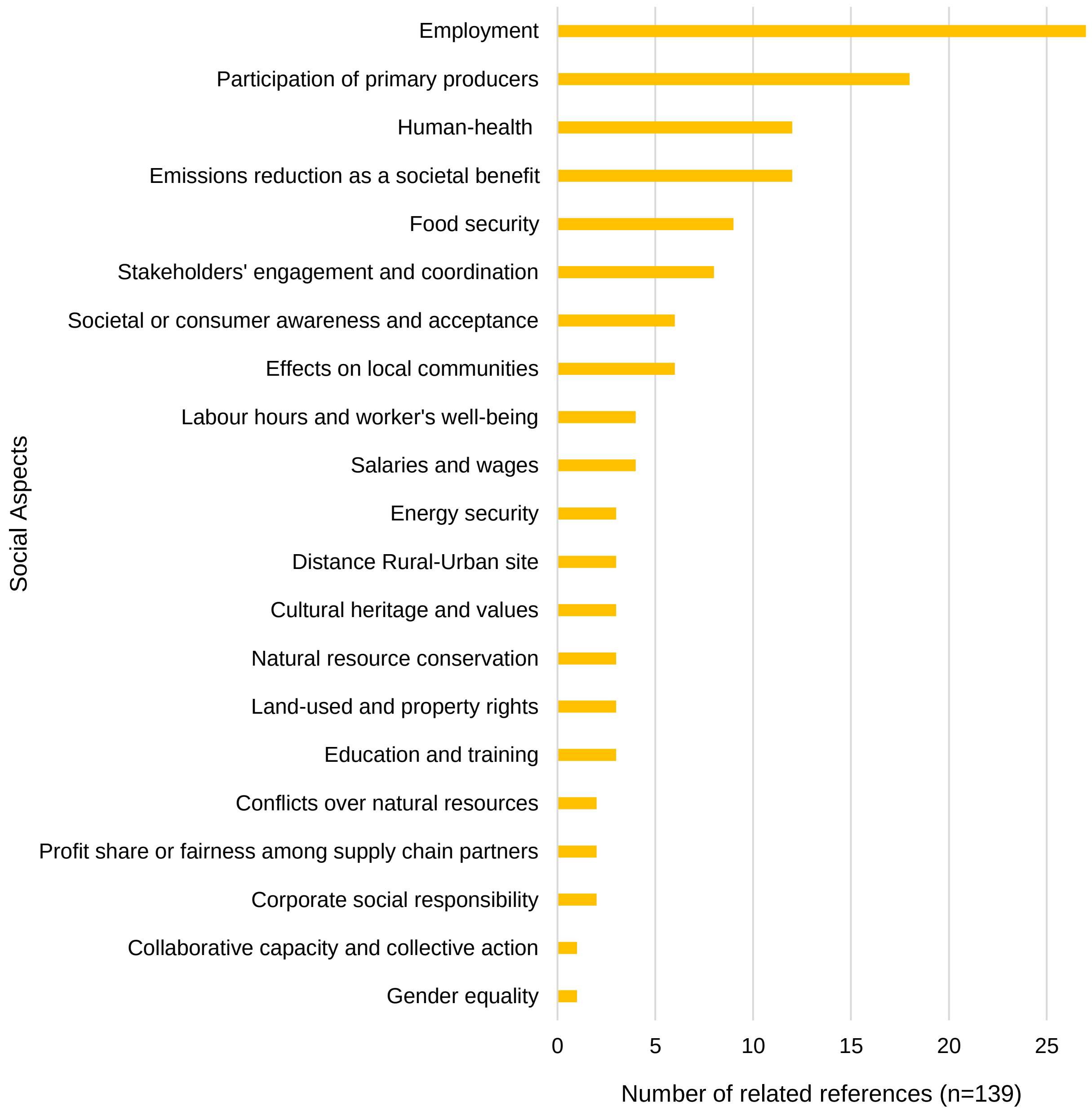


Figure 6 - Social aspects mentioned at the strategical decision-making level of biorefinery supply chains according to the literature analysed (n=139)

5. Discussion

Based on the presented results, bottlenecks are manifold as well as social aspects to be considered, although not yet fully integrated into strategic decision-making levels of BSCs. These factors are discussed in detail in the following sections, examining how new perspectives and approaches are relevant to unlock bottlenecks and include the social dimension of sustainability.

