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Monitoring the bioeconomy: Value chains under the framework of life cycle assessment indicators

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A B S T R A C T

The transition towards a more environmentally friendly economy can be facilitated through the bioeconomy, which relies on the use of biological resources, processes and methods to provide goods and services. However, bio-based value chains are not inherently sustainable and require careful monitoring and assessment of their impacts across all dimensions of sustainability (environmental, economic and social). Quantifying and understanding these impacts require the use of robust frameworks and methodological approaches that are currently lacking, which could be considered a gap in achieving a more sustainable bioeconomy. In this context, the objective of this research report is to fill this gap by identifying and selecting the most appropriate environmental, social and economic indicators within the Life Cycle Assessment (LCA) methodology to ensure a comprehensive assessment of environmental and socio-economic constraints and an effective analysis of bio-based value chains at all stages of the life cycle, from raw material extraction to end-of-life management. A total of 17, 26 and 101 indicators were identified for the environmental, economic and social pillars, respectively. In addition, existing gaps were highlighted, and a future framework was outlined to refine and enrich the currently available indicators and the underlying methodology.

The indicators provided constitute a building block for effectively exploring and assessing the sustainability of bio-based value chains by a wide range of stakeholders (e.g., policy makers, entrepreneurs, certification bodies) to facilitate informed decision-making, pave the way for balanced economic growth, improve social welfare and environmental protection, and overall promote more sustainable and resilient bio-based value chains.

1. Introduction

The circular economy represents a paradigm shift in the production and consumption system to address resource scarcity, environmental impact, value creation and employment (Lainez et al., 2018; Wohlgemuth et al., 2021). This new economic model considers the valorization of biowaste where the best waste is that which is not produced and those that are unavoidable are considered resources that can be reused and recycled. It is a key element for sustainable development and represents an opportunity as a driver for climate action and energy transition (Egea et al., 2021; Kircher, 2021; Stark et al., 2022).

To drive and encourage this shift towards more sustainable value chains and foster a change in mindset among actors and stakeholders, it is essential to properly measure and analyze how the current value chains, mostly unsustainable, are provoking detrimental, or even irreversible, effects over the surroundings. There is a need to be aware of the impacts, where efforts should be focused on how the transition should be developed to be efficient and sustainable (Geng et al., 2019; Hegab et al., 2023; Velenturf and Purnell, 2021). With data and with appropriate assessments methodologies, it is easier to make informed decisions, to foster systems thinking, to promote a collaborative value chain among all the actors involved, and thus to take a step forward towards a sustainable bioeconomy (Bröring and Vanacker, 2022; Eisenreich et al., 2022; Robaey et al., 2022).

The development of the bioeconomy must encompass the environmental, social and economic pillars within sectoral value chains towards more responsible behavior in resource use, production processes and consumer use and end-use. When it comes to impacts, some representative indicators in the environmental, social and economic dimensions are related to greenhouse gas emissions, air quality, extensive use of

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resources, effects on soil quality and biodiversity, effects on social communities, job creation capacity, economic growth, market competitiveness, social equity, among others. With appropriate assessment methodologies, it is easier to make informed decisions, promote systemic thinking and a collaborative value chain among all the actors involved. Among the various alternatives, the Life Cycle Assessment (LCA) methodology stands out for its valuable insights, its well-developed and standardized procedure, and its frequent use by researchers and stakeholders (Notarnicola et al., 2017; Sinkko et al., 2023; Vance et al., 2022). It offers a comprehensive and systematic approach to assess environmental, social and economic impacts throughout the entire life cycle of a product, a process, a stage of the value chain or even the entire value chain (Böckin et al., 2022; Costa et al., 2019).

The LCA methodology offers several advantages compared to other methods, such as the Greenness Grid methodology, which focuses more on the production stage, the techno-economic assessment (TEA), which provides information on the conceptual design of the process and its economic feasibility, or the safe-and-sustainable by design (SSbD) framework, which is more related to preliminary design or optimization (Guinée et al., 2022; Pinto et al., 2020; Shah et al., 2016). LCA considers all stages of the value chain and makes it possible to identify trade-offs between different alternatives and to identify the most sustainable and appropriate strategies for the development of bioeconomy activities (Patel et al., 2022; Robert et al., 2020; Hildebrandt et al., 2019; Simonen et al., 2017).

But despite these advantages, LCA also presents significant challenges and gaps that need to be addressed (Bishop et al., 2021; Dieterle et al., 2018). It is essential to harmonize the way in which the LCA methodology is carried out, especially in the case of LCC and S-LCA, as they are less developed approaches to the methodology. Although there is a standardized guideline for LCC: ISO 15,686, it is mainly applied to analyze buildings, built assets and their components, rather than value chains in the context of the bioeconomy (ISO, 2008). In the case of S-LCA, the lack of standardization and the challenges of data collection are the main issues to be addressed in the near future. In addition, in order to guarantee that the transition to the bioeconomy is grounded in sustainability approaches, the three pillars (environmental, social and economic) should be analyzed and ensured throughout the entire value chain, which is not currently being implemented.

This manuscript aims to analyze and provide a framework for comprehensively assessing the three pillars of sustainability through the use of appropriate indicators, especially in the context of the bioeconomy sector. Identifying metrics that recognize the balance between environmental performance, economic growth and social equity is critical to moving towards more sustainable value chains. The importance of this research report lies in the fact that it provides strategic guidance to decision makers, entrepreneurs and other stakeholders (e.g. certification bodies, scientific community) to build environmentally sound, economically resilient and socially acceptable bio-based value chains, being this the main ultimate goal of the study. The set of indicators provided is user-friendly and could be effectively applied by stakeholders to ensure progress towards an efficient, durable, profitable and egalitarian sustainable bioeconomy.

Accordingly, the gaps and related research questions (RQ) that this study aims to address are as follows:

- Broad application of environmental indicators, while social and economic dimensions are scarcely assessed. **RQ1**: What are the available social and economic indicators that could be added to the assessment to evaluate the overall sustainability along the entire bio-based value chains?
- Despite the ready availability of indicators for sustainability assessment, their abundance and dispersion in the literature makes it difficult to use the appropriate ones. **RQ2**: Which are the most relevant and robust indicators for assessing the sustainability of bio-based value chains?
- Lack of harmonization of S-LCA and LCC methodologies. **RQ3**: What are the main inconsistencies in the application of these methodologies? **RQ4**: What requirements could help resolve these inconsistencies and provide a more comprehensive assessment of socio-economic impacts?
- Economic assessment often focuses on cost-effectiveness and technical feasibility to the exclusion of other relevant economic aspects. **RQ5**: What economic aspects and criteria should guide the economic evaluation?

2. Methodological approach

In order to identify suitable indicators within the life cycle approach, an in-depth analysis of standardization guidelines, directives, regulations and literature review was carried out, in particular with regard to S-LCA indicators. This analysis could be considered as the first step on reaching the main research objective of this report: providing a framework and a strategic guide of suitable indicators to effectively assess the sustainability potential of a process embedded on the bioeconomy sector.

2.1. Data analysis and collection

Given the different maturity levels of each LCA dimension, a customized analysis approach was adopted for each pillar, leading to a division of this section into three different life cycle methodological approaches: environmental, economic and social.

2.1.1. Environmental LCA

Environmental LCA (E-LCA) is a comprehensive and systematic methodology that assesses the environmental burdens associated with a product, process or service activity throughout its life cycle, considering all stages from resource extraction to end-of-life management strategies according to four main methodological steps, which are standardized and described in ISO 14,040 and ISO 14,044: i) definition of goal and scopes, ii) life cycle inventory, iii) impact assessment and iv) interpretation of results (Finkbeiner, 2014; ISO, 2009; Sala et al., 2021; Schaubroeck and Hauschild, 2022).

There are several calculation methods that could be used to score and characterize environmental loads. While in the European context the ReCiPe calculation method is the most widespread, several guidelines have been developed with the objective of providing the most consensual calculation methods for the quantification of environmental burdens. These guidelines, the international life cycle data system (ILCD) Manual (European Commission, 2010), the Environmental Product Footprint (PEF) framework (European Commission, 2021) and the UNEP-SETAC Life Cycle Initiative Guidelines (UNEP-SETAC, 2019a, 2019b) propose recommendations on data collection, systems modeling, indicators to be used for impact assessment, quality assessment and communication of results. Due to their relevance and authority in the field of LCA, these documents were selected as reference documents as well as for identifying specific calculation methods that are highly recommended to obtain the most accurate environmental scores.

