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Priorities for the sustainability criteria of biomass supply chains for energy

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ABSTRACT

The sustainability of biomass supply chains is a topic of significant debate, given its importance in the emerging bioeconomic context. This study aims to identify the criteria perceived to have the highest preference when evaluating the sustainability of biomass supply chains. The data includes the assessments of 122 international experts providing their evaluations through a questionnaire distributed between November 2019 and February 2020. The questionnaire presents pairwise comparisons of 12 sustainability sub-criteria organised into economic, social, and environmental categories. The results are analysed using the analytic hierarchy process (AHP) in combination with kernel methods to identify consensus regions in the experts' assessments. The responses showed that a large majority of experts belong to two distinct priority groups: an *environmental oriented* group (N = 78) and an *economic oriented* group (N = 21). The environmental-priority provided average weights of 22% to economic criteria, 22% to social criteria, and 56% to environmental criteria (highest priority); whereas the economic-priority group of experts assigned weights of 64% to economic criteria (highest priority), 13% to social criteria, and 23% to environmental criteria. Variations in the priorities were explained by the experts' contextual factors and backgrounds. In both groups, however, there was a consensus to prioritize the reduction of greenhouse gas emissions among environmental criteria, and revitalization of rural areas among social criteria. The results and methods proposed have broad applications in policy making, particularly in the comprehensive assessment of biomass feedstocks and supply chains, providing valuable insights for sustainable decision-making.

1. Introduction

Growing concerns regarding climate change and the need to reduce greenhouse gas emissions have increased interest in renewable energy sources, with biomass garnering particular attention (Edenhofer et al., 2014). Biomass constitutes the biodegradable fraction derived from a diverse array of sources, encompassing products obtained from both forests and agriculture, either cultivated as primary products, generated as residue, or derived as waste materials (Bowyer et al., 2012). Notable examples of biomass include food and feed crops, dedicated energy crops (e.g., switchgrass or prairie perennials), agricultural residues (e.g., corn stover), wood waste, mill residues, non-commercial biomass from wooded areas, animal manure, as well as industrial and municipal waste (RED, 2009).

Modern biomass practices strive to minimise negative impacts on the environmental, social, and economic systems (Goldemberg and Coelho, 2004). Extensive research efforts have been dedicated to assessing the environmental impacts of utilizing biomass for energy (Mao et al., 2018). Nonetheless, the sustainability of biomass production, especially concerning the extraction of wood biomass from forests, has emerged as a subject of considerable debate and contention in recent years (Stupak et al., 2021). Concerns persist that the methods and quantities of biomass extraction from specific ecosystems may result in negative consequences for biodiversity, soil quality, as well as air and water quality, among other factors (see, e.g., Fernando et al., 2010; Pedroli et al., 2013; Ranius et al., 2018; Searchinger et al., 2018).

Various methodologies have been devised to evaluate the sustainability profiles of distinct biomass supply chains, encompassing criteria and indicators (C&I), life cycle assessment (LCA), environmental impact assessment, cost-benefit analysis, and exergy analysis (for an extensive

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review, see Buytaert et al., 2011). Frameworks and software tools, such as ToSIA (Tools for Sustainability Impact Assessment of Forest-Wood-Chains; Lindner et al., 2010; Lindner et al., 2012) or the DPSIR framework (Drivers, Pressures, State, Impact, and Response Model of Intervention; Smeets and Weterings, 1999; Gabrielsen and Bosch, 2003), have been proposed, with applications in the assessment of biomass supply chains for energy, whether sourced from forests (e.g., Werhahn-Mees et al., 2011; Locoh et al., 2022) or agriculture (e.g., Gutzler et al., 2015).

Despite variations in methodologies and approaches, a common element shared among these alternatives is the utilization of criteria and sub-criteria linked to the three primary sustainability dimensions: social, economic, and environmental (Purvis et al., 2019). However, a significant challenge remains in establishing relative priorities for each criterion and sub-criterion, to facilitate effective comparisons or decisions at policy level (Tarne et al., 2019). This challenge essentially constitutes a multi-criteria decision analysis (MCDA) problem, which can be addressed through analytical hierarchy processes (AHP), as proposed by Saaty (1980). AHP is a structured process that enables decision-makers and experts to assign weights to various criteria based on their relative significance, with broad applicability in the field of sustainable management policies (Schmoldt et al., 2001; Meyar-Naimi and Vaez-Zadeh, 2013; Kulisic et al., 2021).

Nonetheless, a potential issue arises when experts and decision-makers fail to reach a consensus on the weights assigned to diverse sustainability criteria. In cases of extreme disagreement, the conventional use of AHP, or even fuzzy AHP (Buckley, 1985), in collective assessments can pose challenges (for a comprehensive review, see (Oliva et al., 2019)). These methods often aim to achieve a single consensus, frequently through averaging responses. Previous studies have attempted to address this by estimating an aggregated evaluation (Tarne et al., 2019; Yang et al., 2017), which can be misleading, particularly in polarized cases, as an average of expert priorities may not adequately represent their collective judgments.

In this context, our study seeks to assess the priorities associated with sustainability criteria pertaining to biomass supply chains for energy production. We draw upon the insights of a panel of experts in the field of bioenergy. Given that sustainability debates often surface at various points within supply chains, the findings from our research hold relevance for any other applications of biomass in the broader bioeconomy. Our objectives aim at: i) determining whether experts assign equal priority to all sustainability criteria; ii) identifying the most significant priorities; and iii) assessing whether consensus exists among experts regarding the overall sustainability of biomass supply chains. We address potential disagreements by analyzing individual expert preferences employing a kernel approach for identifying and mapping consensus. Ultimately, our goal is to provide valuable insights into the sustainability of biomass and inform decision-makers with an empirical basis to properly assess future energy alternatives or to frame biomass demand for a growing bioeconomy.

2. Literature review

There has been a surge in the number of studies dedicated to the comprehensive evaluation of the sustainability of biomass supply chains, including field, regional, and national domains (Blair et al., 2021), under the general goal to ensure that the current utilization of biomass resources do not compromise future generations benefits (Stupak et al., 2007). In a broader perspective, the discourse surrounding the sustainability of forest biomass supply chains considers technical, economic, environmental, and social factors. While some studies have introduced supplementary dimensions, such as institutional considerations (Turcu, 2013) and cultural elements (Soini and Birkeland, 2014), the tripartite framework, encompassing environmental, economic, and social aspects, has gained widespread acceptance (Purvis et al., 2019).

