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Biorefineries as a driver for sustainability: Key aspects, actual development and future prospects

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A R T I C L E I N F O

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A B S T R A C T

The overexploitation of resources, the increase of the world population and the trend of consumption based on "use and throw away" is causing an increasing pressure on waste management. In this sense, it is necessary to promote sustainable practices in the valorization of waste streams as a strategy for the co-production of bioproducts and bioenergy. This approach can lead to more sustainable production chains, as lower environmental burdens are expected. However, even if a promising cascade production technology could be used, the technical and economic feasibility of biorefineries remains a challenge. This report aims to provide various insights on how to assess biorefineries from a sustainability perspective, including also available standards and guidelines that enable reliable, accurate and transparent sustainability assessments. It also shows where to focus for the inclusion of biorefineries in the value chain, for communicate/visualize their potential, and for the promotion of bio-based products from recovered resources. The outcomes and main conclusions of this report could be summarized as the importance and the need of assessing biorefinery scenarios under a sustainable perspective to have an increased market potential, considering the main aspects available on the international guidelines, certification schemes and voluntary standards.

1. Introduction

Consumption patterns leading to uncontrolled generation of waste are becoming a major management environmental problem. This implies the need to develop new production models that use these wastes as raw materials for the manufacture of other goods. These "recovered or revalued" products could be considered suitable to enter the market value chain, from the multicriteria point of view based on environmental protection, economic profitability and social acceptance (Nizami et al., 2017).

In this framework, the development of biorefineries is contemplated a key with a win-win approach. Lignocellulosic wastes are converted into valuable bioproducts, such as biofuels or bio-based chemicals, and in addition, the management of a huge amount of waste is avoided, favoring the circularity of resources and avoiding the impacts derived from end-of-life treatments or disposal (Sauer et al., 2014). On the other hand, the selection of one type of biorefinery or another will depend on the characteristics, resource availability in terms of the type of waste generated, the technology available and the demands of society in terms of bioproducts with market penetration potential (Nizami et al., 2017; Saha and Mukhopadhyay, 2020).

In this sense, future biorefineries should be developed taking into account the integral use of biomass feedstock, to meet circular economy criteria on waste reduction, making full use of available resources and ensuring market opportunities for bioproducts, taking into account both demands and competition with their counterparts.

Furthermore, as one of the main bottlenecks in the development of a biorefinery scheme is the technical and economic feasibility, the integration of mass and energy flows, together with the optimization of resource use, must be addressed. The main advantage of using bio-based waste materials is that it encourages the integrated use of resources, favoring circular economy strategies: recycling, reusing and remanufacturing, among others. Several reports have evaluated the use of food waste, lignocellulosic waste, municipal solid waste, paper waste and manure as the main bio-based resources to produce chemicals, biofuels and bioplastics, among others (Arias et al., 2022; Khatami et al., 2021; Lettner et al., 2018; Sepúlveda et al., 2021). Thinking about the main concepts of the circular bioeconomy with the use of waste feedstocks allows the development of a holistic approach in which environmental, social and economic pillars are evaluated (Ubando et al., 2020).

The development of biorefineries has intensively increased in the last

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List of acronyms

SCL	Standardization, qualification, and labelling
GHG	Greenhouse gases
LCA	Life Cycle Assessment
SDG	Sustainable Development Goals
CoC	Chain Of Custody
FSC	Forest Stewardship
RED	Renewable Energy Directive
LC	Life Cycle
GRI	Global Reporting Initiative
PEFC	Programme for the Endorsement of Forest
ISCC	International Sustainability and Carbon Certifications
RSB	Roundtable on Sustainable Biomaterials
ISO	International Organization for Standardization
PEF	Product Environmental Footprint
LCC	Life Cycle Cost
JRC	Joint Research Center
DPSIR	Driving Forces- Pressures- Stages- Impacts- Responses
PSR	Pressure-State-Response
ESS	Ecosystem Services Cascade
ML	Machine Learning
AI	Artificial Intelligence
BBI	Bio-Based Industries Initiative
LCSA	Integrated Life Cycle Sustainability Assessment
RACER	Relevant-Accepted-Credible-Easy to monitor-Robust
EEA	European Environment Agency
ISPRA	Italian Institute for Environmental Protection and Research

decade given their potential to contribute to the circular economy through the comprehensive use of resources and the objective of extending their useful life (Parada et al., 2018). A large number of biorefineries have started to use waste streams to obtain high value-added products, instead of directly using virgin renewable materials, such as the case of dedicated energy crops (first-generation biofuels). On the other hand, the development of biorefineries could help to promote rural and regional development, a key factor when assessing the social pillar of sustainability, and to avoid the dependence on delocalized resources and goods in the global value chain (Muntoni, 2019; Parada et al., 2018).

The potential for biorefineries is expected to grow in the coming years, as it is estimated that the demand for bioproducts could reach 113 Mt/year by 2050, expecting an annual growth rate of 15%.

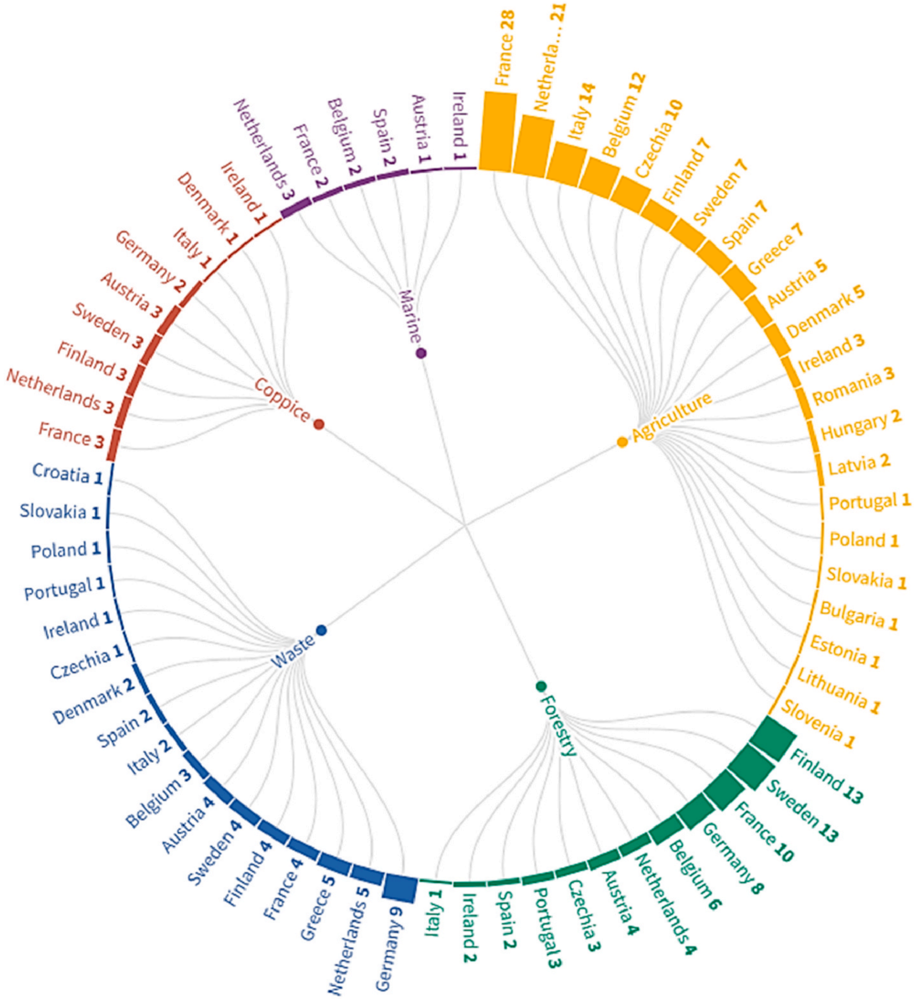

Fig. 1. Feedstock used for multiproduct biorefineries in the European context (the numbers represent the amount of biorefineries per type of feedstock and country). Own elaboration by using the European Commission database (Parisi et al., 2020).