The ILCD Handbook has been developed by the Joint Research Center of the European Commission in accordance with ISO standards as a more detailed technical guide for conducting LCA studies (European Commission, 2010). The Handbook consists of several volumes, each focusing on a specific methodological topic related to the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) phases. In the case of the PEF framework, it is based on the ISO 14,040 series and the ILCD manual, with the objective of providing specific guidance to companies on how to assess and communicate the environmental performance of their products and, indirectly, to ensure the reliability of environmental reporting to public authorities and non-governmental organizations (NGOs) (European Commission, 2021; Pirson et al., 2022). Finally, the UNEP-SETAC Life Cycle Initiative Guideline, founded by the united nations environment programme (UNEP) and the society for environmental toxicology and chemistry (SETAC), is a "multi-stakeholder public-private partnership" working to establish an international consensus on indicators for assessing environmental impacts throughout the life cycle (Jolliet et al., 2018). The resulting guidelines from its ongoing work provide practical recommendations on agreed environmental indicators and LCIA characterization factors (UNEP-SETAC, 2019a, 2019b).

All the aforementioned guidelines and documents have been analyzed in order to identify the type of indicators that are more adequate to develop an environmental assessment of a value chain of a bioeconomy sector, as well as to identify the specific calculation methods that are highly recommended for obtaining the most accurate environmental scores.

2.1.2. Economic LCA

According to the Directive 2014/24/EU (European Commission, 2022), Article 68, which refers to Life Cycle Cost Assessment, this analysis should include all relevant stages that are part of the life cycle of a product or service, or in this case, for the entire value chain, as can be seen in Fig. 1.

On the other hand, it should also be mentioned that different approaches could be considered when developing an LCC assessment. According to Leal-Filho (2020) three perspectives are possible (Leal-Filho, 2020): the perspective of product manufacturer, including production costs and expected revenues (P2 in Fig. 1) are included on the analysis, the perspective of product manufacturer and value chain, encompassing also materials suppliers and design phase (P1 in Fig. 1), so the system is expanded, and, finally, the consumers' perspective (P3 in Fig. 1), where only the cost and expected revenues of this phase are considered in the LCC analysis. Even though Leal-Filho (2019) does not include the end-of-life (EoL) and value recovery stage (P4 in Fig. 1), the authors of this report considered it an essential stage to be included in the LCC, given the need to move from linear to circular production models, which is key to improving the effective transition to a sustainable bioeconomy (Leal-Filho, 2020).

In general, two main types of costs should be assessed, those referred to as "costs borne by procurement", including procurement, consumption of materials and resources, maintenance and end-of-life costs, and those referring to "costs imputed to environmental externalities linked to the product, process or value chain", incorporating costs related to pollution, emissions and mitigation strategies. Specifically, as determined in the UNE-EN 16,627 standard on sustainability of construction works, four main types of costs and externalities could be defined in the suppliers of materials and resources, as well as in the design phase: land and associated fees/consulting, raw material supply costs, transportation of materials and resources, and prefabrication requirements prior to the production phase (BSI EN 16627, 2015). In the next phase, the production phase, all costs associated with it should be included, incorporating both material and resource costs (i.e., chemicals and energy), equipment purchase costs, operating costs (such as labor costs), maintenance, repair, environmental and also decommissioning or disposal costs. At this specific stage, the type of economic evaluation performed is similar to that performed by the techno-economic evaluation and also the cost-benefit analysis, as well as the expected revenues should also be scored (OIT, 2001):

$$LCC = C_{ic} + C_{in} + C_e + C_o + C_m + C_s + C_{env} + C_d \quad (1)$$

Where LCC is life cycle cost, C_{ic} are the initial costs (i.e. purchase costs), C_{in} defines the installation and commissioning costs, C_e are the energy costs, C_o the operation costs (including labor costs, among others), C_m refers to maintenance and repair costs, C_s considers the down time costs (the loss of production and quality), C_{env} are the environmental costs (derived from pollution, emissions and mitigation actions) and C_d refers to the decommissioning or disposal costs.

Moving up the value chain and reaching the "use phase", the costs associated with this phase could be classified into operational energy and water use costs, maintenance costs, repair costs, replacement costs and refurbishment costs. It should be noted that these types of costs are general; some of them could not be applied to all the sectors that make up the bioeconomy value chains. For example, in the case of the food industry, maintenance, repair and replacement costs do not make sense for food products consumed by users, so each value chain must be assessed in a precise and adapted way, taking into account that all externalities and related costs must be assessed within the scope of the LCC analysis (Leal-Filho, 2020).

Finally, for the last stage of the value chain, the one related to EoL strategies, three main types of costs could be identified: transport costs to collect all waste streams and waste produced, costs related to the treatment of waste for reuse, recycling or recovery, and also the cost associated with the final disposal of waste (i.e., landfills disposal). These criteria establish the economic aspects that should be evaluated throughout each stage of the value chain, addressing one of the research questions of the study.

2.1.3. Social LCA

The social LCA aims to assess the effects of an activity or service related to the value chain on the social dimension, and taking into account all stakeholders: workers, consumers, local community, society and value chain actors (Ashby, 2024; Imbert and Falcone, 2020).

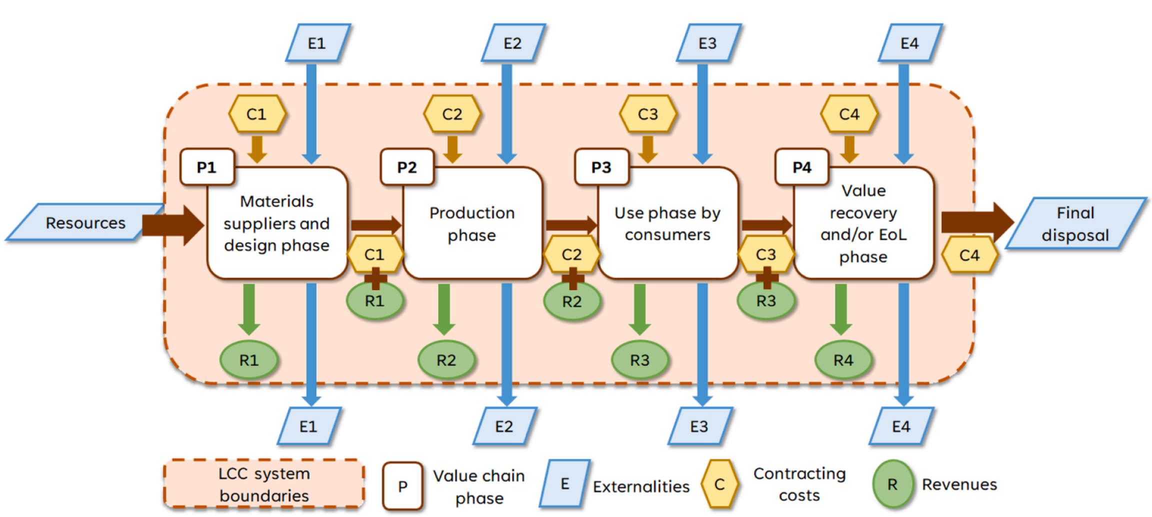

Fig. 1. Main stages of the LCC system boundaries for a value chain. Adapted from UNEP-SETAC Life Cycle Initiative (2009).

Although its standardized guide is not yet available, it is currently under development and follows the same methodological procedure as the LCA (ISO 14,040 standard), but there are still no suitable indicators for assessing, integrating and interpreting the social dimension, which makes it difficult to analyze this third pillar of sustainable development (Rivela et al., 2022).

In addition, one of the issues necessary for the development of an accurate S-LCA is the identification of stakeholders to analyze the social indices, which could lead to subjective and non-transparent results of the analysis. The lack of unification on the methodological approach and communication channels among the stakeholders concerned, as well as the inaccessibility of an adequate database to obtain the data to perform the analysis, implies a complicated situation for the S-LCA framework (Alejandrino et al., 2021; Arodudu et al., 2017).