The economic dimension of biomass supply chains entails ensuring sufficient revenues for the continuous operation of a system over a specified period (Scarlat et al., 2015). In the literature, techno-economic analyses have been broadly employed to evaluate the economics of various projects and assess the economic impact of different technical choices (Lo et al., 2021). Among the most common focus, it can be mentioned the technical efficiency, renewability, production, capital, maintenance and operation costs, as well as the environmental externalities (Genoud and Lesourd, 2009; Menikpura et al., 2012; Lo et al., 2021). In general, this dimension has been traditionally regarded as critical, as high costs can preclude adoption of bioenergy systems notwithstanding their environmental and social merits (Chong et al., 2016).

The environmental dimension has become an important issue for the evaluation of biomass supply chains, particularly in recent studies. In the literature, environmental LCA stands as the preferred tool for assessing the environmental impacts of products across their entire life cycle (see reviews Cambero and Sowlati, 2014; Wang et al., 2018). Environmental aspects typically encompass greenhouse gas emissions, soil degradation, biodiversity loss, and water resource quality, among others (Abbasi and Abbasi, 2010; Zahraee et al., 2020). Particularly, the achievement of low or zero GHG emissions, an optimized water-energy nexus, and well-protected ecosystems are issues that have become increasingly significant for the biomass industry (Zahraee et al., 2020b). Social aspects, on the other hand, have received siginifcantly less attention in the design of biomass supply chains, although in recent years their consideration in different studies has been growing (Cambero and Sowlati, 2014; Zahraee et al., 2020). In this case, the key issues have revolved around poverty alleviation, indirect effects on crop and land, and impacts on social resources like water systems, among others (Zahraee et al., 2020).

Although all these aspects play some role in the sustainability assessment of biomass supply chains, the large majority of studies have concentrated on a single evaluation factor, particularly employing either economic or environmental assessment tools (Cambero and Sowlati, 2014 provides a large review of studies, from which only four address several factors). However, to make informed decisions in the design of forest biomass supply chains for bioenergy and bioproducts, decision-makers must consider viable alternatives and assess holistically their potential economic and environmental performance, as well as their societal impact.

In the pursuit of assessing the comprehensive sustainability of bioenergy systems, two internationally recognized frameworks have been developed: the International Organization for Standards (ISO) 13,065 Standard on Sustainability Criteria for Bioenergy (ISO, 2015), and the Global Bioenergy Partnership (GBPE) sustainability indicators (FAO, 2011; GBEP, 2020). The latter is an initiative coordinated by the Food and Agriculture Organization of the United Nations (FAO) which involves 23 partner countries, 13 international organizations (including the IEA, European Commission, IRENA, UN Environment, and UNDP), and 11 additional international organizations as observers. As a result, the GBEP's Task Force on Sustainability has established 24 sub-criteria, organised under environmental, social, and economic criteria, with each criterion overseen by different international institutions and country groups, chosen for their relevance, practicality, and scientific basis. Their use, feasibility and practicality have been tested in several countries and studies in recent years (e.g., Bentsen et al., 2019; Pirelli et al., 2021; Vera et al., 2022).

3. Material and methods

3.1. Sustainability criteria

In this study, biomass supply chains are defined as the cultivation, harvesting, processing, storage and transportation of different biomass feedstocks to be used for energy. The assessment is based on three main criteria (economic, social and environmental), each divided in four sub-criteria. We proposed a fixed number of sub-criteria so as to limit the number of parameters that would characterise biomass supply chains while at the same time cover as many sustainability aspects as possible. The ambition was to reduce the number of comparisons to facilitate the retrieval of responses, aiming at minimising the input from each stakeholder but at the same time securing enough data would be used to characterise the supply chains. The criteria were largely based on the GBEP sustainability indicators for bioenergy (2020), and the criteria and sub-criteria (alternatives) were organised following a hierarchical structure (Fig. 1).

In the economic criterion (A1), the sub-criteria were: value added (A1.1, assuming an improvement from the reference scenario), cost minimisation for society (A1.2, including e.g., waste management, forest risks mitigation, phytoremediation), efficient use of local resources (A1.3, including land but also infrastructure, SMEs or people, among others) and increased investments in the economy (A1.4, including forestry and agriculture). For the social criterion (A2), demand for new jobs (A2.1, in terms of job opportunities and new jobs to compensate the loss of traditional agricultural or forestry related employment), revitalization of rural areas (A2.2, e.g., dynamizing local economy), increased well-being (A2.3, e.g. health, clean environment, social activities, tourism and recreation, work safety) and social acceptance (A2.4, e.g. public support to projects). Finally, the environmental criterion (A3), included: GHG emission reduction (A3.1 including increased carbon sink and soil carbon accumulation), improved land use management (A3.2 including, e.g.: agroforestry, sustainable intensification, carbon farming), water, air, soil quality and water availability (A3.3, e.g., the use of idle agricultural land, soil improvements, water stress) and ecosystem and biodiversity (A3.4, e.g., conservation of habitats, protection of species).

3.2. Data collection

A questionnaire was prepared where criteria and alternatives were displayed in a set of pairwise comparisons, to be analysed following AHP methods (for details, see Appendix **A1**). A pool of international experts was constructed using existing lists of experts involved in IEA Bioenergy activities, previous projects and a literature review. To be included in the list as an expert, the interviewee had to fulfill the following criteria: have worked for more than two years for an energy research centre or company, have been involved in several biomass or energy related projects, and/or have produced publications in the field. In addition, the questionnaire included self-declared questions related the experts' background and experience. The total list included 306 experts and particularly represented experts from Australia, Canada, Europe and the USA.

The questionnaire was sent to experts by email during November 2019 to February 2020. The experts' profile was categorised as private sector (including those self-defined as working for private sector, industry or consultancy), government (including those self-defined as working for national governments, federal government, regional government or development agency), and research (including those self-defined as working for universities or research centres).