5.1 Unblocking bottlenecks

The results suggest that strategies to overcome the bottlenecks identified require a systemic perspective which widely interwinds techno-economic to socio-ecological systems. One of the primary challenges is that bio-resources have different properties than fossil-based resources such as bulkiness, low density, moisture content and high seasonality factors. Hence, logistic planning is considered a key bottleneck of new bio-based SCs elements such as the optimal spatial configuration, harvesting time and frequency, storage conditions, as well as considerations regarding the necessary infrastructure and transportation modes are of fundamental importance. Aligned to these results, Wohlfahrt *et al.* (2019) argue that artificial intelligence and information sharing could allow better planning to access the availability and sourcing of the bio-resources at local and regional scales. However, the hardships involved in feedstock procurement are not yet fully considered by the current studies, even if the deployment of new SCs and final product reliability will depend significantly on sourcing strategies (Corona *et al.*, 2018; Shastri *et al.* 2011). Grass availability, for example, is often treated as a surplus resource by several of the studies analysed and indicate that if prices are negotiated with farmers, they would be willing to introduce grasses in their crop rotation plans and to supply to the biorefinery (Prieler *et al.* 2019; Mandl, 2010). The interdependencies between decision-making at the farm level and biorefineries are highlighted (Cundiff et al., 2020). It must be considered, however, that the opportunity cost and willingness to participate or not in the SC might not be only based on monetary bargaining power. For example, bio-resources availability and procurement might be subject to shortness in supply due to weather-related events which are potentially increased by climate change effects (Nilsson et al., 2020). This should be considered and planned toward risk mitigation measures. Moreover, policy changes might also alter the uses of farmlands in association with income support schemes from agricultural policy, thus affecting land use and bio-resources availability (Boke Olén et al., 2021).

Farm management practices (whether on the land or the sea) have different impacts and are subject to contextual and cultural constraints, also considering the amount and type of fuel used for transport operations, the working conditions or how revenue streams are shared along the SC. Thus, the importance of raising attention to the social dimension and socio-ecological interactions from upstream up to downstream levels of SCs, considering that ecosystems and the livelihood of those involved in farming activities would be substantially influenced by the development of new bio-based SCs. Hence, primary producers should not be perceived only as suppliers but as a fundamental part of the planning and design decision process. In this regard, a better understanding of farmers' motivations and decision-making is still needed (Panoutsou *et al.*, 2017) and is required for more fair and inclusive SCs. This might involve rethinking incentives and compensation methods for their services towards environmental protection, livelihood assets and living conditions (Liu et al., 2021).

Alternative arrangements through collective ownership of infrastructure and other resources could be fostered, along with new SC coordination forms, alternative designs and biorefinery scales. This could include designing more local and closed-loop SCs with the valorisation of by-products in more symbiotic systems (Lemire et al., 2019). In addition, strategies for biorefinery product range are also highly context-dependent. For example, the significant representation of biofuel-based biorefineries present in the results reflects also the high number of study cases in the United States of America, which together with Brazil, are the two global leading countries in bioethanol production (Machado et al., 2015). On the other hand, strategies in European countries indicate the prioritisation of proteins as the main focus of new BSCs, aligned with ecological footprint reductions due to the dependency on soybean meal imports for the feed market (Ravindran et al., 2022; Ravindran et al., 2021). Aligned with Vance et al., (2022)'s results, current sustainability assessments such as LCAs faces diverse challenges, requiring multidimensional approaches, including temporal elements and regionality. BSCs and therefore their planning process are manifold and context-dependent, as well as their products and scale.

Furthermore, enhancing understanding regarding consumer behaviours and societal awareness of products and services derived from BSCs is still needed and necessary. Although it is often indicated that the maximum value should be extracted from bio-resources towards high-value-added products (Baghel *et al.*, 2020; Parsons *et al.*, 2019), 'value' might change according to when different perspectives are taken and could mean that economically profitable products from the biorefinery perspective might not be relevant or accepted. This is related to what Muscat *et al.* (2020) describe as different priorities given the context, values or societal responses to CBE developments. The priorities in producing food, feed, fuel, chemicals and other materials are also context-sensitive and dependent on influential factors such as policy support, power relations or acceptance of novel biorefinery technologies. Such components are not contemplated to large extent in the current planning process of BSCs and which directly relates to social dimensions of sustainability as suggested by the presented results.