In this regard, in order to reduce uncertainties in conducting social assessment, UNEP, SETAC and the Life Cycle Initiative developed in 2009 some guidelines for conducting S-LCA. Recently, in 2020, UNEP and the Life Cycle Initiative published an updated version entitled "Guidelines for Social Life Cycle Analysis of Products and Organizations" to define a new frame of reference due to the absence of consensus on S-LCA and to propose the initial pathway on the organizational perspective (UNEP, 2020).

With this in mind, together with the objective of identifying the most appropriate indicators to assess the social perspective of the bioeconomy, a literature review was conducted to identify the social LCA indicator. First, a search was conducted in renowned scientific databases such as Web of Science (WoS) and Scopus using the keyword sets "bioeconomy", "bioproduct", "S-LCA", "social life cycle analysis", "bio-based", "biofuels", "social LCA", "bioenergy", among others. The period selected for evaluation corresponds to those articles published up to the year 2022. All the manuscripts identified were managed through the Mendeley® software, eliminating all those that were duplicated. The titles, abstracts and keywords of each article were then analyzed to determine their suitability for the topic. Articles published in a language other than English were eliminated, as well as those not related to the scope of the bioeconomy sectors and without open access format. Finally, for the remaining manuscripts, a full-text analysis was performed to include only those articles that used the life-cycle approach in the social assessment. A total of 43 articles were considered as the final sample to collect the social indicators (Table 2SM). To illustrate the main topics of these manuscripts and their interrelationships, a VOSviewer map was created (Fig. 2) showing the prevalence of the keywords: *life cycle, life cycle assessment*, and *sustainable development* keywords and their interrelationships with each other and with many other areas, including environmental impact, circular economy, and life cycle costing.

2.1.4. Parameters retrieved

Three separate databases (consisting of Excel® spreadsheets) were created to collect all the information obtained throughout the analysis. The parameters collected include a brief description of each indicator,

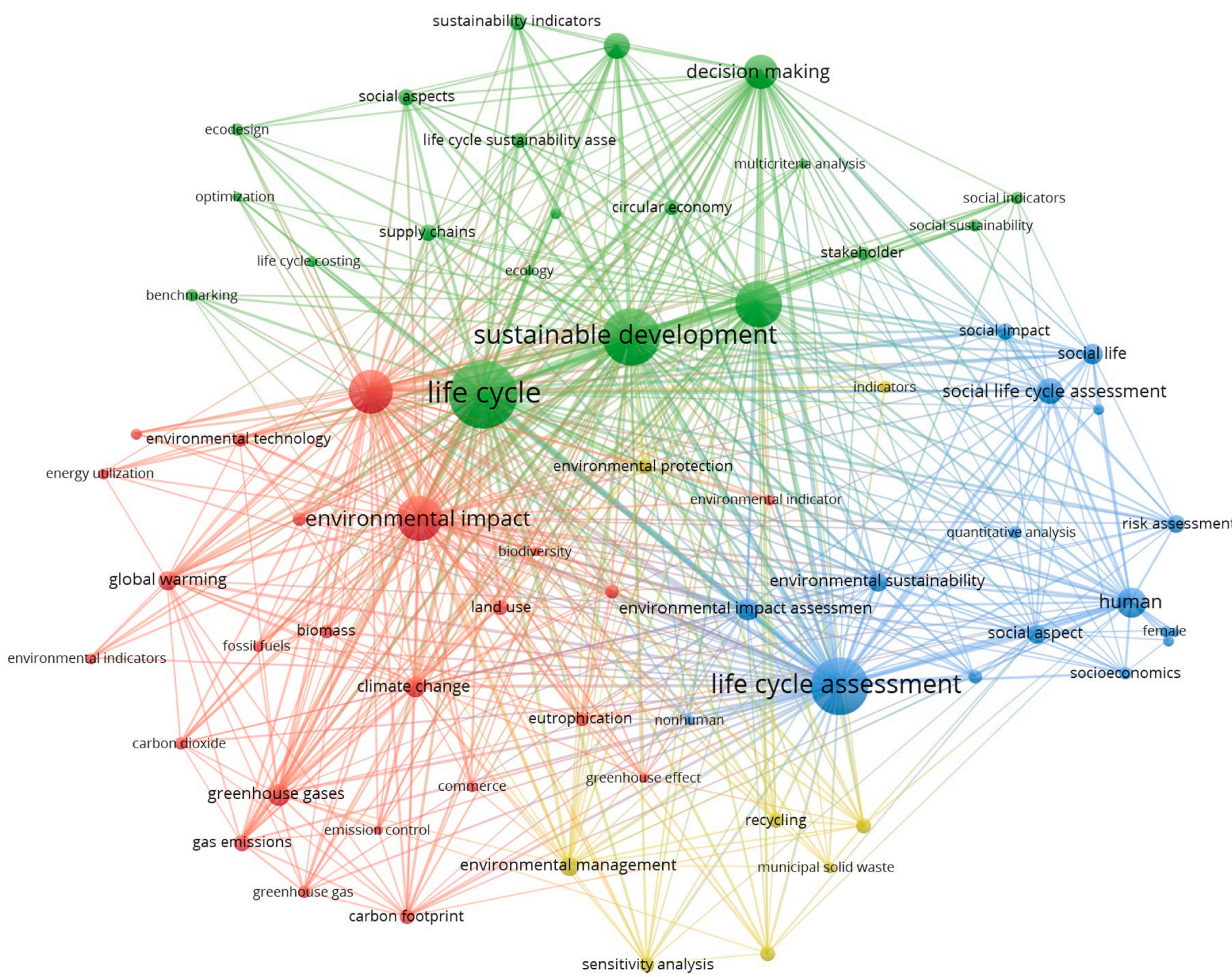

Fig. 2. VOSviewer map of the network of keywords reported by the scientific literature analyzed.

the impact category to which the indicator belongs, the metrics or characterization model used, the unit and type of measurement, and the source from which the indicator was obtained. In addition, each indicator was classified according to the sector and life cycle stage to which it applies. The sectors were classified according to the Bioeconomy Strategy (European Commission, 2018) as Agriculture, Forestry, Fisheries and Aquaculture, Bio-based Textiles, Wood Products and Furniture, Paper, Bio-based Chemicals and Pharmaceuticals, Plastics and Rubber, while the life cycle stages were defined as Raw Materials, Materials and Products, and End-of-Life. A description of each parameter is given in Table 1.

In categorizing the indicators according to impact categories, the pre-existing categories from the documents analyzed for the environmental pillar were used to organize the environmental indicators. However, it is important to note that, in the case of the social and economic dimensions, these categories were presented in a markedly different manner or, in some cases, not reported at all. Given this discrepancy, recommendations from established sources were adopted to define the impact categories for the social and economic dimensions.

For the social dimension, indicators were categorized, following the recommendation of the UNEP-SETAC Life Cycle Initiative guidelines (REF), according to six categories of stakeholders (children, workers, consumers, local community, society and value chain actors) and associated issues (impact categories). Children encompasses evaluating the impacts on the younger population, where issues such as their safety, education, well-being, and protection from any harmful or exploitative practices are central aspects of this stakeholder category. The category of workers is the most precise and specific category to be assessed, as it must be in line with the International Labor Organization (ILO), which clearly identifies the needs and requirements of workers' welfare, working conditions, wages and equal opportunities, among others. Consumers are the stakeholders who use the services/goods purchased by themselves or provided by others. It is important to note that in social LCA the consumer "stage" is only to consider the activities associated with the purchase of the products or services along the value chain, but not their subsequent or downstream use. In the case of Local Community consider various issues, from accessibility to resources, information and services, to the potential for job creation and equality, safety and healthy living conditions. Society goes a step further compared to local communities, as all social groups related and indirectly related to the product or value chain under evaluation are being considered. Among the stakeholders included in the social LCA, this is probably the most general, as it aims to include all possible interconnection between the global society. Finally, in the value chain actors, the objective is to assess the social impacts of the relationship between producers and suppliers, considering all stages of the value chain (Adami Mattioda et al., 2017; Thomas & Turnbull, 2017).