Nonetheless, entrepreneurs and stakeholders need to be aware of the minimum size of biorefineries to ensure that they are economically sustainable and profitable. It has been reported that, approximately, $50 \cdot 10^4$–$70 \cdot 10^4$ t/year is the minimum production capacity to ensure the potentiality of biorefineries in the market, a threshold that could be reduced when waste streams are used as inputs (Muntoni, 2019).

But, on the other hand, some authors have claimed that the development of small-scale biorefineries is as well beneficial to foster the economic, environmental and social welfare of the workers and citizens living in nearby neighborhoods. The reason behind this assertion within the economic pillar is that costs associated with transportation, processing and disposal are being avoided, which has a positive impact on profitability (reduced costs imply higher profits) (Ding and Grundmann, 2022). This is at the same time related to the environmental aspect, as emissions derived from the aforementioned activities are avoided, and finally, for the social pillar, the development of small local biorefineries will contribute to job creation and to incentivize farmers to be more sustainable in agricultural activities (i.e., increase crop yields, reduce the amount of fertilizers and pesticides, more sustainable use of water sources, etc.) (Solarte-Toro and Cardona Alzate, 2021).

In this regard, how are these already commercial biorefineries being developed? Depending on the type of feedstock, the most used feedstocks for multiproduct biorefinery are agricultural, followed by forestry and residues (Fig. 1). The reason behind this is that most of the biofuels currently produced are first generation, so crops are harvested directly for energy issues, rather than for food production. Given the discussion between the food and biofuel sectors, and the need to ensure security of food supply to community needs, there is a need for a transition to second and third generation biofuels and bioproducts, using forests, waste streams and marine resources.

On the other hand, instead of focusing only on the type of feedstock most used for biorefinery facilities, it is as well important to analyze the type of products obtained. As depicted in Fig. 2, the bio-based product that stands out is chemicals, followed by biofuels and the production of composites and fibers, with Germany being the region where a gross amount of biorefineries are producing them, followed by France and the Netherlands. Examples include Alberta Pacific Forest Industries, which uses wood as a feedstock to produce not only pulp, but biomethanol, heat and electricity, with a production capacity of 765 ktons of wood/day. In terms of multiple bio-based feedstocks in the same production plant, Maabjerg Energy uses wood chips, manure, sewage sludge, municipal solid waste and straw as feedstocks to co-produce biomethane, bioethanol (approx. 80–103 m^3/year), fertilizer, electricity and heat. Another example of this multiple production scheme is ZeaChem, which uses various cellulosic feedstocks (wood waste, wheat straw, corn stover) to produce bioethanol and ethyl acetate ester, with a production capacity of 10 tons/day (Cardona-Alzate et al., 2020).

But, although biorefinery production schemes are already starting to develop into large-scale production capacities, there is still a long way to go. In fact, less than 2% of lignocellulosic waste is used as feedstock to produce value-added bioresources (Nguyen et al., 2021).

So what is the main problem biorefineries face in not being able to quickly penetrate the value chain? In the search for integrated systems that favor a comprehensive assessment of the market penetration potential of biorefineries, along with the accurate evaluation of their degree of sustainability and circularity, the development of regulatory policies, as well as collaboration between policy makers, stakeholders and the social community, is essential.

The integration of biorefineries into the market value chain implies the development of complex production schemes that guarantee the recovery or production of valuable products from biomass. Biorefineries are not at the same level of development as their conventional fossil-based counterparts, where the technology has been tested, optimized and validated. One of the main limitations when evaluating new biorefinery approaches is the lack of industrial-scale processes (Dragone et al., 2020; Mariana et al., 2021; Meramo-Hurtado and González-Delgado, 2019)**. It is necessary to ensure the economic profitability of biorefineries to guarantee their success, seeking to ensure their viability in order to drive investment interests** (Arias et al., 2023; Laude and Jonen, 2013; Prabha et al., 2022)**.**

In this sense, the identification of production capacity, market

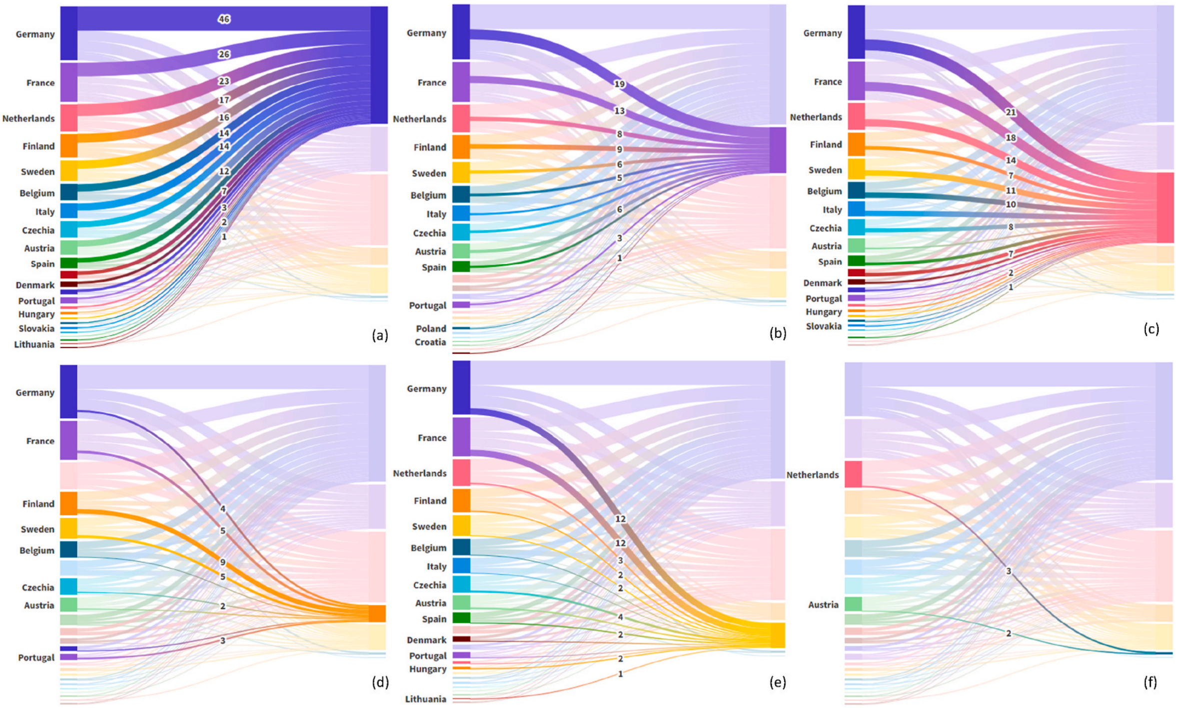

Fig. 2. Multiproduct biorefineries in Europe. (a) Chemicals (b) Composite and fibers (c) Liquid biofuels (d) Pulp & paper (e) Starch & sugar (f) Biomethane (the numbers represent the amount of biorefineries per type of feedstock and country). Own elaboration by using the European Commission database".