5.2 Incorporating social sustainability

The most common social aspect taken into consideration in the studies analysed is employment creation. As a social criterion, it is an important indicator to alleviate poverty and prevent rural outmigration while helping to promote better livelihoods (Mulyati and Geldermann, 2017; Osmani and Zhang 2017; Cambero and Sowlati, 2016). It is, however, noteworthy to discuss to what extent job creation is a suitable social indicator and not an economic one. It could be considered both, expressing the complex nuances of dividing and assessing 'sustainability' based on the triple-bottom-line framework. In this regard, the quality of jobs might be rather as important as the number of jobs created and considered as social aspects in terms of salary and wages, rights, skills development, working conditions and health. It thereby supports similar findings of Mies and Gold (2021) on the strong reliance on job creation as a social measurement reflecting predominant economic perspectives. This, therefore, foresees the consideration of non-traditional social indicators which could include stakeholders' groups and conflicting interests (Mies and Gold 2021), collaboration as well as fairness in the distribution of profits or opportunities (Assefa and Frostell, 2007).

The number of jobs created can be an indicator more easily quantified considering that current research methods on BSC planning are broadly focused on mathematical programming whereas other indicators such as cultural heritage, collaborative capacity or conflictual situations might be more difficult to address in quantitative models. This endorses Lehtonen (2011), arguing that it is impractical to assume that the social dimension of sustainability can be assessed through the same tools and methods used for economic or environmental dimensions. To this end, methodologies to assess social impacts are still not well developed and qualitative or semi-qualitative indicators could be appropriate only to a specific context (Cadena *et al.*, 2019a). Cadena *et al.* (2019a), Osmani and Zhang (2017) and Gnansounou *et al.* (2017) further acknowledge the hardships of including social aspects, adding to the fact that social elements are strongly dependent on the local context. The UNEP-SETAC guidelines for S-LCA (Benoît Norris et al., 2013), for example, guide toward metrics proposition but further indicators might be more suitable depending on the setting for which is applied. However, considering that social sustainability issues is often restrained to concerns related to developing countries such as human rights (Janker et al., 2018), the social aspects identified by this study indicate a start in the direction of relevant social aspects to be considered in the strategic decision-making of BSCs..

The use of single indicators such as job creation also implies only positive social outcomes expected from new bio-based SCs, whereas conflicts could arise from different stakeholders' aims and interests as well as the need for local community acceptancy in the deployment of BSCs. The acknowledgement of such aspects in the planning process enables the need for collaborative capacity upfront of actual installations and therefore in the prevention and mitigation of conflicts. Moreover, the key role of SC coordination among trade partners (e.g. primary producers or end-users), as well as participation (e.g. local agents or broader society), might be often overseen as a social aspect in BSC planning because current research approaches are mostly focused on strategies developed from the biorefinery perspective. This reflects the limited possibilities of including multiple research fields and methodological diversity that could be able to grasp and address the social dimension of sustainability. In alignment with Pagell and Shevchenko (2014) observations, the adoption of multi-disciplinary or transdisciplinary approaches would be helpful to address this shortcoming in the development of sustainable SCs. Beyond that, the execution-oriented character of SC design (Melnyk et al., 2014) might prevent the inclusion of social considerations once they might also lay beyond common boundaries used in SC design. This validates the argument and the need for new reinterpretations of SCs (Wieland, 2021; Gruner and Power, 2017). New BSCs for the CBE would depend on the availability of a workforce along SC phases and involved in the diverse activities of farming, technological transformations and governance systems. In alignment with Salvador et al., (2022), this anticipates the demand for human resources with a unique set of skills and knowledge, which would further require innovative learning processes. The development of long-term strategies that can promote not only new jobs but also education, capacitation and healthy environments to work in, while encouraging gender diversity and the participation of younger generations is not only a social aspect to be included in the planning of bio-based SCs but the very base of sustainable development as defined by the WCED. To fulfil this research gap and integrate social aspects would require the adoption of more transdisciplinary and interdisciplinary research, methodological diversity, forecasting tools and transformative knowledge (Urmetzer et al., 2020; Devaney and Henchion, 2018). In the section below, new perspectives and approaches are explored and discussed for the integration of the social dimensions while intertwined with techno-economic and socio-ecological dimensions to unlock BSCs bottlenecks.