In the case of the economic pillar, the categorization has been carried out according to the impact categories found in the literature, mostly based on the reports developed by Arulnathan et al. (2023), Roh et al. (2018) and Mead and Black (2009), identifying a total of 8 classification categories: *Productivity, Profitability, Feasibility, Stability, Autonomy, Customers, Operability* and *Innovation* (Arulnathan et al., 2023; Mead & Black, 2009; Roh et al., 2018). The Productivity category seeks to encompass indicators that evaluate economic output per resource consumed, both materials and labor, with the objective of realizing whether "best practices" are being applied in terms of resources and employees (DePamphilis, 2022; Glickman, 2014). *Profitability* seeks to introduce suitable indicators to measure the gross profits of the evaluated scenario and its overall efficiency over a defined period. These indicators usually involve the estimation of future revenues to identify the economic potential of the scenario being evaluated, as is the case of net present value and internal rate of return indicators, among others (Arulnathan et al., 2023; Novy-Marx, 2013).

In the development of a value chain, the possibility of fluctuations in raw material prices, availability and sales prices of the desired products is high and common, thus affecting the amount of expected income. Given this, it is important to take into account some flexibility to ensure that the value chain remains profitable, and this is the reason behind the introduction of the Feasibility category, which evaluates the availability and profitability of related resources, capital or labor to ensure the viability of a value chain scenario (Carlson et al., 2019; Pauceanu, 2016). This aspect is closely related with the category of *Autonomy*, which focuses on indictors that measure dependence on resources, subsides and financial aspects (Arulnathan et al., 2023).

When initiating a business model in a value chain, it is important to consider the risks and bottlenecks that could be faced in the present and near future. Risk could encompass several aspects, such as investment, government regulation and market dynamics, constraints that could be addressed within the *Stability* category (Allen & Wood, 2006; Yescombe & Farquharson, 2018). In line with the previous one, *Customers* also have a crucial role on the economic decision-making of a value chain, as its

Table 1
Description of the parameters collected in the databases and two examples from the environmental and social pillar, respectively.

Parameter	Definition of parameter	Example 1	Example 2
Indicator	"A quantitative, qualitative or binary variable that can be measured or described to assess an aspect of a defined criterion" (BS EN 16,751:2016).	Radiative forcing as global warming potential (GWP100)	Investments with direct benefit for local community
Indicator description	A brief explanation of what the indicators represent.	Increase in the average global temperature resulting from greenhouse gas emissions (GHG)	–
Impact category	The classes used on E-LCA to represent environmental issues of concern (ISO, 2006). This parameter is only reported for environmental indicators.	Climate change	Local community
Metric/ characterization model	The metric, equation or model used to measure the indicators.	Baseline model of 100 years of the IPCC (based on IPCC, 2013)	–
Unit	The unit of measurement of the indicator.	kg CO_2 eq	%
Type of indicator	To specify whether the indicator is measured with qualitative or quantitative metrics.	Quantitative	Quantitative
Sector	Bioeconomy sectors where the indicator can be applied. The bioeconomy sectors are those identified in the Bioeconomy Strategy and include Agriculture, Forestry, Fishing and Aquaculture, Bio-based Textiles, Wood products and Furniture, Paper, Bio-based chemicals and Pharmaceuticals, plastics and rubber.	All	All
Life cycle stage	The different periods in the lifetime of a system. Three life cycle stages are distinguished: 1) Feedstock, which refers to the stage at which resources are acquired; 2) Materials & Products, including the production, distribution and use of materials/products; 3) End of life, which involves the disposal or valorization of the product/material at the end of its useful life.	All	All

economic profitability (or of a particular stage) is directly dependent on satisfying and increasing customer demand. The two remaining categories selected, *Operability* and *Innovation*, aims to identify the costs associated with the value chain or process under evaluation to ensure the operability of related activities and the efforts, both economic and human, to promote innovative solutions and strategies to be, for example, more sustainable (Maradana et al., 2017; Mead & Black, 2009; Gibon et al., 2013).

2.2. Screening indicators: criterion for selection

Based on the indicator selection methodology reported by the Joint Research Centre (Vidal-Legaz et al., 2016) and the INDECO project (Reyntjens & Brown, 2005), a total of four criteria were applied to select suitable indicators, which are described in detail below:

Criterion 1. Relevance. The indicators selected should cover relevant aspects of sustainability for bio-based value chains, in line with the FAO guideline *Aspirational principles and criteria for a sustainable bioeconomy* (FAO, 2021), ISO 14,040:2006 *Environmental management — Life cycle assessment — Principles and framework* (ISO, 2009), Directive 2014/24/EU (European Commission, 2022), and Guidelines for Social Life Cycle Assessment of Products and Organizations (United Nations Environment Programme, 2020).

Criterion 2. Operability. The indicators should be easily measurable, qualitatively and/or quantitatively, with readily available data, models and calculation methods.

Criterion 3. Robustness and reliability. Indicators should be up to date and validated by international documents, guidelines, research reports or experts in the field. Priority shall be given to indicators recommended by authoritative institutions recognized for their expertise in sustainability assessment. This criterion ensures that the selected indicators are based on the latest scientific knowledge and have a high level of credibility. Examples of recommended indicators could be those proposed by organizations such as the Joint Research Center or the UNEP-SETAC Life Cycle Initiative.

Criterion 4. Avoid overlaps. The final set of indicators should not include indicators that measure the same specific aspect of sustainability. By avoiding duplication, the assessment becomes more agile and focused on capturing different issues. In the case of the social pillar, a deliberate exception was made and several indicators measuring the same specific aspect were included. This was done to ensure that, in case of missing data, there were alternatives to assess those aspects.

By adhering to these criteria, the indicators selected to assess the sustainability of bio-based systems will effectively cover the relevant aspects of sustainability, be easily measurable, validated by experts, and free of redundancies.

3. Results and discussion

3.1. Preliminarily analysis of available indicators

3.1.1. Environmental LCA approach

The indicators identified to measure the environmental impacts of bioeconomy activities are described in Table 1SM of the Supplementary Material. By limiting the search to specific and highly relevant sources in the field, a manageable set of 56 environmental indicators was compiled. In summary, these guidelines collectively provide a diverse set of indicators and impact categories, highlighting the multidimensionality of environmental impacts. Fig. 3 provides a summary view of the information presented in Table 1SM, presenting the indicator count for each type of impact category as specified by the methodological guidelines.

It is important to note that these guidelines had already undergone a screening process to select the most robust and reliable indicators and, consequently, the reported impact categories reflect the areas where most notable progress has been made in quantifying the environmental impacts of bioeconomy activities. The distribution of indicators among the different impact categories underscores the consideration of a broader range of specific issues. For example, the impact category "Eutrophication" includes indicators that measure eutrophication in freshwater, marine and terrestrial environments. Similarly, "Resource depletion" encompasses several indicators that address the depletion of minerals and metals as well as fossil fuels, providing a more complete picture of resource use and its consequences. Another reason is that some impact categories include indicators that assess the same impacts but use different characterization models. As an example, the impact category "Water use/scarcity" includes two indicators that measure potential water deprivation, one (Weighted Potential User Deprivation) uses the Available Water Availability Maintenance (AWARE) model, while the other (Water use related to local water scarcity) follows the Swiss Method of Ecological Scarcity.

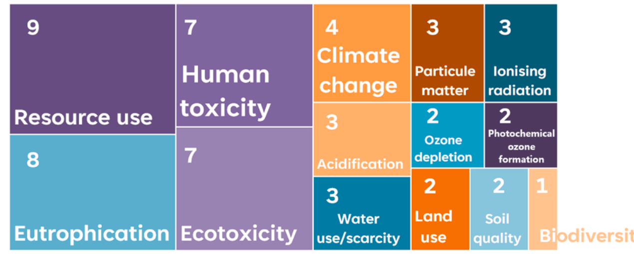

Fig. 3. A screenshot showing the count of indicators classified by impact categories according to the HAP, ILCD and UNEP-SETAC Life Cycle Initiative guidelines.