3.3. Data analysis

The results were analysed using an adapted AHP approach (for details, see Appendix **A2**). This is a method designed to weight priorities among different alternatives, using pairwise comparisons based on linguistic terms to rank different criteria and goals (Saaty, 1980). The approach made use of the hierarchy of the criteria and alternatives established, and created a pairwise comparison matrix, where each criterion and alternative is compared with each other. The matrix contains entries that reflect the relative importance or preference of each element compared to the others, which are assigned a numeric value based on the scale of preference: 1 (both alternatives are considered equally important) to 9 (one alternative is given full priority).

The matrix was then normalised and the resulting priority vector for each expert was estimated for each criterion and sub-criterion (Saaty, 1990). The pairwise comparisons permitted the assessment of the

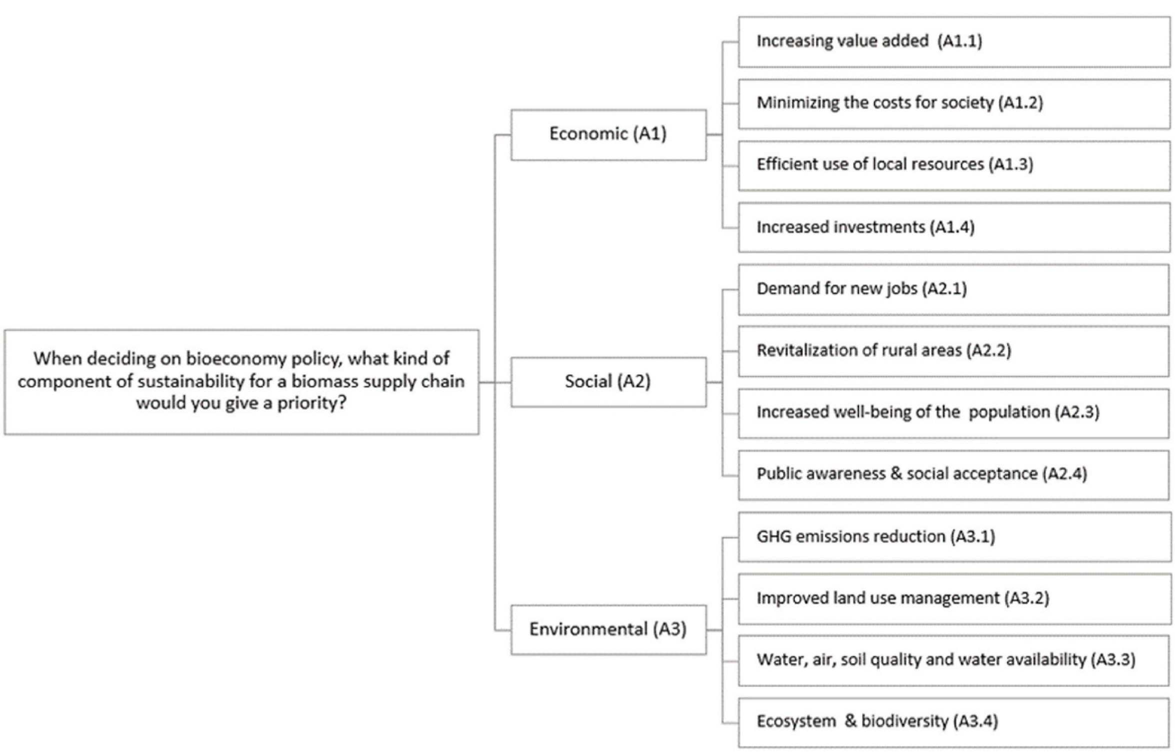

Fig. 1. Hierarchy of the sustainability alternatives considered in the assessment. Four alternatives are proposed for each sustainability criteria (economic, social and environmental).

consistency in each experts' responses, by calculating the consistency ratio (as proposed by Saaty, 1987; see Appendix **A2**), which is the ratio of the consistency index (CI) to a random index (RI). The CI is calculated as the difference between the highest eigenvalue and the number of criteria or alternatives, divided by the number of criteria or alternatives minus one. The RI is a constant value that depends on the number of criteria or alternatives (being 0.58 and 0.90 when there are 3 and 4 alternatives, respectively). The closer the resulting CR is to 0, the more consistent the responses.

The analysis did not directly disregard inconsistent responses, but instead, a weight value (p) was applied to each of the experts' responses, formulated as:

$$\begin{cases} p = 1 - CR; \, when \ CR \leq 1 \\ p = 0; \, when \ CR > 1 \end{cases} \quad [1]$$

The histogram of all experts' weights for the criteria and sub-criteria were then analysed, in order to assess the overall experts' consensus for a given criteria or sub-criteria priority. The analysis used weighted kernel density estimation methods (see Silverman, 1986; Worton, 1989), applied to the resulting distribution of weights, for each criteria and sub-criteria individually. Consensus regions were defined as the minimum space entailing a fixed percentage of the total weights alternatives, using the resulting percent volume contours. These percentages were fixed at two levels: 20% (defining the core consensus region) and 80% (defining the largest consensus region). By these means, areas under these thresholds entail the weights for a given criterion where the 20% and 80% of all the experts present the minimum disagreement with each other, and help define the cores in the responses and potential subgroups within the expert population. This was applied to the three main criteria and all sub-criteria pairwise, and displayed using ternary plots as well as hierarchy diagrams.

Finally, the results of the experts' priorities were further assessed according to their profile, background and region where they work. The statistical methods were performed in R statistical software (R Core Team, 2022) and the analysis using ternary plots was performed using the Ternary package (Smith, 2017).

4. Results

In total, 193 experts completed the questionnaire. However, incomplete answers reduced that number to 122 questionnaires from 23 countries, which were included in the calculations. The countries with the largest number of experts were Germany (N = 36), Canada (N = 31), Sweden (N = 15), Finland (N = 6), the USA (N = 5) and Czech Republic (N = 3). Australia, Austria, Belgium, Denmark, Estonia, Latvia and Spain were represented with two experts each, and Brazil, Bulgaria, Croatia, Hungary, India, Italy, the Netherlands, Poland, South Korea and Switzerland, with one. Two additional experts were self-defined as working for European or global organizations.