5.3 Integrative Strategies

The successful planning and deployment of sustainable bio-based SCs would only be possible with strategies that can embrace social aspects but also the plurality of uncertainties, risks or barriers represented here as bottlenecks. However, current research methodologies in BSC are mostly focused on economic objectives and just starting to consider environmental aspects, whereas social elements remain widely omitted in its strategic planning. Following system thinking approaches and futures research (Mingers and White, 2010; Evered, 1983), strategic decisions should be seen as a joint effort of planning in complex environments to tackle shared societal challenges. In operations research and management science, the concept of *strategy* has its traditional origins in military practices, being closely linked to the idea of competition and control amongst organisations or between SCs (Taha, 2017; Christopher, 2011). In contradiction, the development of a CBE depends on strategies that promote close cooperation between stakeholders and SC partners toward efficient uses of renewable bio-resources (Stegmann et al., 2020). This imposes a paradox: while studies in SCM might develop strategies that induce competitive behaviour between SCs, the successful planning of bio-based SCs predicts cooperation and circular partnerships in the planning process of BSCs.

To unlock bottlenecks and ultimately account for social sustainability, we propose a systemic overview of biorefinery systems for the strategic planning of BSCs (Figure 7). Following the previous work of Ahlborg *et al.* (2019), Wohlfahrt *et al.* (2019) and Marshall (2016), the conceptual model aims to shift toward new perspectives and BSCs boundaries represented as socio-technical-ecological system (STES). The visualization comprehends the several phases of the BSC, entailing the sourcing of alternative bio-resources up to its end-uses including circularity as a central feature and EC (2018b) waste hierarchy. The comprehensive overview of the system exposes the intertwining factors comprehending the source of bio-resources (from marine or terrestrial ecosystems), the biorefining process (technological innovation), and stakeholders (economic, social and governance dimensions). Following, the social aspects identified were organized by S-LCA impact categories in addition to ‘Institutions and Government’ which depict the governance level and further bottlenecks identified concerning policies, laws and regulations. Nevertheless, overcoming current economic (un)feasibilities of bio-based SCs will hardly happen only through market-related mechanisms (Lewandowski 2015) and in agreement with Mac Clay and Sellare (2022), social dimensions are also related to measures aiming to mitigate potential negative impacts to less (economically) powerful actors. Thus, the optimal design and sustainability strategies involving human-environment interactions are dependent on multi-level efforts and influential factors which are connected to financial incentives, participatory approaches, power relations, social awareness, cooperation or partnerships among different stakeholder groups. Unfortunately, these dimensions are currently hardly included within the planning and design process of BSCs. Therefore, the presented results should assist in *designing in* human dimensions aligned to a systemic perspective helping to guide further research and planning processes of BSCs to overcome bottlenecks and incorporate social dimensions of sustainability.