3.1.2. Economic LCA (LCC) approach

Table 2 presents the indicators found in European Directives, standards and peer-reviewed articles to measure the effects of value chain development under the economic perspective, according to the definitions and requirements described in Section 2.1.2 of this research report. The articles that underwent economic evaluation showed a lack of specificity in distinguishing between life cycle cost (LCC), cost-benefit, and techno-economic evaluations, which is a major limitation for accurately addressing the economic pillar from a Life Cycle perspective. A predominant trend observed in these studies is a combined evaluation approach, where indicators and methodological approaches are often interchanged, contributing to the observed ambiguity.

3.1.3. Social LCA approach

A total of 702 indicators were identified for the social perspective, most of them developed to quantify or qualify the precepts and recommendations provided by the UNEP-SETAC Life Cycle Initiative guideline, recognized as the most prominent document for the implementation of the social LCA approach. Given the extensive number of indicators identified at this initial stage, a detailed list of these indicators is compiled in the Supplementary Material; while in the main manuscript, a summary of these indicators is presented in Fig. 4. The indicators are shown grouped according to their respective stakeholder categories (Fig. 4A) and their frequency of occurrence within the set of documents analyzed (Fig. 4B). By integrating these social and previously presented economic indicators into the assessment framework, a more holistic evaluation is proposed, thereby aiming to address the overall sustainability assessment of bio-based value chains.

During the analysis, it was observed that many scientific articles lacked measurable indicators and, instead, some referred to social subcategories as indicators (e.g., child labor). Similarly, the use of databases such as PSILCA (Product Social Impact Life Cycle Assessment) and Social Hotspots Database (SHDB) was observed, without the authors providing the specific sample of indicators applied. As can be seen in Fig. 4, the categories of workers and local community stakeholders have the highest number of indicators available, with a significant difference

Table 2
LCC indicators (Arulnathan et al., 2023; Briassoulis et al., 2023; Neugebauer et al., 2016; Gibon et al., 2013).

Indicator	Impact category	Type	Equation
Cost efficiency	Productivity	Quantitative	$\text{Marginal cost} = \frac{\text{Change in total cost}}{\text{Change in production}}$
Profitability (P)	Profitability	Quantitative	$P = \sum_{l=1}^{L}\sum_{c=1}^{C}\left(\frac{\text{Gross output}_{C,l}}{\text{Labor cost}_{C,l}}\right)$ $\text{Gross margin} = \frac{(\text{Revenue} - \text{Cost of goods})}{\text{Revenue}}$ $\text{Net profit} = \frac{\text{Net income}}{\text{Revenue}}\cdot 100$
Net present value (NPV)	Profitability	Quantitative	NPV = Value expected of cash flows − value of invested cash
Input rate of return (IRR)	Profitability	Quantitative	NPV set to zero and determination of discount rate
Payback	Profitability	Quantitative	$\text{Payback} = \frac{\text{Total investment}}{\text{Revenue or savings}}$
Return on investment (ROI)	Profitability	Quantitative	$\text{ROI} = \frac{(\text{Actual value of investment} - \text{cost of investment})}{\text{Cost of investment}}$
Return on assets, costs, sales	Profitability	Quantitative	Ratio of net income to assets or operating profit to net sales
Gross operating surplus	Feasibility	Quantitative	Value added – (pay roll + taxes + subsidies)
Risk aspects	Stability	Quantitative and Qualitative	$\text{Risk aspects} = \frac{\text{Number of risks identified}}{\text{Number of risks managed}}$
Contribution to GDP	Stability	Quantitative	% Contribution on sector GDP based on indicators related to capital, labor, profits and taxes. To assess the supply chain, the summatory of the elements of each stage should be done.
Complexity of production	Autonomy	Quantitative	$\text{Complexity} = \frac{\text{Input of goods and services}}{\text{Output of goods and services}}$
Diversification	Customers	Quantitative and Qualitative	$\text{Diversification} = \frac{\text{Number of products}}{\text{Number of markets}}$
Reliance on import and contribution to exports (RI&CE)	Stability	Quantitative	$\text{Reliance} = \frac{\text{Amount of imports}}{\text{Total inputs needed}}\cdot 100$
Subsides	Autonomy	Quantitative	Subsides= Gross domestic product – Net National Income – Depreciation + Indirect taxes + Factor income from abroad – Factor income to abroad
External financing	Autonomy	Quantitative	$\text{External financing} = \frac{\text{Income from external organism}}{\text{Total net income}}\cdot 100$
Investment capital	Operability	Quantitative	$\text{Investment capital} = \frac{\text{Investment generated in activity}}{\text{Total investments}}\cdot 100$
Capital productivity (CP)	Productivity	Quantitative	$CP = \frac{\text{Net annual income}}{\text{Average value of total assets}}$
Labor productivity (LP)	Productivity	Quantitative	Economic output per labor hour
Market share	Customers	Quantitative	% of market share of the activity or value chain
Expenses on innovation	Innovation	Quantitative and Qualitative	Number of innovation strategies (i.e., patents) and its successful
Fixed capital investment (FCI)	Productivity	Quantitative	FCI=∑purchase equipment cost Lang factor
Cost of manufacture (COM)	Operability	Quantitative	COM= 0.18·FCI + 2.73·Cost of labor + 1.23·(Cost of utilities + cost of raw materials + cost of waste treatment)
Minimum selling price (MSP)	Feasibility	Quantitative	Lowest selling price to ensure that NPV >0
Minimum feedstock capacity	Feasibility	Quantitative	Minimum amount of feedstock required to ensure productivity
Supply chain related value added (VA)	Productivity	Quantitative	$VA = \sum_{l=1}^{L}\sum_{c=1}^{C}(\text{Total income}_{C,i} - [\text{Operating costs}_{C,i} + \text{Material costs}_{C,i}])$
Human capital related rate of return (HCRR)	Productivity	Quantitative	HCRR=eˆ(f(rate of return to edutcation years of schooling))
Process productivity	Productivity	Quantitative	$P = \sum_{l=1}^{L}\sum_{c=1}^{C}\left(\frac{\text{Gross output}_{C,l}}{\text{Labor cost}_{C,l} - \text{Work hour loss}_{C,l}}\cdot \text{HCRR}_{C,l}\right)$
Consumer satisfaction (CS)	Customers	Quantitative	CS = max (willingness-to-pay of product option i – internal production cost of the same product option i)

compared to the other categories. The rationale behind is simply based on the mandatory issues that value chain actors must comply with according to what is required by legislation, directives and policy makers. For example, as far as workers are concerned, compliance with working environment conditions, minimum wage, occupational health and safety and employee welfare are crucial factors, while in the case of the local community, indicators should measure aspects such as favorable living conditions, promotion of job creation and economic growth, and ensuring food security. By addressing these inconsistencies in the implementation of S-LCA, such as the lack of a common definition of indicators, the transparency of the indicators used, or the stakeholders addressed, more consistent and comparable results could be achieved, contributing to further progress in this area of sustainability. In this line, more efforts should be made to develop a greater number of indicators for both value chain actors and society at large, which can have a significant impact and influence on the achievement of a sustainable bioeconomy.

Awareness of more sustainable actions in value chains must be present at all stages, from resource and raw material extraction to end-of-life management strategies. If this is not the case, if one branch of the value chain fails to promote more sustainable activities, then a cascading effect will develop, thus ending up being unsustainable. This is why more efforts must be made in education, dissemination, knowledge and integration of society and local communities in the steps to conquer a sustainable bioeconomy. All actors with common actions and strategies could have the strength to go beyond adequate, efficient and effective value chains. This is why the social pillar of sustainability, still not standardized and little developed at present, is key to accelerating the transition.