After the results were analysed, countries were grouped in three main geographic areas in order to have enough responses to represent their distribution as a histogram (which was fixed in N > 20). The geographic areas were defined as *Germany* (N = 36), *North America* (N = 36), including Canada and the USA, and *Nordic* (N = 21), including Finland and Sweden. The self-reported expertise of the respondents was mainly in bioenergy (N = 49), forestry (N = 40) and agriculture (N = 15). The rest of the respondents had mixed backgrounds, including biomaterials and bioplastics (N = 5), and related sciences. Concerning their professional backgrounds, there were 19 government based respondents, 38 from the private sector and 65 researchers; in addition to these, 4 did not report or had mixed backgrounds.

The consistency of the answers was moderately high: 52% and 79.3% of the responses showed strong consistency (CR < 0.10), and moderate consistency (CR < 0.20), respectively. The highest consistency was among the environmental sub-criteria (62% and 88%, using CR < 0.10 and CR < 0.20, respectively) and lowest in the economic sub-criteria (39%, 72%). There were no significant differences in the mean priority weights for the criteria and sub-criteria either using a moderate consistency threshold (CR < 0.20) or including all answers. The environmental criterion (mean weight 0.46) was ranked first, followed by the economic (0.35) and social (0.19) criteria.

However, there were important divergences among experts ranking the criteria and a different message arose when the analysis considered the clusters of expert's assessment (Fig. 2). Most of the responses were clustered in two well-defined consensus regions: a large group of experts with a stronger preference for environmental criteria over economic (*environmental oriented*), and a smaller but distinct group prioritising economic over environmental (*economic oriented*). In the case of social criteria, they were ranked with lower priority in both groups.

The average weights considering all answers would yield 35%, 19% and 46% for the economic, social and environmental criteria, respectively. However, analysed separately, the economic priority group (weights over 50% in this criterion) would yield 64%, 13% and 23% for the economic, social and environmental criteria, respectively and the environmental priority group, would result in 22%, 22% and 56%, respectively. The analysis rendered the nearly equal values when using a moderate consistency threshold in (CR < 0.20). This would change the allocation of the alternatives' weights: *GHG emissions reduction* is the prioritized alternative when all answers and environmental priority are considered, whereas in the case of the economic-priority group, for full prioritisation for *increasing value added* and *investments* (Fig. 3).

Trade-offs between alternatives (sub-criteria) were also analysed pairwise. In this case, the priority weight of each main criteria associated with sustainability pillars was considered equal. The consensus regions also reproduced the two groups' preferences (Fig. 4), particularly concerning *GHG reduction* (A3.1, reflecting two distinct cores), *creation of new jobs* (A2.1), *social acceptance* (A2.4), *increased investments* (A1.4) and *minimising costs for society* (A1.2). Taken as such (i.e., irrespective of the priority of the main criteria or *pillar*), the *use of local resources* (A1.3), *revitalization of rural areas* (A2.2) and *GHG reduction* (A3.1) were the alternatives where the consensus region reflected the highest priority, for economic, social and environmental alternatives, respectively.

Polarization in expert opinions also manifested when analyzing their backgrounds or regional affiliations. Interestingly, these distinct polarized groups were consistently observed across various backgrounds and regions. Given that these two groups held opposing priorities, particularly in terms of economic and social criteria, the overall average was somewhat consistent when combined, although with large variability (standard deviation and variance) around both the mean and median values (Fig. 5). Due to this large variability, no statistically significant differences were found, in general, when subjecting the data to various tests, regardless of the experts' backgrounds or regional origins. Applied as such, only significant differences were found concerning the weight for the social criterion related to the experts' background (p-value = 0.022) with a smaller lower value for those experts from other categories than bioenergy, forestry and agriculture, and concerning the alternative increased investments and the experts' region (p-value = 0.007) with stronger support among experts from North America.

However, there were evident differences between groups, particularly concerning the regional areas where the experts work, which emerged in the histograms by each experts' variable. All classifications reflected two clearly distinct groups; especially, in the case of the experts from the Nordic countries the group *environmental-priority* had a stronger orientation towards environmental alternatives (weight over 0.60 in the social criterion) and in the case of experts from North America the support was lower, even in the environmental-priority group (weight lower for both social and economic criteria). In addition, experts from North America showed stronger support for social criteria, despite the fact that it was the lowest prioritized option among all groups.