demands, technological bottlenecks, economic challenges and environmental impacts are key aspects to assess from an early stage of development, including also an estimation of the biorefinery prospects in the future market value chain (Cristóbal et al., 2018; Tschulkow et al., 2020)**. In this sense, the development of comprehensive and multi-objective assessments in the field of sustainability and circularity could help on the way to biorefinery development. But, on the other hand, lack of data to perform the assessments and regulatory barriers could be an obstacle, hindering their penetration into the market value chain** (Leibensperger et al., 2021; Singh et al., 2021; Zhang et al., 2012)**. In this aspect it is also worth mentioning that most of the available research reports focus on conducting environmental and techno-economic assessments, rather than being aware of certification schemes, international standards, planetary boundaries, and if they did, separately, not as a comprehensive assessment of all approaches combined** (Campbell-Johnston et al., 2020; D'Amato et al., 2020; Lange et al., 2021; Ncube et al., 2022; Rebolledo-Leiva et al., 2023; Salvador et al., 2022; Ubando et al., 2020; Zabaniotou, 2018)**.**

Given the importance of assessing the potential of biorefineries through all the above aspects, this report aims to provide the framework of methodologies and perspectives to address the gaps and bottlenecks that delay or hinder the development of biorefineries and to provide criteria to address their sustainability potential along the entire value chain: from feedstock extraction/processing to bioproduct use and disposal.

1.1. Biorefineries from a sustainability perspective

When assessing a new biorefinery process it is important to focus on both sustainability, based on the triple bottom line of environment, society and economy, to categorize a production scheme as a sustainable process, but also on the technical aspects, from an early stage of design to a more developed one, in order to ensure the effectiveness on the production capacity. Indeed, the European Union has determined sustainability criteria for the use of biomass, seeking to ensure carbon savings and environmental protection: the reduction of GHG emissions, compared to fossil fuels, must be at least 35%, and the harvesting of biomass feedstocks must not take place on land previously used as carbon stock or in areas of high biodiversity (OECD Science, T. and I.P.P., 2019). Although the environmental pillar is usually covered, as the use of lignocellulosic feedstocks often leads to a reduction in pollutant emissions, economic viability is not always guaranteed (Ubando et al., 2020). For the social dimension, more difficulties arise due to lack of data and guidelines, while economic feasibility is often reduced to the development of a common cost-financial document, and the environmental issue is often focused on the category of global warming potential (Palmeros Parada et al., 2017).

Environmental burdens are scored using life cycle assessment methodology, technical and economic characteristics are assessed by performing a techno-economic analysis, often coupled with a Monte Carlo study to address the uncertainty of the results, and social-LCA or socio-economic analysis to assess the social dimension. But, in fact, even if appropriate methodologies are used to assess the three pillars of sustainability, the lack of data could reduce the ability to develop them adequately. This reduced scope of sustainability assessment could provide "false" values when assessing the adaptation of a biorefinery to a sustainable practice. In this sense, future challenges for sustainability and circularity criteria and assessment should focus on the development of adequate and transparent guidelines that encompass all pillars within a comprehensive sustainability assessment (Palmeros Parada et al., 2017).

Multi-criteria assessment is graded as a possible sustainability evaluation tool, as both bio-physical (i.e. mass-based balances), social (i.e. job creation, health and safety) and economic (i.e. associated costs and incomes) pillars are compiled in a system-wide assessment method (Palmeros Parada et al., 2017). The scores obtained could be used for decision-making on where to focus to provide a sustainable biorefinery approach (Parajuli et al., 2015). But this integration and scoring of the three pillars of sustainability to be used as a decision tool is still a debate because of three reasons:

- The first one is the lack of common scoring methodology, because while the environmental and economic pillars could be assessed quantitatively, the social one is usually determined under a qualitative method.
- The second reason is based on the fact that a huge amount of subjective interpretation can be made when evaluating the pillars, especially in the case of the social one.
- Finally, the fact that there are no specific guidelines or formal recommendations for conducting sustainability assessments and, in fact, most of the time the criteria and indicators for assessing the sustainable potential of a scenario are different depending on the sector and activity.

These facts are even more debatable and significant when developing a sustainability assessment of a biorefinery process, as there are a larger number of stakeholders involved: primary sector (involved in the production of feedstock), secondary and tertiary sector (involved in the generation of waste streams that can be used as inputs in the biorefinery), policy makers and government, among others. In addition to the difficulty of developing accurate assessments, one of the main barriers in the commercialization of bio-based products is that the benefits are not large enough to offset the investment and operational costs. In addition, compliance and strict requirements assessed in policies and standards, as well as community demands and acceptance, hinder the penetration of new bio-based products into value chains and the market (Ubando et al., 2020).

At this point of the debate, the development of congruent management policies, adequate guidelines and cooperative links between the parties involved, could help in addressing sustainability in an adequate manner. On the other hand, according to the IEA Bioenergy Task 42 reports, a series of principles have been developed that should be compiled, at least, to define a biorefinery process as sustainable, taking into account the socioeconomic and environmental pillars. These are "basic" principles and, at the same time, could be contemplated as guidelines to assess the sustainability potential of a biorefinery in a general way and as a tool to identify key points for decision making. The scope of each principle, as well as the dimension of the analysis, is different, aiming to be applied to specific assessment scenarios depending on their needs.

The most general is "The System Principle" based on the overall assessment of biorefinery technology and process design, followed by the "The Consistency Principle" in which this analysis focuses more on resource management than on technology and process development. In order to identify, in a more concrete way, the sustainability potential, the use of "The Measurability Principle" is used to directly assess the sustainability potential of the biorefinery through the use of quantitative and qualitative indicators and criteria. The last two principles are more related to comparative assessments, while "The Independency Principle" assesses the environmental and socioeconomic performance of the technological procedure and the biorefinery pathway, "The Comparability Principle" is more based on the comparison between different feedstocks (Parajuli et al., 2015).

Furthermore, it is important to keep in mind that the production process is not the only aspect to be evaluated when conducting a sustainability study, but all actors in the value chain. From the background point of view, primary and secondary producers of biorefinery feedstocks and inputs should promote sustainable practices. For example, in the case of the agricultural and forestry sector, minimizing the use of fertilizers, pest products, use of appropriate machinery, use of indigenous species, avoidance of genetically modified species, etc. Thus ensuring environmental protection (maintenance of biodiversity, avoidance of soil degradation and atmospheric emissions, efficient use of water resources and prevention of water pollution) (Levidow, 2015). From the foreground point of view, how consumers use the product, its quality and service capacity are equally important. Likewise, the production process should think about the residues that will entail the use of the bio-product by other facilities and/or community members. Sustainability actions should be promoted and ensured over the global value chain (collection - production - consumption - disposal or reuse).