3.2. Final selection of the most appropriate indicators

A final selection of the most suitable indicators has been included in this research article, covering a range of metrics that help assess and monitor the environmental, social and economic dimensions of bioeconomy value chains. These indicators are considered suitable tools for stakeholders, policy makers and individual actors seeking to promote the transition to sustainability, enabling informed decision making and

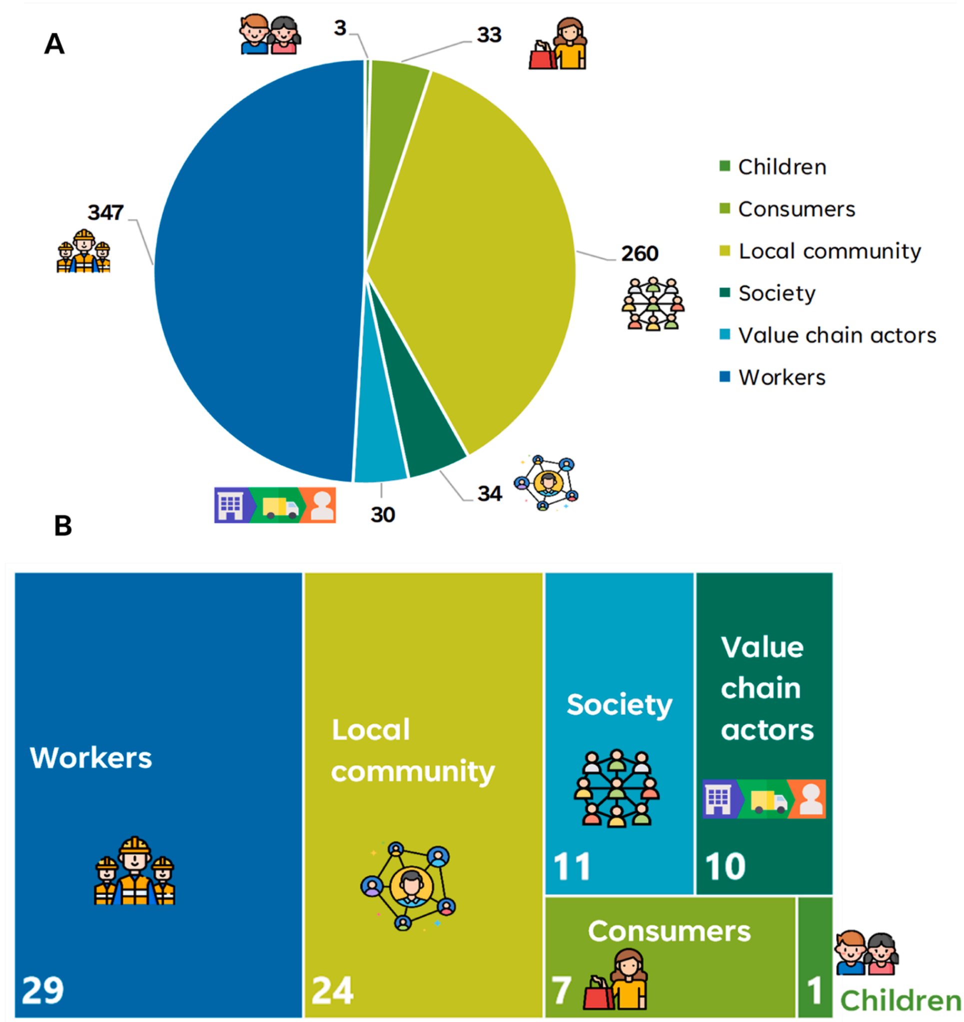

Fig. 4. Preliminary classification of indicators according to stakeholder category (A) and the number of bibliographic references found per stakeholder category (B).

tracking progress towards a more sustainable future.

The final set of indicators was the result of an extensive analysis of those available in the literature and international documents, taking into account their relevance, measurability, reliability and comprehensiveness. The objective of the selection of these indicators is to provide a tangible and measurable approach, in the search for a sustainable and balanced coexistence between economic growth, environmental preservation and social welfare.

3.2.1. E-LCA pillar

From a total of 56 indicators initially compiled from the UNEP-SETAC Life Cycle Initiative, the ILCD and the PEF (as described in Table 1SM), a sound selection process led to the selection of 17 indicators (Table 3) according to the predefined criteria defined in *Section 2.2*. The preference for the PEF framework indicators stems from their advanced stage of development, which makes them more robust and capable of providing consistent and comparable LCA results, as this is vital for comparing sustainability performance across various sectors of the bioeconomy. Special attention was given to the inclusion of the indicator measuring biodiversity loss ("Potential species loss"), as recommended in the UNEP-SETAC Life Cycle Initiative guidelines, due to its primary importance in assessing the environmental sustainability of the bioeconomy. Most of the selected indicators are applicable to all life cycle stages and sectors within the bioeconomy. However, some indicators are tailored to specific stages, exemplified by the "Soil Quality Index", which addresses impacts at feedstock production and end-of-life stages (De Laurentiis et al., 2019).

These selected indicators collectively enrich the assessment of environmental sustainability throughout the complex landscape of the bioeconomy and across the entire value chain, providing valuable insights for well-informed decision-making and fostering a more environmentally sustainable future.

3.2.2. Economic pillar (LCC)

In the case of the LCC, most of the previously identified indicators have been considered as significant and essential to assess the economic perspective of a value chain under the bioeconomy concept. A total of 26 indicators were finally selected, covering all the different categories predefined in the economic pillar. From the final selection, four indicators have been extracted: "market share", "consumer satisfaction", "contribution to GDP" and "complexity of production". The reason behind this is based on the difficulty of having data available for their calculation, together with their complexity to be accurate and transparent. The final list of indicators is available in the Supplementary Material, and it is illustrated on the following Fig. 5.

3.2.3. Social pillar (S-LCA)

On the broad set of 571 indicators initially identified, 101 were ultimately found to be relevant and robust, ensuring comprehensive coverage of stakeholder groups and related social issues within the social assessment. The Supplementary Material provides a detailed list of selected S-LCA indicators for the social pillar, which covers a wide range

Table 3
Final selection of the E-LCA indicators. Code: (1) PEF Framework, (2) ILCD Handbook, (3) UNEP-SETAC Life Cycle Initiative.

Indicator	Impact category	Description	Metrics/ Characterization model	Unit	Stage	Sector	1	2	3
Radiative forcing as global warming potential (GWP100)	Climate change	Increase in the average global temperature resulting from greenhouse gas emissions	Baseline model of 100 years of the IPCC (based on IPCC 2013)	kg CO_2 eq	All	All	X	X	X
Ozone Depletion Potential (ODP)	Ozone depletion	Depletion of the stratospheric ozone layer protecting from hazardous ultraviolet radiation	Steady-state ODPs as in (WMO 2014+ integrations)	kg CFC-11 eq	All	All	X	X	
Impact on human health	Particulate matter	Impact on human health caused by particulate matter emissions and its precursors (e.g., sulfur and nitrogen oxides)	PM method recommended by UNEP (UNEP, 2016) (Fantke et al., 2015)	Disease incidence	All	All	X		X
Tropospheric ozone concentration increase	Photochemical ozone formation	Potential of harmful tropospheric ozone formation ("summer smog") from air emissions	LOTOS- EUROS model (Van Zelm et al., 2008) as implemented in ReCiPe 2008	kg NMVOC eq	All	All	X	X	
Accumulated Exceedance[1] (AE)	Eutrophication terrestrial	Eutrophication and potential impact on terrestrial ecosystems caused by nitrogen and phosphorous emissions mainly due to fertilizers, combustion, sewage	Accumulated Exceedance (Seppälä et al., 2006, Posch et al., 2008)	mol N eq	All	All	X	X	
Fraction of nutrients reaching freshwater end compartment (P)	Eutrophication freshwater	Eutrophication and potential impact on freshwater ecosystems caused by phosphorous emissions mainly due to fertilizers, combustion, sewage	EUTREND model (Struijs et al., 2009) as implemented in ReCiPe	kg P eq	All	All	X	X	
Comparative Toxic Unit for ecosystems	Ecotoxicity, freshwater	Impact of toxic substances on freshwater ecosystems	USEtox model 2.1 (Fankte et al., 2017)	CTUe	All	All	X	X	
Fraction of nutrients reaching marine end compartment (N)	Eutrophication marine water	Eutrophication and potential impact on marine ecosystems caused by nitrogen emissions mainly due to fertilizers, combustion, sewage	EUTREND model (Struijs et al., 2009) as implemented in ReCiPe	kg N eq	All	All	X	X	
Weighted user deprivation potential	Water use	Depletion of available water depending on local water scarcity and water needs for human activities and ecosystem integrity	Available WAter REmaining (AWARE)	m^3 world eq	All	All	X		X
Accumulated Exceedance[2] (AE)	Acidification	Acidification from air, water, and soil emissions (primarily sulfur compounds) due to combustion processes in electricity generation, heating, and transport	Accumulated Exceedance (Seppälä et al., 2006, Posch et al., 2008)	mol H^+ eq	All	All	X	X	
Soil quality index	Land use	Transformation and use of land for agriculture, roads, housing, mining or other purposes. The impact can include loss of species, organic matter, soil, filtration capacity, permeability	Soil quality index based on LANCA (BECK, 2010 and Bos et al., 2016)	Dimensionless (pt)	Feedstock End of life	All	X		
Abiotic resource depletion – ADP ultimate reserves	Resource use, minerals and metals	Depletion of non-renewable resources and deprivation for future generations	CML 2002 (Guinee, 2002) and van Oers et al., 2020	kg Sb eq	All	All	X	X	
Abiotic resource depletion, fossil fuels – ADP-fossil	Resource use, fossils	Depletion of non-renewable resources and deprivation for future generations	CML 2002 (Guinée et al., 2022) and van Oers et al., 2020	MJ	All	All	X		
Comparative Toxic Unit for humans	Human toxicity, cancer effects	Impact on human health (cancer effects) caused by absorbing substances through the air, water, and soil. Direct effects of products on humans are not measured	USEtox model (Rosenbaum et al., 2008)	CTUh	All	All	X	X	
Comparative Toxic Unit for humans	Human toxicity, non- cancer effects	Impact on human health (on-cancer effects) caused by absorbing substances through the air, water, and soil. Direct effects of products on humans are not measured	USEtox model (Rosenbaum et al., 2008)	CTUh	All	All	X	X	
Human exposure efficiency relative to U235	Ionizing radiation, human health	Impact of exposure to ionizing radiations on human health	Human health effect model as developed by Dreicer et al., 1995 (Frischknecht et al., 2000)	kBq U^{235} eq	All	All	X	X	
Potential species loss	Land use impacts on biodiversity	Effect of land occupation displacing entirely or reducing the species which would otherwise exist on that land. Indicator accounts for the relative abundance of species and their overall global threat level	Species-area relationship (SAR) model. Method described by Chaudhary et al., (2015)	–	All	All			X