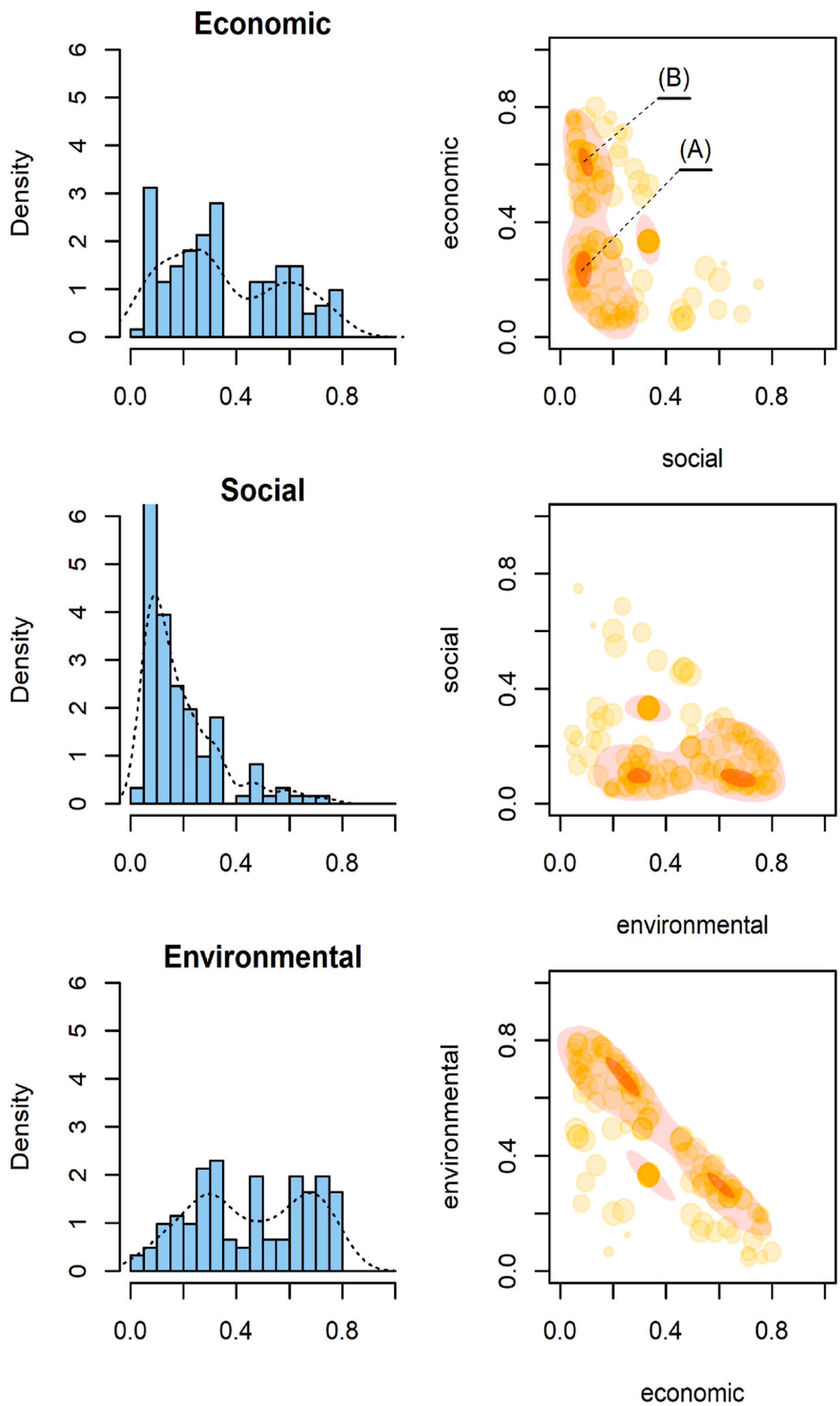

Fig. 2. Distribution of experts' weights for the three main sustainability criteria, weighted according to their consistency. Each respondents' weight and consistency ratio is derived from pairwise comparisons using an analytical hierarchy process approach. A one-dimension kernel function is used for each criteria (left) and a two-dimension kernel function for the criteria compared pairwise (right). The areas represent the consensus regions encompassing 20% (*core* area) and 80% of the responses, weighted according to their consistency (represented by the dark and light red colour, respectively), representing two consensus areas: (A) *environmental oriented* and (B) *economic oriented*. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

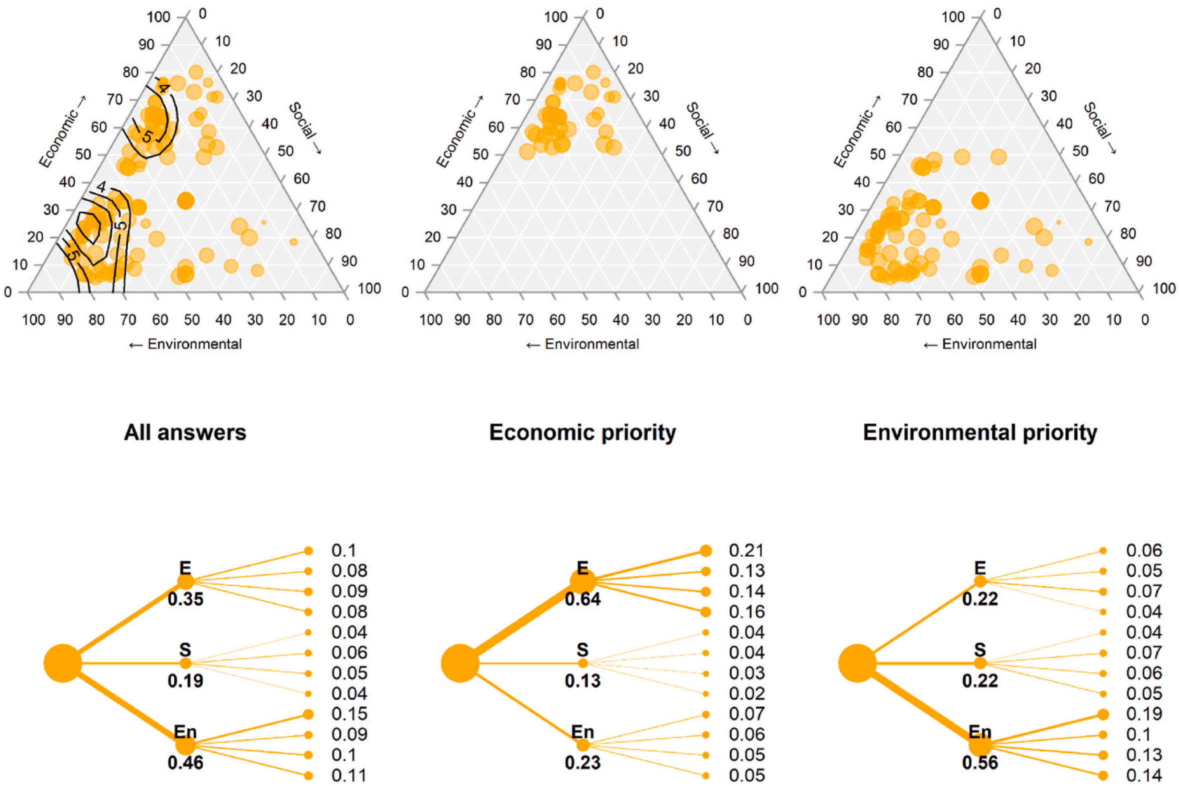

Fig. 3. Average weight for each of the alternatives and criteria considered, for all answers combined, for the *economic oriented* group (selecting respondents with <0.5 wt for the social criterion, N = 21) and for the *social oriented* group (selecting respondents with >0.5 wt for the social criterion, N = 78). E = economic, S = social, En = environmental, alternatives for each criterion are defined in Fig. 1. Contour lines represent the density or answers (consensus regions).

5. Discussion

The sustainability of biomass supply chains is a subject of important debates due to their relevance in the emerging bioeconomy context. Most interactions with the ecosystem in bioenergy occur along the biomass supply chain and not at the end-use, which makes well established bioenergy supply chains a good learning ground to form a comprehensive evidence-based for bioeconomy policy framework. This study formulates an assessment of the different sustainability criteria concerning biomass supply chains, with end-use for energy but also applicable for end-use in a wider bioeconomy.