1.2. Biorefineries: current state on the European Union under the Sustainable Development Goals

The development of biorefineries in the European context is increasing, mainly due to the need to comply with legal and political requirements that promote the development of more circular actions in the production of goods and services. **The link of biorefineries with the Sustainable Development Goals (SDGs) is strong, as some of the SDGs focus directly on the circular use of resources, government** support **for research and implementation of best practices in productive sectors, climate action, economic growth, well-being, and research and innovation practices.**

The degree of achievement and trends in each of the SDGs is different for each country in the European Union, and this is in addition related to sustainability actions and how each region works on improving circularity, environmental protection, economic growth and social welfare. In this sense, the European Commission provides a database to document European sustainable development, for each of the SDGs (Eurostat, 2023). The European Union, in 2021, achieves an SDG Index score of 71.4/100, being the SDGs 2 (No hunger), 13 (Climate Action), 14 (Life Below Water) and 15 (Life on Land) requiring the greatest efforts to go further in sustainable actions.

The regions that achieved higher index score values compared to the European Union average score are the northern ones, with an average value of 80.6, while the southern and the central achieved lower scores, 68.3 and 68.0, respectively. On the other hand, in order to be aware on the current status on the degree of achievement according to each SDG, Table 1 shows the actual status of each country, denoted “Major challenges” in red, “Significant challenges” in orange, “Challenges remain” in yellow and “Goal achieved” in green.

One of the SDGs most closely related to biorefinery production approaches is SDG 13, Climate Action, since protecting and maintaining the environment is one of the pillars of sustainability. As can be seen in Table 1, most of the regions that are part of the European Union have a very low achievement in the sub-targets identified for this SDG13. The rationale behind this is mainly based on the recurrent use of fossil fuels for the production of goods and services, leading to significant emissions and detrimental effects on the environment, the extensive use of resources, leading to their depletion, and the amount of waste produced, which is disposed of through unsustainable practices, instead of being reused and recycled, for example. The disposal of waste in landfills, one of the most common practices, carries a high environmental burden, but incineration could also be categorized as a low-value and detrimental procedure for waste management.

On the other hand, seeking to be aware of what is the real strength and development of some issues more related to the sustainable use of resources, incentives to research development and the amount of waste and emissions by region, Fig. 3 is represented. The subfigures were created according to the European Commission database, using the topics more related to the sustainability approach.

The consumption of raw materials is directly related to the efficient use of resources, if the integral use is developed, then the consumption of virgin materials is lower. In this sense, a more sustainable use of resources is being developed, which in turn could be related to the amount of waste generated and the circular use of materials in European regions.

Table 1

Growth of development on achieving SDGs by the European countries (Source: European Commission database about the degree of achievement of SDGs (Eurostat, 2023).

	SDG1^{1}	SDG2^{1}	SDG3^{1}	SDG4^{1}	SDG5^{1}	SDG6^{1}	SDG7^{1}	SDG8^{1}	SDG9^{1}	SDG10^{1}	SDG11^{1}	SDG12^{1}	SDG13^{1}	SDG14^{1}	SDG15^{1}	SDG16^{1}	SDG17^{1}
Finland	🟩	🟥	🟨	🟩	🟨	🟨	🟩	🟨	🟩	🟩	🟩	🟥	🟥	🟨	🟧	🟨	🟨
Sweden	🟨	🟧	🟨	🟨	🟨	🟨	🟩	🟨	🟩	🟩	🟨	🟧	🟥	🟥	🟥	🟨	🟨
Denmark	🟩	🟧	🟨	🟨	🟨	🟨	🟩	🟨	🟩	🟩	🟨	🟥	🟥	🟥	🟨	🟨	🟩
Austria	🟩	🟧	🟨	🟨	🟨	🟨	🟩	🟨	🟩	🟩	🟨	🟥	🟥	🟥	🟥	🟨	🟧
Norway	🟩	🟧	🟨	🟨	🟨	🟧	🟩	🟨	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟨	🟩
Germany	🟨	🟥	🟨	🟧	🟧	🟨	🟨	🟨	🟩	🟨	🟨	🟥	🟥	🟧	🟧	🟧	🟩
Swizerland	🟨	🟧	🟨	🟧	🟨	🟨	🟩	🟨	🟩	🟨	🟩	🟥	🟥	🟥	🟥	🟧	🟥
Estonia	🟨	🟥	🟨	🟩	🟧	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟨	🟨	🟨	🟧
Slovenia	🟩	🟧	🟨	🟨	🟧	🟨	🟨	🟨	🟨	🟩	🟧	🟥	🟥	🟥	🟧	🟨	🟧
France	🟩	🟥	🟨	🟧	🟨	🟧	🟨	🟧	🟩	🟨	🟨	🟥	🟥	🟧	🟥	🟧	🟧
Czech Republic	🟩	🟧	🟧	🟧	🟧	🟨	🟧	🟩	🟨	🟩	🟨	🟧	🟥	🟥	🟧	🟨	🟧
Belgium	🟩	🟥	🟨	🟧	🟨	🟨	🟧	🟨	🟩	🟩	🟨	🟥	🟥	🟧	🟧	🟨	🟥
Netherlands	🟩	🟥	🟨	🟨	🟨	🟨	🟧	🟨	🟩	🟨	🟨	🟥	🟥	🟥	🟥	🟧	🟥
Island	🟩	🟧	🟨	🟧	🟨	🟧	🟩	🟨	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟨	🟧
Poland	🟩	🟧	🟨	🟧	🟧	🟨	🟧	🟨	🟧	🟩	🟧	🟧	🟥	🟥	🟧	🟧	🟧
Ireland	🟨	🟧	🟨	🟨	🟧	🟨	🟧	🟨	🟧	🟨	🟨	🟥	🟥	🟧	🟧	🟨	🟥
United Kingdom	🟨	🟥	🟧	🟨	🟧	🟨	🟧	🟨	🟩	🟧	🟨	🟧	🟥	🟧	🟧	🟧	🟥
Slovakia	🟨	🟥	🟨	🟧	🟧	🟨	🟨	🟧	🟧	🟩	🟧	🟧	🟥	🟥	🟧	🟧	🟧
Latvia	🟧	🟥	🟧	🟨	🟧	🟧	🟨	🟧	🟥	🟧	🟨	🟥	🟥	🟨	🟨	🟧	🟥
Portugal	🟨	🟧	🟨	🟨	🟨	🟨	🟧	🟨	🟧	🟨	🟧	🟧	🟥	🟥	🟥	🟧	🟧
Hungry	🟨	🟥	🟨	🟧	🟥	🟨	🟧	🟧	🟧	🟨	🟨	🟧	🟥	🟥	🟧	🟧	🟥
Spain	🟧	🟥	🟨	🟧	🟨	🟨	🟧	🟥	🟧	🟧	🟨	🟧	🟥	🟥	🟥	🟧	🟧
Italy	🟧	🟥	🟨	🟧	🟧	🟨	🟧	🟧	🟨	🟧	🟨	🟧	🟥	🟥	🟥	🟧	🟧
Croatia	🟨	🟧	🟧	🟧	🟧	🟧	🟨	🟧	🟧	🟨	🟧	🟧	🟥	🟧	🟧	🟧	🟧
Lithuania	🟧	🟥	🟧	🟨	🟧	🟨	🟥	🟧	🟧	🟧	🟨	🟥	🟥	🟧	🟨	🟧	🟧
Luxemburg	🟨	🟧	🟨	🟧	🟧	🟧	🟥	🟧	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟨	🟥
Greece	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟥	🟧	🟨	🟧	🟥	🟥	🟥	🟧	🟧	🟧
Malta	🟨	🟥	🟨	🟥	🟥	🟧	🟧	🟩	🟧	🟨	🟧	🟥	🟧	🟧	🟥	🟧	🟧
Romania	🟥	🟧	🟧	🟥	🟧	🟧	🟨	🟧	🟥	🟧	🟥	🟥	🟧	🟨	🟥	🟧	🟧
North Macedonia	🟥	🟥	🟥	🟥	🟧	🟥	🟧	🟥	🟥	🟧	🟥	🟧	🟧	🟥	🟧	🟥	🟨
Serbia	🟧	🟥	🟧	🟥	🟨	🟥	🟧	🟧	🟥	🟧	🟥	🟥	🟧	🟥	🟥	🟥	🟨
Cyprus	🟨	🟥	🟧	🟧	🟧	🟥	🟧	🟧	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟨	🟥
Bulgaria	🟧	🟧	🟧	🟥	🟧	🟧	🟧	🟧	🟥	🟧	🟧	🟥	🟧	🟧	🟧	🟧	🟧
Turkey	🟥	🟧	🟧	🟥	🟥	🟨	🟧	🟥	🟥	🟥	🟥	🟨	🟧	🟥	🟥	🟧	🟨
European average	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟧	🟨	🟨	🟨	🟧	🟥	🟥	🟥	🟨	🟧