[1] Accumulated Exceedance (AE) that characterizes the change in the critical load exceedance of the sensitive area where eutrophying substances are deposited.
[2] AE that characterizes the change in critical load exceedance of the sensitive area in terrestrial and major freshwater ecosystems where acidifying substances are deposited.

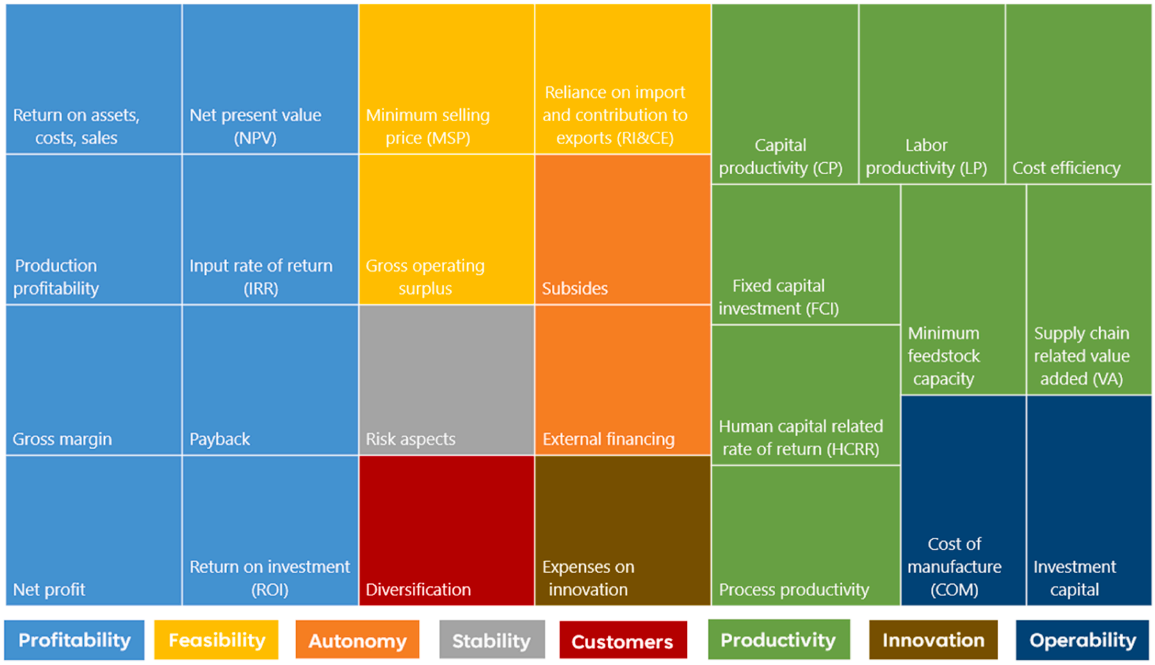

Fig. 5. Final selection of indicators for the economic pillar per impact category.

of social dimensions ranging from labor conditions and occupational health to community well-being and the overall well-being of society. These indicators are strategically categorized based on guidance from the UNEP-SETAC Life Cycle Initiative, providing a structured approach to assessing social impact. Particular attention was paid to integrating the full spectrum of stakeholders, with the objective of gaining a comprehensive understanding of the social implications arising from the implementation of this framework and ultimately promoting equitable development within the bioeconomy. In addition, several indicators were selected for each stakeholder group and impact category to ensure the robustness of the assessment process, even in cases where specific data may be lacking, which is often the case in social assessments.

By using these indicators as part of the systematic LCA assessment, bioeconomy stakeholders are expected to gain valuable information on how their activities have an impact (so-called hotspots). Furthermore, by advancing the understanding of the societal implications, the way is being paved for sustainable development that not only preserves our environment and drives economic growth, but also defends and improves the quality of life of the people and communities involved in the bioeconomy value chain.

4. Present gaps and future framework

This section aims to outline the current gaps between the three pillars of sustainability and proposes a forward-looking framework to address them for a more comprehensive assessment of sustainability in the bioeconomy. Environmental Life Cycle Assessment is recognized by the European Commission as the most important framework for assessing the potential environmental impacts of products (European Commission, 2013, 2023). However, within its current framework, some gaps persist, particularly with regard to the coverage of certain critical issues, which hinder its overall effectiveness and comprehensiveness.

Measuring impacts on biodiversity remains a major issue in E-LCA. With alarming rates of biodiversity loss, where at least 10,000 species are potentially becoming extinct each year (WWF, 2023), it is imperative to address it. The initial step towards this goal is to measure the impact of economic activities on biodiversity, where efforts are underway to develop metrics that effectively account for this impact (Chaudhary et al., 2015; Chaudhary & Brooks, 2018) and implement them to promote environmentally friendly production systems that preserve biodiversity (Lucas et al., 2021). However, several modern social pressures, such as noise, artificial light and plastics, have not yet been adequately covered by available indicators (Winter et al., 2017). Furthermore, as Lago-Olveira et al. (2023) emphasize, the current approach does not cover all taxonomic groups (e.g., amphibians, freshwater species) when assessing biodiversity in the context of LCA (Lago-Olveira et al., 2023).

Another relevant concern within sustainability assessment is the evaluation of ecosystem services. These services encompass the various direct and indirect benefits that humans obtain from natural or semi-natural ecosystems. They can be broadly classified into provisioning, regulating, and cultural services, following the common international classification of ecosystem services (CICES) framework (Haines-Young & Potschin, 2018). Understanding and assessing these ecosystem services could provide a more holistic perspective on the sustainability of a particular process, product or service. It could allow determining whether environmental improvements are within the carrying capacity of ecosystems and provide valuable information for improving the services provided by nature, guiding recommendations for their enhancement, not focusing solely on reducing impacts. Although significant progress has been made, such as the adaptation of the cascade modeling framework to integrate it within the LCA methodology (Rugani et al., 2019) and the development of a computational framework that extends LCA to include techno-ecological synergies in the assessment (Liu et al., 2018), there are still not fully developed and validated methods to assess impacts on ecosystem services.