Supply chains involve different feedstocks, from forestry and agriculture, and involve several activities (e.g., procurement, storage, pre-processing, transportation and delivery) resulting in distinct environmental profiles and impacts (Allen et al., 2016; Zahraee et al., 2020). In addition, there are broad differences between countries concerning feedstocks available, procurement methods and operations along the chain (Díaz-Yáñez et al., 2013; Kons et al., 2022). The focus of this paper was to provide a prioritisation of the criteria and sub-criteria (alternatives) most commonly used to evaluate biomass supply chains, that could apply to any supply chain irrespective of the particular feedstock, procurement methods or activities associated.

In this sense, the formulation of the questionnaire was designed to produce a broad representation of experts' knowledge concerning sustainability. The number of respondents was large for an AHP based analysis, where the most important factor is expertise (Saaty and Özdemir, 2014) and compares well with similar studies: for example, Schröder et al. (2019) addressed only 34 experts and Tarne et al. (2019) interviewed 54 decision-makers to weight sustainability criteria, using alternative methods. All experts included had verifiable experience in the field, represented countries where modern bioenergy is well established, and included a number of profiles in the public administration, industry and research fields.

The approach taken largely fits within C&I approaches (Buytaert et al., 2011), and the criteria used in the questionnaire were based on the Global Bioenergy Partnership (GBEP, 2020) sustainability indicators for bioenergy, which provides a solid basis for analysis. In this study, the number of sub-criteria was, however, reduced (from 24 to 12), as we restricted the sub-criteria available to four options per criteria (*pillars*), in order to avoid overwhelming the experts with an excessive number of comparisons, particularly resulting from the application of AHP methods (Saaty, 1980). Whereas pairwise comparisons between 4 alternatives implies 6 questions, pairwise comparisons between 8 alternatives required 28 questions. The reduction was done by merging some of the criteria (e.g., A3.3, *water, air, soil quality and water availability*), or removing some criteria from the original GBEP list (e.g., *change in unpaid time spent by women and children*). The final list of criteria and sub-criteria was consistent with recent studies using similar approaches (e.g., Schröder et al., 2019; Ossei-Bremang and Kemausuor, 2021), and despite the reduction, provided a solid basis for sustainability assessment.

The method to prioritize the proposed criteria was based on AHP, which is a widely used and effective approach to assess complex decision-making problems with multiple criteria, and has been one of the most used methods in MCDA (Pohekar and Ramachandran, 2004). By breaking down decisions into smaller components and using pairwise comparisons, experts and decision-makers can prioritize criteria and alternatives based on their relative importance and make more informed decisions and comparisons. In this sense, AHP has proved to be a suitable method for C&I approaches (Mendoza and Prabhu, 2001) and for decision making for sustainable development (an extensive review can be found at Dos Santos et al., 2019; How and Lam, 2018).

The main use, however, differed from classic AHP applications, where experts are acting directly as judges, and the main goal is to find agreement and high consistency, both in each experts' answers and among themselves (Saaty and Özdemir, 2014). AHP provides an

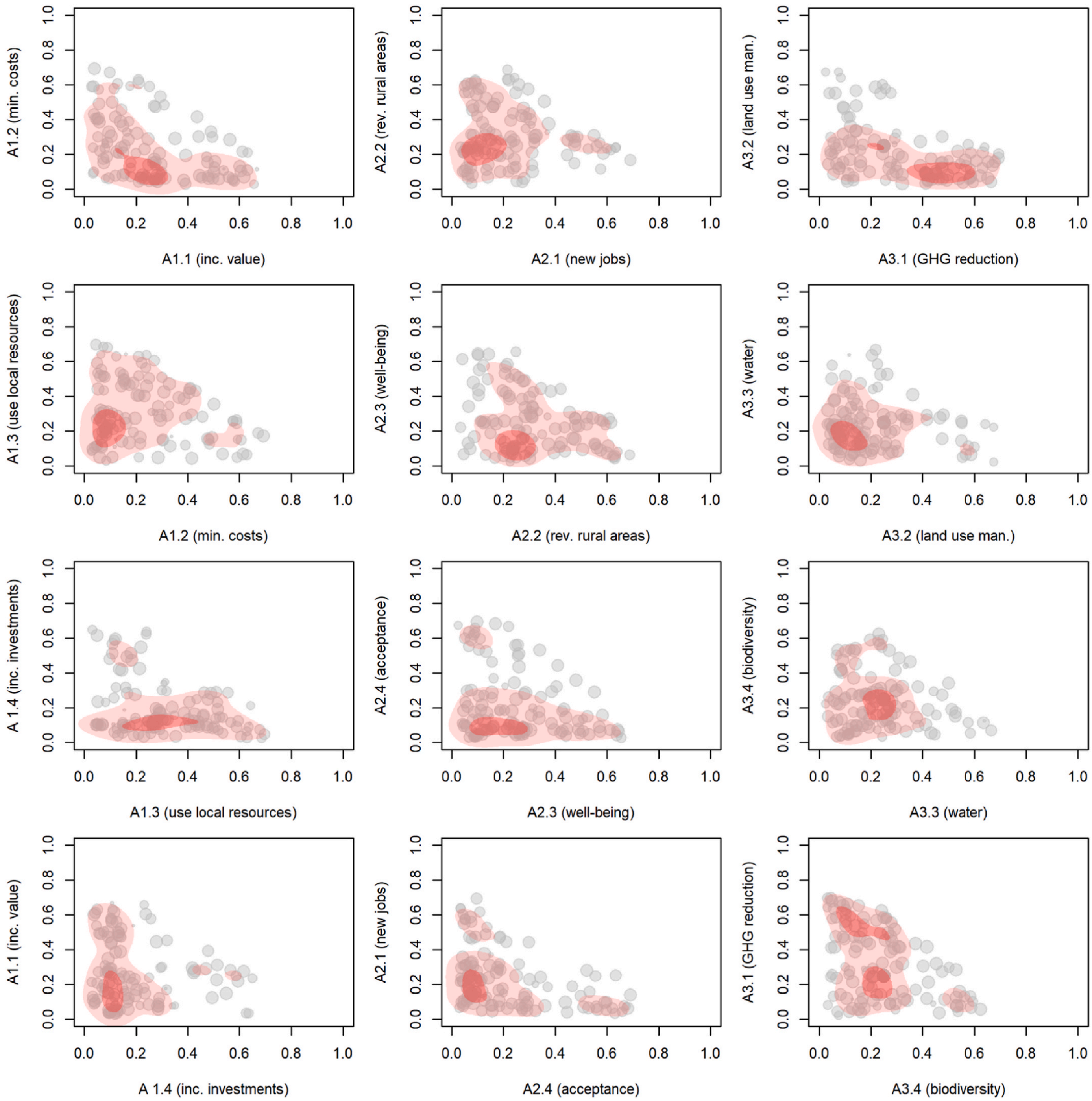

Fig. 4. Distribution of experts' weights for each individual sustainability alternatives, adjusted according to their consistency. Each individual weight and consistency ratio is derived from pairwise comparisons using an analytical hierarchy process approach. A two-dimension kernel function is applied for the criteria compared pairwise; the areas represent the consensus regions encompassing 20% (*core*) and 80% of the responses. A1: Economic criteria, A2: Social criteria, A3: Environmental criteria.