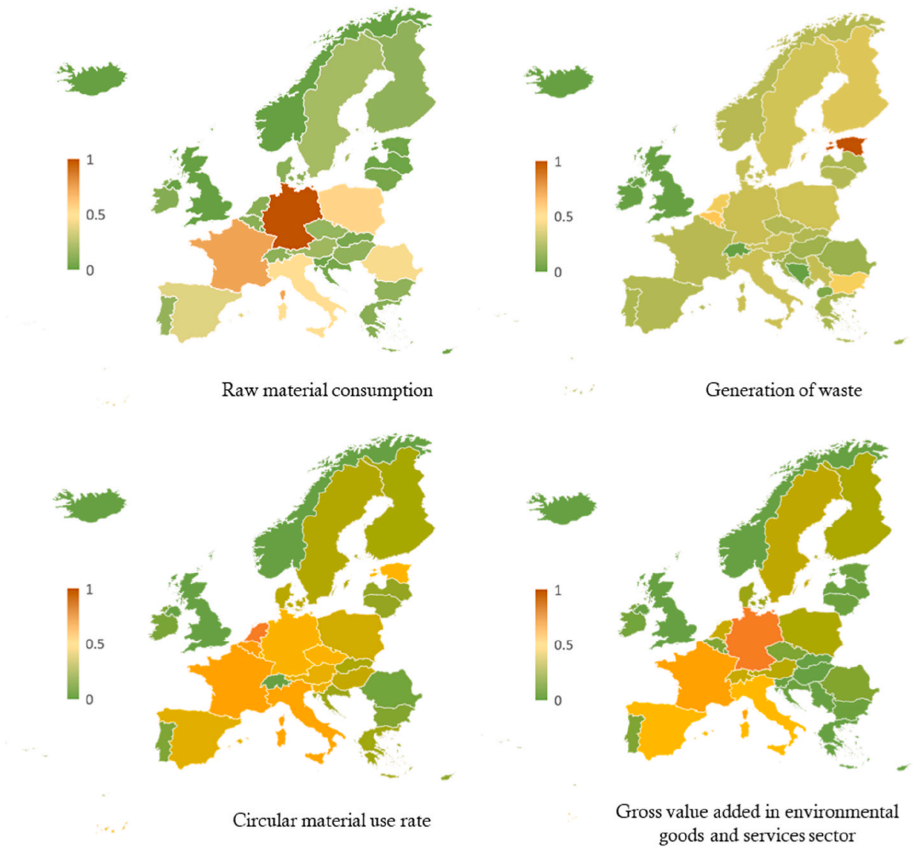

Fig. 3. Some indicators, based on the database of the European Commission, related with sustainability practices and actions in the European context.

The connection between these three aspects is interesting (Fig. 3), as the regions with the highest consumption of raw materials are not the ones that produce the largest amount of waste. Given the scores obtained, the conclusion that could be derived from these interrelationships is that an extensive use of virgin materials does not imply that the production of goods and services is linear, or that it contributes to a greater amount of waste streams produced.

The integration of circularity action plans, inferring an integrated use of resources, and the development of biorefinery facilities with the aim of "reusing" waste streams into raw material streams, helps to ensure that the regions with the highest demand for virgin materials are not the least sustainable. Even so, extensive consumption of virgin materials could lead to their depletion and associated environmental impacts (e.g., extensive use of forest resources could lead to deforestation, while increased consumption of agricultural raw materials could lead to soil degradation and erosion). It is therefore important to develop management and action plans to avoid impacts on the quality and health of the environment given the extensive use of resources.

It is true that reducing the consumption of raw materials is not easy, as it is necessary to respond to society's demands, but the implementation, management and development of adequate practices in the global value chain of production could be beneficial from the point of view of sustainability actions. This should be the main awareness of production facilities: to be efficient, to be consistent with material consumption and to be conscious of the impacts on society, economic issues and the environment. It is besides observed that, in general, those regions that are more aware of the development of more circular production actions are those that achieve a gross value in the environmental goods and services sectors. This probably derives from the enhancement of the development of more sustainable actions, in accordance with regional environmental and sustainability policies and regulations, and, of course, from the community members' acceptance of the production and consumption of bio-based products derived from more sustainable production processes.

1.3. Sustainability criteria and certification schemes

The implementation of a standardized scheme that aims to assess the sustainability of a product or technology must take into account a number of aspects that are essential for its adequacy, reliability and applicability (Pelkmans et al., 2013). Some of the criteria that should be analyzed first when assessing the sustainability and suitability of a biorefinery include:

- Ensuring food quality and availability (the use of food-related feedstock for the development of the biorefinery should not affect the population needs and demands for food products (Leong et al., 2021)).
- Guarantee that the technology used is as efficient as possible, in order to foster the use of renewable and bio-based feedstock resources.
- Provision of an integral use of both resources and products produced.
- Implementation of best practices guidelines to protect the human well-being.
- Be in line with circular actions.
- Promote and analyze the market potential and be aware of all the value chain practices (both background and foreground).

To give an example on how a prior analysis of the biorefinery aiming to be developed is essential to ensure its effectiveness: if a new biorefinery is going to be developed but the technology is not efficient in terms of production yield and energy requirements, what are the consequences? It will encounter low production capacity, a huge amount of feedstock required for the production of target product, intensive use of energy, more intense emissions per product manufactured, low incomes, which will translate into fewer jobs or lower worker salaries, among others. In this sense, the impact of the biorefinery on the pillars of environmental, social and economic sustainability will be negative: high emissions, high resource consumption, low productivity and, therefore, high production related costs and lower job creation, making the biorefinery approach analogous, or even worse, to conventional refinery facilities.