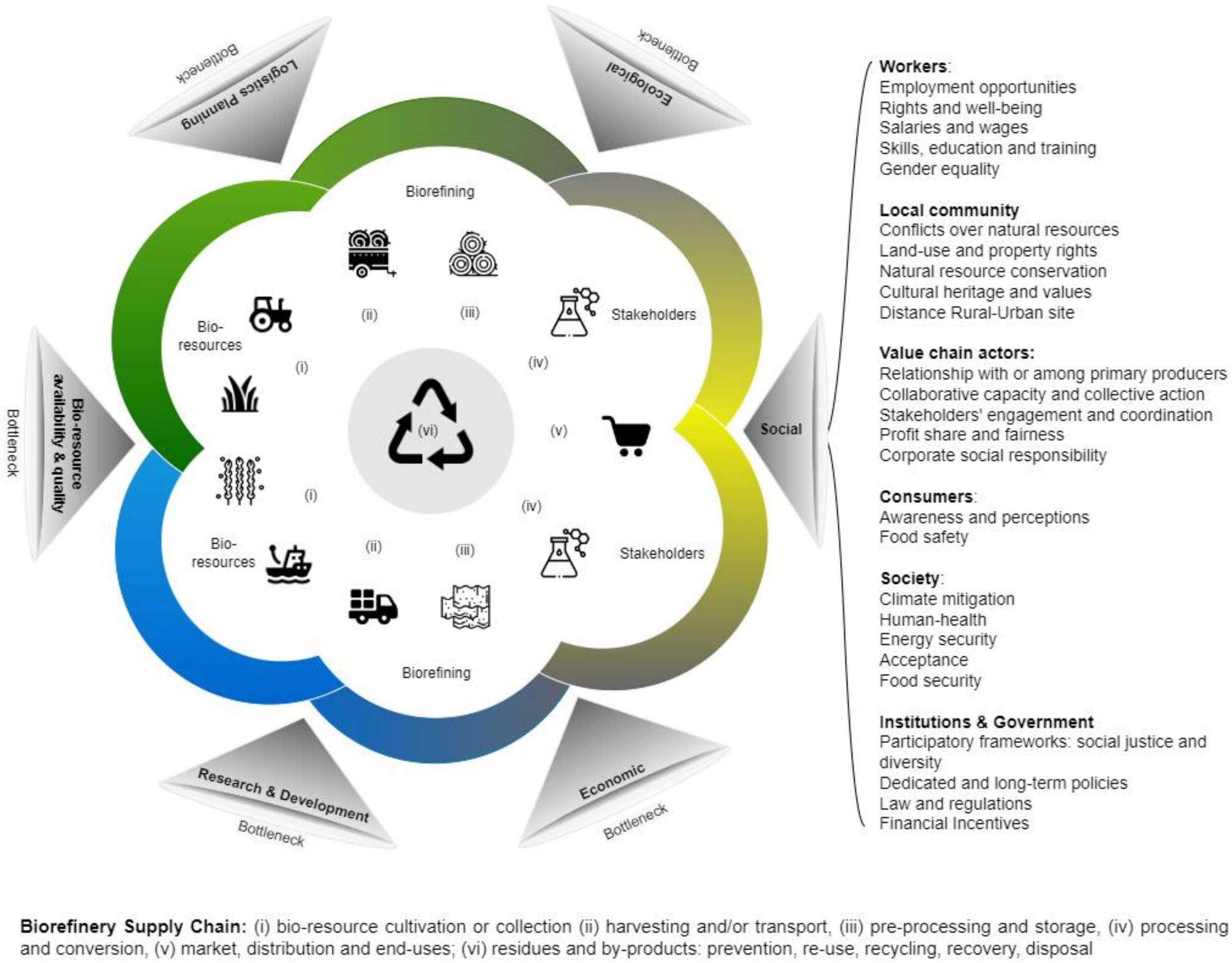


Figure 7 – Representation of the biorefinery system and related bio-based supply chain for strategic planning considering bottlenecks and the integration of the social dimension of sustainability.

Icons by Flaticon.com

This study is not without limitations, mostly due to the scope of our analysis. This is, firstly, because the set of keywords might not be exhaustive to yield studies in the biorefinery context. Secondly, further bottlenecks and social aspects might belong to other research fields that are not addressed here or not yet included in biorefinery studies, for example, those in social science fields, industrial engineering, land-uses, as well as specific areas on agriculture and marine research. The literature analysed comprehended peer-review articles in the English language and also with scope addressed to bio-resources sourced in temperate climates, which largely comprise countries in the Global North. Hence, it neglects non-English peer-reviewed materials, other forms of knowledge or contexts as well as potential spillover effects of new bio-based SCs in third countries, which should be addressed in future research. Nevertheless, the results presented contribute towards advancements in the fields of BSC and SCM while unveiling bottlenecks and addressing the overlooked social dimension of sustainability for strategic planning of BSCs. This helps to bridge the two research fields and highlights the need for inter-transdisciplinary efforts in the advancements of CBE research and biorefinery systems planning.

6. Conclusion

In the context of a CBE, questions have been raised on how new BSCs are being planned, as well as how the availability and sourcing of alternative bio-resources could be materialised towards more sustainable strategies. Our results exposed the need for interdisciplinary efforts and methodological diversity in the planning of BSC. This is highlighted through the identification of bottlenecks affecting successful planning as well as the importance of incorporating social sustainability upfront in strategic decisions. These findings critically explore the importance of extrapolating current boundaries of analytical frameworks currently adopted in biorefinery research and therefore in the development of more integrative strategies framed through system thinking and new sustainability frameworks such as STES. This could assist policymakers, supply chain managers, engineers, and project developers in the planning and design of BSCs but also avoid shortcomings in its deployment process. Considering the relative newness of the topic, it is recommended to update the conducted review with advancements in the research field as well as the inclusion of multidisciplinary teams, stakeholder groups, and other forms of cultural and local knowledge in the strategic planning of BSC. Finally, this would support not only the development of socially desirable bio-based SCs but also deeper sustainability transformations in our production and consumption systems towards a CBE.

Declaration of Competing Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Appendix A – Supplementary material

Descriptive analysis regarding supply chain phases and products.

Appendix B – Supplementary material

Table covering the list of articles reviewed by the study.

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