acceptable tolerance level for the degree of inconsistency (Saaty and Vargas, 1984). Saaty (1987) recommended allowing some level of inconsistency (CR not more than 0.10), in order to reflect new knowledge along the answers, although this is still considered a strict interpretation, and some studies have relaxed this threshold (Mahmoud and Hine, 2013; Kulisic et al., 2021; Kulišić et al., 2022).

In our case, it was equally important to reflect possible disagreements among experts as well as to identify differences in priority allocation. The use of weighted kernel methods was a compromise to consider all experts' answers while at the same time, adjust the aggregation according to their consistency, which we believe to be a novel and valid approach for the prioritisation of criteria. In addition, it was an effective and visual approach to define consensus regions within the decision space. In fact, Steinhilber (2016) proposed building decision-makers prototypes according to their sensitivity concerning sustainability criteria. It was applied in Beyer et al. (2016), defining experts in *environmentally oriented*, *economically oriented* and *socially oriented*. In our case, the analysis permitted the identification of homogeneous groups of experts defined by their main sustainability priority whether on environmental or social criteria.

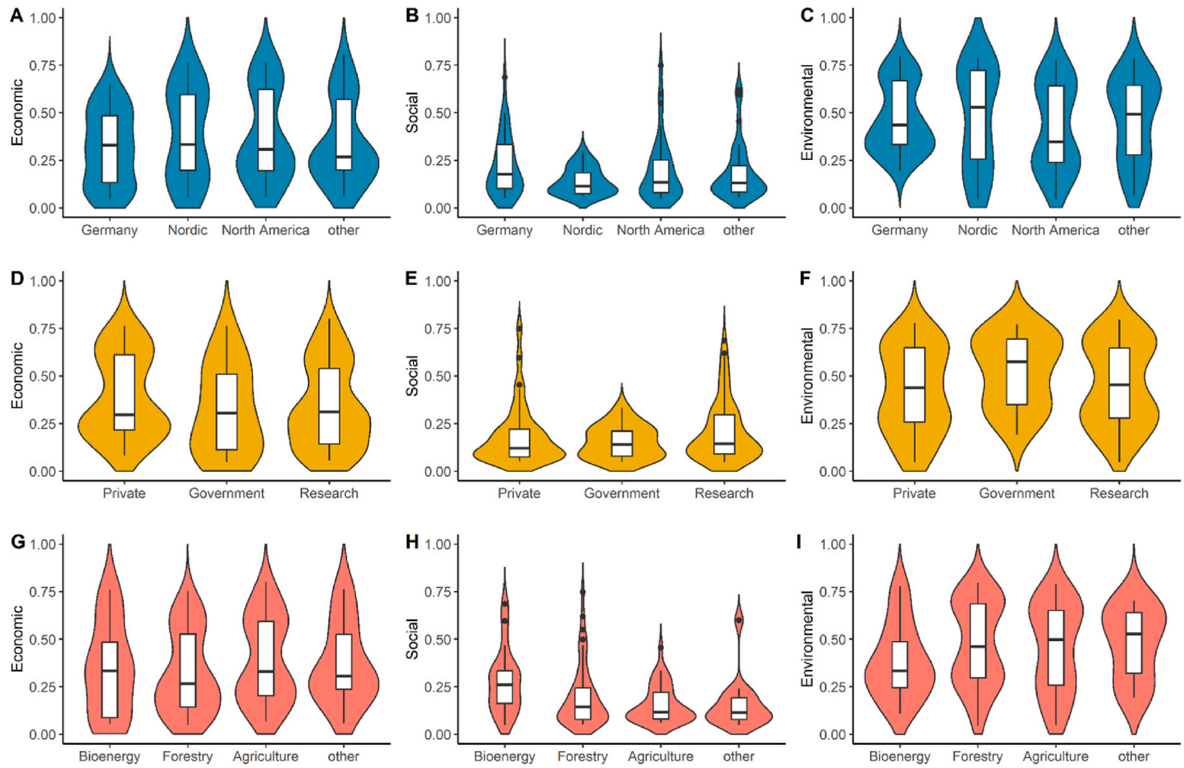

Fig. 5. Distribution of the weight values for the categories *Economic*, *Social* and *Environmental*, according to the interviewees profiles. Top (A, B, C): grouped by main region, *Germany* (N = 36), *Nordic countries* (Finland, Sweden, N = 21), *North America* (Canada, US, N = 36) and others (rest of the countries, N = 29). Middle (D, E, F): according to the position of the interviewees within the private (N = 38), government (N = 19) and research (N = 65) sectors. Bottom (G, H, I) according to their background, in bioenergy (N = 49), forestry (N = 40), agriculture (N = 15) and other, mainly in bioeconomy related sciences (N = 18). The boxplot represents the median with a thick line in the centre, the interquartile range, the 1.5 x interquartile range and outliers, following standard practice.

Most experts belonged to the first group and ranked highest priorities to environmental criteria, stressing a high environmental concern when assessing biomass supply chains. These concerns are reflected in the literature, as the amount of research concerning environmental assessments of biomass supply chains surpasses those focused on economic or social (Cambero and Sowlati, 2014). Particularly, emissions reduction plays a fundamental role in the development of bioenergy systems, it is broadly stressed in policy documents (RED, 2009, RED II, 2018), which can explain the highest support among government related experts, and it is also the most common focus of several optimization studies in the design of forest biomass supply chains (Cambero and Sowlati, 2014).