When delving deeper into the social dimension of LCA, several significant and interrelated gaps become evident, posing challenges for a comprehensive assessment. On the one hand, social impact assessment requires a wide range of data, including, among others, labor conditions, community well-being, human rights and local stakeholder participation. However, obtaining accurate and up-to-date primary data on these various social dimensions remains a persistent challenge. This challenge is intensified when conducting an assessment along an entire value chain, which involves collecting data from numerous operators spread across various regions, countries and sectors of the bioeconomy. The multiplicity of stakeholders and the diverse geographic and operational contexts further complicate efforts to conduct a comprehensive social

LCA. In addition, to address this data scarcity problem, most of the social indicators currently available are qualitative, which presents a significant challenge in establishing accurate metrics and facilitating quantifiable comparisons.

Moreover, the social dimension lacks a uniform and collectively accepted framework. As can be gathered from the analysis in this research report, social indicators are often scattered in various sources, using different terminology and methodological approaches. Unlike environmental impact assessment, which has well-defined impact categories and a relatively structured and standardized procedure, social indicators lack such a cohesive structure. This inconsistency and fragmentation make it difficult to develop a rigorous and comparable assessment in the social domain. Consequently, the absence of an applicable framework hinders the effective integration of social aspects into the broader sustainability assessment within the bioeconomy.

One of the most important gaps in assessing economic prospects is related to the availability of data, as well as their variability and uncertainty. The success of the profitability of a value chain depends to a large extent on consumption trends and social demands for a service produced along the value chain. In this regard, the variability of market trends, as well as the lack of an accurate prediction of expected economic benefits in the near future, are important bottlenecks that are being addressed. The development of a future LCC has the potential to mitigate these uncertainties. However, insufficient and scarce historical data on the economic performance of specific value chains pose challenges for making accurate predictions of long-term projects or products in the future. Another gap, or issue for improvement, is based on the fact that the LCC is mainly based on direct economic costs, but externalities, such as environmental costs or environmental taxes, are not included as an element to be evaluated. At present, there is an "emissions market" in which different value chains can "trade emissions" to comply with legal emission limits per product, process or service they produce. Given its potential impact on demonstrating the economic viability of a scenario under evaluation, sustainability assessments should also be aware of and incorporate this element in the analysis of the economic pillar.

It should be noted that the main bottleneck in making an efficient, accurate and comparable assessment of the economic aspect from a life cycle analysis point of view is the lack of standardization. The absence of a recognized and internationalized methodology and guidance implies additional difficulties in comparing the benefits and disadvantages of different value chains, or even in the decision-making process, where the lack of unified and analogous criteria makes it difficult to select the best alternatives to be implemented within a bioeconomy perspective. Moreover, it also poses a challenge when trying to replicate the economic assessments made, as there is no common standard that applies equally to all sectors.

Considering the three pillars of sustainability as a compendium, the last gap that could be identified involves the integration of environmental, economic and social LCA assessments. While efforts have been made to assess each dimension individually, not much has been done as a whole. A future framework should focus on developing methods and tools for effective integration of these three dimensions. This will enable stakeholders to make more informed decisions, taking into account the trade-offs and synergies between social, environmental and economic sustainability. Further research and collaboration on frameworks to refine and enrich these indicators is essential, ensuring a sound basis for assessing the footprint of the bioeconomy.

Taking into account the insights gained from the analysis of indicators according to the LCA methodology conducted in this study, several final recommendations have been developed to contribute to a more comprehensive and consistent assessment of bio-based value chains under the three pillars of sustainability.

- The three pillars of sustainability should be assessed to make more informed decisions and taking into account trade-offs and synergies between the sustainability pillars.
- Sustainability assessments of bio-based value chains should cover all stages, from raw material extraction to end-of-life management, in order to avoid cascading effects, where unsustainable practices at one stage affect subsequent stages, amplifying or changing the overall sustainability impact of economic activity. For example, avoiding inefficient use of resources at different stages of the chain.
- A common definition of "indicator" should be followed in social assessments, and it is recommended to use the one adopted by the UNEP-SETAC guidelines, due to their extensive and recognized work in the field of S-LCA.
- The indicators analyzed should be communicated to allow transparency and a deeper understanding of the assessment, fostering accountability, informed decision making and facilitating the identification of areas for improvement.
- The social assessment should include the full range of stakeholders to ensure understanding of all social impacts associated with the implementation of bio-based activities along the value chain.
- Economic assessment should go beyond the profitability of production processes to encompass all stages of the value chain and economic issues, such as those related to social and environmental externalities (e.g., costs of emissions, carbon credits, cost of public health constraints related to economic activity).
- When conducting an economic assessment within the LCA framework, it should be within the scope of LCC and not be influenced by the techno-economic and cost-benefit analysis frameworks.

Furthermore, given the recurring constraint of limited data availability, particularly in the social and economic dimensions, a strategic recommendation is to collaboratively enhance existing databases and create new ones. By pooling resources and expertise, stakeholders can collectively contribute to building a robust data infrastructure, thus strengthening the foundation for comprehensive and insightful sustainability assessments.

Although previous literature reviews have been conducted on the environmental, social and economic dimensions (European Commission, 2010, 2021; Neugebauer et al., 2016; UNEP-SETAC, 2019a, 2019b; Rebolledo-Leiva et al., 2023), to our knowledge, no analysis has been conducted that covers all three pillars of sustainability at the indicator level (some cover impact categories and in relation to a specific pillar). There is a need to address a unified framework covering the three pillars according to criteria to cover the entire value chain and to ensure the relevance and robustness of the indicators provided.

5. Final conclusions

Bioeconomy represents a promising pathway to a sustainable future, offering solutions to mitigate resource depletion and environmental degradation. However, it is essential to emphasize that sustainability is not inherent to the bioeconomy and therefore monitoring its sustainability is a fundamental step in supporting a more sustainable future where environmental protection, social welfare and economic growth are central to the transition. Achieving sustainability within the bioeconomy requires a robust framework and methodological approaches, and in this regard, LCA has emerged as a powerful methodology for analyzing bio-based value chains, providing a holistic approach that encompasses all three pillars of sustainability. However, LCA also presents significant challenges and gaps that need to be addressed, such as the lack of standardized guidelines for economic and social assessments, and the comprehensive assessment of the three pillars of sustainability (environmental, social and economic) and throughout the entire value chain. In this context, the identification and selection of indicators to effectively assess the environmental, economic and social dimensions of sustainability has become a priority. This has been the main objective of this research report, in which a first analysis of available indicators has been carried out, followed by a careful selection of the most appropriate and complete set of indicators to measure the environmental, social and economic pillars of sustainability. As a result, a total of 17 indicators have been identified for the environmental pillar, 26 for the economic pillar and 101 for the social pillar, providing a crucial basis for effectively exploring and assessing the sustainability of bio-based value chains. In addition to contributing to current sustainability assessments, the sustainability indicators outlined in this study also lay the groundwork for future advances in the bioeconomy. By adopting these indicators, stakeholders can foster innovation, drive policy change, and promote practices that align with the changing landscape of sustainable development. In the long term, the implementation of this framework could contribute the development of a an environmentally and economically resilient, and socially equitable bioeconomy.

The report also highlights gaps in the identified indicators and in the scope of life cycle analysis methodologies to finally conclude the imperative of further research and collaborative work to refine and enrich these indicators, improve their underlying methodology, and strive to improve data availability according to the three dimensions of sustainability in a unified framework. In the near future, it is highly recommended for emerging and existing production models within the bioeconomy to incorporate appropriate indicators and methodologies to validate their sustainability. In addition, joint efforts should be made to promote the adoption of certification schemes that ensure the alignment of production systems with recognized sustainability, efficiency, and effectiveness standards. Furthermore, the implementation of circularity principles within the bioeconomy is of utmost importance and should therefore be included as a pillar of the framework in future steps to ensure that the bioeconomy is not only sustainable but also circular.

CRediT authorship contribution statement

Sara Lago-Olveira: Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Ana Arias:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Ricardo Rebolledo-Leiva:** Methodology, Investigation. **Gumersindo Feijoo:** Supervision, Writing – review & editing. **Sara González-García:** Supervision, Writing – review & editing. **Maria Teresa Moreira:** Supervision, Writing – review & editing.

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

Not applicable

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Supplementary materials

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