In this regard, the use of criteria and indicators for the quality assessment of biorefinery quality in the economic value chain for the production of goods and services is essential. The requirements for the compilation with sustainability principles and criteria have been first developed by RED II (EC, 2018), collecting the necessary guidelines for compliance with criteria that reveal the transition from unsustainable use of resources to a circular bioeconomy and a sustainable biorefinery.

The first two initiatives that embraced sustainability principles the Forest Stewardship Council (FSC, 1994) and the Roundtable for Sustainable Palm Oil (2004), for the forestry and agricultural commodity sectors, respectively. Following these two guidelines, the Renewable Energy Directive (RED 1, EC, 2009) has been established, mainly focused on the standardization of biofuels in the transport sector, but furthermore applicable to other productive activities. This Directive includes environmental as well as economic and social thresholds, for which one of the most developed and recognized methodologies for their scoring and assessment is the Life Cycle (LC) methodology.

In the case of the corporate level, it is widely used in the Global Reporting Initiative (GRI), CanopyStyle and Rainforest Alliance initiatives. Besides those aforementioned, there are other well-established standards for assessing the sustainability capacity of the biorefinery scenario under assessment, such as the Programme for the Endorsement of Forest (PEFC) and the International Sustainability and Carbon (ISCC) Certifications.

From an environmental point of view, GHG emission scoring is one of the main impact categories that are fundamental when conducting a sustainability assessment. There are well-established protocols in the measurement of GHG emissions, such as the GHG Protocol tools, which grade all CO_2 emissions related to the biorefinery process, from feedstock extraction to processing and waste treatment, but the system boundaries depend on the scope of the assessment, and on the allocation selected. Taking this into account, not only the main production process must comply with sustainability principles, but also the extraction of raw materials must be categorized as sustainable practices. Thus, it is necessary to develop and implement sustainability documentation and labelling to provide stakeholders and community members with information on the origin of raw materials and the production chain of the obtained bio-based products (OECD Science, T. and I.P.P., 2019).

In addition to the GHG protocol, the ISCC has developed a methodology for the calculation of total CO_2 emissions from the life cycle of biomass-based feedstocks. This includes emissions from the harvesting and extraction stages, carbon stock changes due to the cultivation of lignocellulosic biomass, emissions from the processing, transport and distribution of biofuels in the market value chain as well as emissions from the use of biofuels in transport. The reduction of GHG emissions is important when assessing the sustainability potential of biorefineries, as it refers to the carbon accumulation gained from the development of improved agricultural practices for CO_2 capture and storage.

Other criteria such as biodiversity protection and ecosystem conservation (i.e. the use of non-binding schemes such as ISCC, Better Biomass or Sustainable Forest Management criteria to assess the environmental benefits/bottlenecks of the harvesting and extraction activities of the feedstock used in the biorefinery) should be contemplated, along with the assessment of the traceability of the products in the chain of custody (CoC). In fact, CoC is one of the essential requirements in the assessment of a biorefinery process and/or products, as it is necessary to identify the process chain of the bioproducts to have a thorough knowledge of all the stages necessary for their final distribution.

In the field of social and economic performance, the use of national regulations is the most used “guideline” by biorefineries to demonstrate their compliance and commitment. The EU Working Time Directive and the International Labor Organization, together with the Fundamental Principles and Rights at Work, are the most prominent. There is still no specific regulation or guideline on the assessment of the social and economic sustainability potential of biorefineries and, making difficult its development and implementation.

To this end, although harmonization of sustainability schemes and guidelines across the three pillars is not easy, it is advisable. The harmonized criteria should be developed taking into account all sectors and actors in the value chain, in order to be equitable. It is true that the enormous degree of diversity of criteria among the different certification schemes and standards makes it difficult to achieve a harmonized scheme, where in addition the lack of data is a major bottleneck (Mai-Moulin et al., 2020).

In the first attempt to harmonize sustainability assessments, the Renewable Energy Directive (RED) defines nine principles for assessing the sustainability of biomass-based processes and those are based on three typologies: GHG emissions, content of bio-based materials and traceability of bio-based products in the chain of custody. Likewise, the Roundtable on Sustainable Biomaterials (RSB) is an initiative that includes 12 principles that not only focus on biomass but on biomaterials in general, in fact, it includes some requirements to foster sustainability actions, such as GHG emissions reduced by at least 10% compared to fossil-based counterpart products and a bio-based content of no less than 25% (Vis et al., 2016).

1.4. Certification programs

In terms of assessing the sustainability potential of a product or process, the most widely recognized and used is the ISCC. The principles assessed are 4, but the number of criteria amounts to 92 (49 major and 43 minor requirements, all major should be met but only 60% of the minor are claimed (Gan and Cashore, 2013), covering all the aspects necessary to categorize a system as sustainable: the environmental pillar through the degree of conservation of biodiversity and carbon stocks and the application of Good Agricultural Practices, the social pillar with the consideration of human rights compliance, allowing for safe working conditions, and adequate training and traceability with the assessment of the chain of custody (Vis et al., 2016).

The RSB (Roundtable on Sustainable Biofuels) program states that the use of forestry and agricultural residues as feedstock for biorefinery facilities should not affect soil stability and organic content. Sustainable biorefinery programs must be mindful of how the extraction and use of feedstock impacts the quality of the environment, and the capacity of the facility must be based on the regenerative capacity of the environment. This program introduces 12 principles, encompassing 37 criteria, which could be used to assess the sustainability of feedstock and biofuel producers, where minimum requirements are mandatory. For example, in the case of biofuels, compared to fossil fuels, in order to be certified, biofuels must reduce greenhouse gas emissions by at least 50%.

In addition to the most important schemes mentioned above, there are others recognized by the European Commission as voluntary schemes to guarantee the sustainability procedure of the production process stages that are part of the global value chain. A brief description of them is depicted in Table 2 (see Table 3).

In addition to the established evaluation systems, intensive research and development activities have been carried out to evaluate its quality and to develop alternative sustainability assessment frameworks. The European STAR-Pro BIO project has evaluated the quality and effectiveness of certification systems for assessing the sustainability potential of bio-based products. It was based on the evaluation of 33 impact categories associated with the pillars of sustainability and circularity criteria: environmental (11 categories), social (14), economic (1) and circularity (6). These are both quantitative and qualitative indicators

Table 2
Certification schemes (CS) recognized by the European Commission.