A second group of experts ranked high priority to economic criteria. Economic criteria have been highlighted in similar studies (Schröder et al., 2019), and are also well represented among sustainability assessments (Cambero and Sowlati, 2014), As in the case of environmental criteria, previous studies using a similar approach found the priority of the different criteria to vary according to the biomass feedstock (Ossei-Bremang and Kemausuor, F., 2021). For example, in the case of energy crops, economic criteria were the most prioritized when discussing overall sustainability, whereas environmental criterion was given priority in residues and wastes. In a study (Wheeler et al., 2018), economic sub-criteria such as net present value were ranked high priority, on average at the same level as fossil fuels extraction. In this case, the subgroup was especially represented by private sector experts, and less by government related experts, which highlights the different focus among stakeholders (Beyer et al., 2016). By region, German experts placed also a relatively higher priority to economic criteria, perhaps reflecting their concerns about energy costs. The research was performed before the start of the Russian-Ukrainian war, which has affected the energy markets globally, and particularly in Europe (Umar et al., 2022). It is possible that the experts' perceptions on economic criteria have changed, increasing their priority allocation in light of geopolitical developments. It can be speculated that conjunctural factors can have a large effect on the overall sustainability priorities related to energy production.

Finally, social criteria were ranked with the lowest priority, which was consistent with the findings in Cambero and Sowlati (2014) and Schröder et al. (2019). Among profiles and backgrounds, bioenergy experts placed a higher stress than other groups on social and lower priority for environmental criteria. Bioenergy experts may be influenced by the overall discussions concerning the role and acceptance of bioenergy (see Searchinger et al., 2018), and may assume that nowadays environmental effects are a matter of governance and practices (Stupak et al., 2016). In fact, global reviews on the environmental effects of the use biomass for energy highlight the difficulty to produce overall conclusions, given the broad range of assumptions needed (Buchholz et al., 2016; Jeswani et al., 2020), and it can be interpreted that specific governance practices are the critical factors, and other aspects such as rural development, can play an important role too. Being in favour of economic criteria does not necessarily exclude respecting environmental boundaries, as a long-term economic gain as well as the return on the investment would rely on stable biomass supply, in terms of both quantity and quality, which assumes respecting the carbon cycle of that biomass.

Although all sustainability criteria deserve important attention, the results of this study particularly stress the role of biomass supply chains in the reduction of GHGs emissions, their potential for revitalization of rural areas and the use of local resources. These alternatives reflect of both a strong climate concern as well as *localism* approaches, related to the efficient use of land and the creation of descentralized multifunctional landcsapes (Rega et al., 2019) that can support efficient energy, food and wood production simultaneously.

From the policy point of view, a direct application of the results of the study is combining the estimated experts' weights with impact assessment data from alternative biomass feedstocks and supply chains (Myllyviita et al., 2013), in order to help decision makers to establish the necessary economic tools to promote those supply chains with the highest positive impact, overall or in key categories. Expanding the methodology proposed can therefore be instrumental to the priotization of given feedstocks and pathways, locally or regionally. In addition, the weights provided can be directly incorporated multi-objective optimization approaches of biomass supply chains or landcape level planning of biomass production, specifically addressing their sustainability (Cambero and Sowlati, 2014).

As is common in studies of this nature, it is important to acknowledge the inherent limitations associated with the use of AHP methods (for a comprehensive review and discussion, see Brunelli, 2014). Additionally, potential biases may arise from the selection of experts and the specific socio-economic and political context in which the questionnaire was administered. Global events in energy markets, including recent geopolitical developments and pandemic-related restrictions, can significantly influence the priorities of both experts and policymakers. These events may potentially amplify trends toward self-reliance in domestic energy production, as noted by Tsangas et al. (2023).

6. Conclusions

Prioritising sustainability criteria is a complex issue; in addition to the inherent difficulty of assessing differing goals there are several tradeoffs and interactions to take into account. The methodology proposed in this study addresses this complexity and disentangles experts' views from the need of a single consensus over priorities. As a direct implication, we propose to map consensus regions, instead of focusing on narrow priority rankings, to reflect the complex aspects of comparing diverse criteria while at the same time providing viable recommendations to policy makers.

The estimated weights for each criteria produced in this study can be used as a basis for future studies, with direct policy applications. The results strongly suggest that GHGs emission reductions, efficient use of local resources, revitalizing rural areas and protecting ecosystems and biodiversity, among others, are the factors that deserve special attention when assessing the sustainability of biomass supply chains and should be particularly emphasized when planning biomass supply chains.

There are limitations, however, derived from the use of the methods and potential biases may arise from the selection of experts and the specific socio-economic and political context in which the questionnaire was administered. As well, there are important variables related to the expert's background, geographical zone and current political framework that require further investigation, and must be incorporated in local decision making for the overall improvement of biomass supply chains. In addition, global events in energy markets, including recent geopolitical developments and pandemic-related restrictions, can significantly influence the priorities of both experts and policymakers and these events may potentially amplify trends toward self-reliance in domestic energy production.

Future research must be oriented to investigate whether such trends can be effectively observed in the global priorities concerning the sustainability of renewable energy production, and supporting studies can delve into the factors that explain the resulting priorities, involving experts and policy makers, as well as the main reasons behind the two main groups identified. The relatively lower scores assigned to social criteria may reflect a lack of understanding regarding their long-term impacts or a shortage of relevant literature on the topic, and it is possible that new social concerns have emerged in parallel with the evolving field.

Despite the obvious limitations and uncertainties, the present paper provides a solid results to assess the sustainability of different supply chains and specific weights for all criteria considered even when no consensus between policy makers can be established, with applications on climate mitigation strategy, energy policy and biomass supply planning.

CRediT authorship contribution statement

Blas Mola-Yudego: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, preparation, Writing – review & editing, Visualization, Supervision, Funding acquisition. **Ioannis Dimitriou:** Conceptualization, Writing – review & editing, Funding acquisition. **Bruno Gagnon:** Writing – review & editing, Investigation. **Jörg Schweinle:** Conceptualization, Writing – review & editing. **Biljana Kulišić:** Conceptualization, Writing – review & editing, Methodology, Investigation, Supervision, Funding acquisition.

Declaration of competing interest

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

Data availability

Data are available in the Appendix A, Supplementary Data.

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Appendix A. Supplementary data

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