Voluntary recognized schemes	Purpose	Sectors involved	Main products	Covers all value chain?
Biomass Biofuels, Bioliquids sustainability voluntary scheme	To assess the sustainability of agricultural and forestry biomass, residues, wastes and renewable energies.	Energy, Food & Manufactured products	Biofuels & biomass products	Yes
Better Biomass	It certifies solid, liquid and gaseous biomass to demonstrate it sustainability to be used for energy, bioproducts and biofuels.	Energy, Floriculture & Horticulture	Biofuels & Agricultural products	Yes
Bonsucro EU	To ensure the sustainability of sugarcane production and all its derived products	Agriculture	Sugar	No. Only production and manufacturing
ISCC	International scheme focused on assess and propose sustainable solutions for all feedstocks and markets	Agriculture, Energy, Floriculture & Horticulture and Manufactured products	Biofuels, Food & Beverages, Cosmetics, Electricity	Yes
KZR INiG system	Used for certifying the production of biofuels, bioliquids and raw materials under a sustainable approach.	Energy	Renewable energy biofuels	Yes
REDcert	Certification of biomass (from energy crops, waste flows and residues) to produce bioenergy	Energy, Floriculture & Horticulture and Manufactured products	Biofuels	No. Only production and manufacturing
Red Tractor Farm Assurance Combinable Crops & Sugar Beet Scheme	Focused on the assurance of food chain from farm to pack	Agriculture	Cereals, nuts, soy, sugar and vegetables	No. Only production and manufacturing
Roundtable of Sustainable Biofuels EU RED	Principles & criteria to assess the sustainability issues to produce biofuels	Energy	Biofuels [aviation, ground transport and shipping biofuels] and bioenergy from biomass	No. Only production, manufacturing and consumption
Roundtable of Responsible Soy EU RED	International scheme to ensure avoidance of deforestation and zero conversion soy production	Agriculture	Soy	Yes
Scottish Quality Farm Assured Combinable Crops	To evaluate the suitability on the management of crops	Agriculture, Food	Crop products	N/A
Trade Assurance Scheme for Combinable Crops	Assurance framework for the trade of crops for food, feed and biofuels production	Agricultural, Food and Energy trades	N/A	No. Only the trade of crops for goods and services
Universal Feed Assurance Scheme	Assurance framework for compile the safety requirements of feed destined to livestock	Agricultural, Animal feed	N/A	No. Only production, manufacturing and trade.
Sustainable Resources voluntary scheme	To verify the sustainable production and use of forestry, agricultural, waste and residues coming from biomass resources	Energy	Power and heat generation	Yes
Sustainable Biomass Program (SBP)	Voluntary scheme for certified biomass resources used for energy production	Energy	Forestry, Floriculture & Horticulture	No. Only production
Austrian Agricultural Certification Scheme [National]	To control the agricultural feedstocks (vegetable oils, oilseeds and cereals)	Energy	Biofuels, bioliquids and biomass fuels	No. Only production (grown and harvesting of feedstock)

and have been selected based on EN 16751:2016 “Sustainability criteria for bio-based products”, NTA 8080–1 “Sustainability produced biomass for bioenergy and bio-based products” and ISO 13065:2015 “Sustainability criteria for bioenergy”. These criteria can be classified and integrated into a sustainability assessment tool (SAI) that encompasses 24 principles and 48 indicators, both qualitative and quantitative (20 for the environmental pillar, 12 for the product and system, 2 for the economic pillar and 14 for the social framework). The assessment of the quantitative indicators is mainly based on the use of LCA methodology, following the guidelines of the ISO 14040:2006, ISO 14044:2006, EN 16760, CEN/TR16957:2016 and the PEF (Product Environmental Footprint), for the environmental pillar and the LCC (Life Cycle Cost) methodology for the economic one. In the case of the social framework, the Handbook for Product Social Impact Assessment has been used in the project, which is based on a qualitative approach using scaling factors (Golaszewski et al., 2020).

1.5. Policy implications

In terms of policies and regulations, these should take into account evolving supply chains and market trends and provide transparent guidelines on how sustainability is to be assessed (Pelkmans et al., 2013). Policy makers should focus on the development of more reliable, feasible and comprehensive certification schemes and methodological guidelines for determining ecosystem capacities (to assess threshold values for sustainable action) (Meyer and Priess, 2014).

The creation of industry and stakeholder associations could be rate as an effective tool for the development of biorefineries and R&D of emerging technologies. An example of this is the industrial association EuropaBio (European Association for Bioindustries), embedded in the EU bioeconomy strategy and the European biotechnology community, which aims to incentivize cooperation between policy makers and stakeholders, social welfare through biotechnology development, investment in R&D activities, improved market penetration of biorefinery products and ensuring food safety when moving towards a bio-based and zero-waste economy (EuropaBio, 2022; European Commission, 2018). These are at the same time one of the main pillars of the Joint Research Center (JRC) Bioeconomy Observatory, which collects data and indicators to assess how bio-based facilities are developing from socio-economic, technological, economic, legislative and scientific perspectives (Scarlat et al., 2015).

On the other hand, the use of quotas is believing to be an effective tool to support the penetration of new emerging technologies in the sector and to promote the improvement of mature technologies to adapt them to sustainable and circular economy actions. The specification and clarification of these quotas is essential, as well as the defined objectives, which must be clear and specific for all stakeholders and community members. Policy instruments should be aware of the time needed to develop a biorefinery concept from scratch, being a long and somewhat uncertain process. In this sense, some risk should be put on the investment, to give a chance to emerging technologies that, in theory, could be more beneficial for the promotion of more sustainability procedures (Hellsmark and Söderholm, 2017).

Governments should focus on developing a specific and precise connection between uncertainty and investment risk. Some of the barriers to achieving real policies on bio-based products are public

Table 3

Proposed alignment between policies interest and sustainability approach. Own elaboration with information provided by (De Besi and McCormick, 2015; Ding and Grundmann, 2022; Kardung et al., 2021; Lühmann, 2020; Woźniak et al., 2021).

Alignment between policies interest and sustainability approach	
Adequate production strategies according to the policy needs.	Documentation and monitoring of the production scheme to detect the possible bottlenecks and development of respond actions to improve them. Use of this data to allow the development of new policies more focused on biorefinery approaches.
Encouragement of high level of R&D through government incentives	Research of new production strategies with higher production yields and reduced impacts: energy efficiency, use of renewable resources, increase the quality of the bio-products, etc.
Promotion of the bio-based products by the policies, politicians, and governments	Advertising campaigns for bio-products focusing on their quality, suitability for use, and adequacy. Use of appropriate labeling for the consumer, focused on promoting its superior characteristics, in terms of sustainability properties, with respect to its fossil-based counterparts.
Support by national policies	National interest alignment to allow more efficient strategies to support economic and social development, and to protect the environment by the efficient use of available resources.
Ensure food security and availability	The support on biorefineries development should not put in danger the availability of food according to the community needs. The policies should bear in mind to stablish a limit vale on the use of food-based resources.
Transparent policies and strategies, and establishment of cooperative alliances	Transparent and supportive policies, European and regional strategies are essential for the development of biorefineries. Cooperation among industries, stakeholders and government through public/private partnerships, as the Bio-based Industries Consortium (BIC), are good tools to enhance cooperation and collaboration to assess R&D, investment tools and policy issues, looking for achieve more sustainable and competitive production strategies with reduced low carbon intensity
Development of adequate legislation for biorefineries development	Legislation could be labelled as a policy tool to define the goals and the integration of biorefineries into the value chain economy.
Cooperation between stakeholders, community members, policy makers and entrepreneurs.	One of the most recurrent highlights of European and national strategies is how the implication of community members and an adequate dialogue could enhance and improve the use of resources, aiming to be more conscious on the consumption of resources, which is crucial to go forward sustainability
Development of management plan, actions strategies and recommendation guidelines on the sustainable use of resources	The use of bio-based feedstocks for biorefinery development should not entail damage on the land and biodiversity. As an example: the use of forestry source as feedstock for biorefineries could entail a detrimental effect on environmental sustainability. The rationale behind this is that, if forest management and harvesting activities of the forest sector are not adequate, the amount of carbon sinks is going to be reduced given the felling of forest areas to use the wood as feedstock and, therefore, wood will not be categorized as a carbon neutral stock.

perception and acceptance (e.g. the use of food crops for biofuel production), uncertainties about the availability of eligible feedstocks in line with Circular Economy and zero waste frameworks, the adaptability of the production scheme and resource use with directives (e.g. Renewable Energy Directives) and the lack of financial schemes, loan guarantees and economic support for emerging technologies (OECD Science, T. and I.P.P., 2019).

Besides, the development of biorefineries is expected to have a positive effect on the bioeconomy, both from a competitiveness point of view, as green chemistry and bio-based products are gaining positions in value chains. The transformation, or integration, of obsolete or productivity-reducing production schemes into biorefinery approaches could be considered a reindustrialization strategy, which has a positive effect on the economy, the environment and society, as new jobs are expected to be created. But in fact, in this effort of biorefineries to penetrate the market, policy development and adaptation is necessary and beneficial. Such policies should be based on the recognition of the quality of the resources and products obtained, the promotion of zero waste, the avoidance of landfill as waste disposal, the establishment of standards standing out innovation (such as ISO CEN 13432 for compost), and the creation of better and adapted regulation for bioproducts and bioprocesses (OECD Science, T. and I.P.P., 2019).

The identified policy drivers for the development of lignocellulosic biorefineries are to support, both with policies and investments, the supply chains of lignocellulosic biomass as feedstock, thereby increasing the availability and capacity of companies and stakeholders to invest in new bio-based process schemes. Second generation installations using renewable energy where lignocellulosic materials are used to produce other high value-added bioproducts rather than for energy recovery are desirable. Finally, another driver for the development of biorefineries is the support of REACH European regulation, as it stimulates the use of bio-based chemicals that are more sustainable, more environmentally friendly and less harmful, criteria that should be taken into account when developing a biorefinery process approach (European Commission, 2021).

2. Results and discussion: how to implement sustainability on biorefineries

2.1. New targets for helping biorefineries market penetration

The BioPreferred Program aims to promote the purchase and use of bio-based products, based on the premise that this increase should lead to a reduction on fossil-based resources and a reduction in environmental degradation. One of the main objectives of the program is a voluntary labelling that could be used for bio-based products, the so-called USDA Certified Biobased Product Label, which aims to provide the social community with information about the bio-based practices and content of one particular product. The label of the product could inform about the amount of bio-based percentage on the product, on the packaging and/or on both product and packaging materials. This bio-based content of the product is calculated through the following equation:

$$Bio-based\ content = \frac{\sum_{i=1}^{n} M_i \cdot BCC_i \cdot OCC_i}{\sum_{i=1}^{n} M_i \cdot OCC_i} \qquad \text{Eq. 1}$$

where M_i is the mass of the component, BCC_i is the bio-based carbon content of the specific component (%) and OCC_i is the organic C-content of the component (%).

Furthermore, it should be noted that in order to assess the bio-based content all measurements must comply with the requirements of ASTM standard method D6866. On the other hand, the labelling has requirements on the amount of bio-based content depending on the type of commodity and product, e.g., the requirements for diesel additives must contain at least 90%, while only 7% is the minimum requirement for insulating plastic foams used in construction.

On the other hand, since one of the main bottlenecks in the development of biorefineries is the risk associated with economic viability, the determination of a target for product and feedstock premiums could be a solution. The importance of setting a target for product prices is greater in comparison to feedstock prices, as their diversity makes it difficult to establish an overall cost value. Another issue of real concern for the effective development of biorefineries is the uncertainty about the availability of residual streams as feedstocks. In this regard, public policy should encourage R&D tools that estimate with certainty the volume of waste materials expected over a range of time. Therefore, coordination between producers at different stages of the value chain and stakeholders is necessary, avoiding pre-selection and management of useless materials at biorefinery facilities (OECD Science, T. and I.P.P., 2019).

2.2. *Developing indicators for biorefinery assessment*

When developing an indicator to evaluate a production scheme and/or a new technology the most important requirements are the following: a) reliability, as it should provide information based on truthfulness and accuracy; b) feasibility, focused on the accessibility, adequacy and quality of the required data for performing the assessment; c) measurability, which can be quantitative or qualitative, and d) relevance, the value obtained should provide valuable information (Meyer and Priess, 2014).

Sacramento-Rivero (2012) stated that in order to adequately develop indicators, three main criteria should be taken into account: avoidance of overlapping indicators, independence between indicators and that LCA is used as the methodology to assess environmental impacts. Those should be focused on the thematic areas of feedstock adequacy, process performance, capacity for manufacturing products, environmental loads and corporate commitment for sustainability actions. Each of the indicators developed for the thematic areas are normalized according to two main criteria: the ideal value (the best-case scenario according to sustainability approaches) and the critical value (the worst one). On the other hand, it should be noted that even most of the indicators proposed by Sacramento-Rivero (2012) could be evaluated by using the traditional LCA methodology, to evaluate the potential of the assessed production scheme or emerging technology in the forward coming future, a prospective LCA should be proposed, with the objective of be aware of its projection (Sacramento-Rivero, 2012).

When using indicators as a tool to measure or evaluate a scenario, different frames could be selected. For practical implementation, the framework developed by the European Environment Agency on Driving Forces- Pressures- Stages- Impacts- Responses (DPSIR) and the one proposed by the OECD and UN, Pressure-State-Response (PSR), are the most widespread. In the case of the DPSIR, the indicators are developed following the logic that are designated as “driving forces” so that they can produce both beneficial and detrimental impacts to achieve sustainability, leading to on the latter leading to impacts on environmental conditions leading to a response from society and the environment (Niemeijer and de Groot, 2008). This framework embraces the connection between society and environmental issues, which, at the same time, are useful to enable cooperation and collaboration between researchers, stakeholders, community members and policy makers (Meyer and Priess, 2014; Svarstad et al., 2008).

The Ecosystem Services Cascade (ESS) could be used to evaluate and assess the suitability of indicators related to the provision of products and services according to demands and needs (e.g., most-demanded products production capacity and water treatment). It is a conceptual framework that aims to connect how processes and ecosystems have a beneficial impact on society, and vice versa. In order to broaden the scope of the framework to assess all bioprocess production schemes, both quantitatively and qualitatively, the “Common International Classification of ESS-CICES” could be used. Following this scheme, indicators are ranked according to the number of casual linkages between the four ESS components (1. Ecosystem structures and processes, 2. Ecosystem capacity, 3. Human land use activities, 4. Ecosystem services), identifying the one with the best rating as the benchmark. Note that three types of causal links are possible: the positive causal link (increase in ‘x’ leads to an increase in ‘y’), the negative causal link (increase in ‘x’ implies a decrease in ‘y’) and the variable causal link (increase in ‘x’ could lead to an increase/decrease in ‘y’) (Meyer and Priess, 2014).

Another concern for stakeholders and policy makers is how these indicators could be compared and ranked, aiming to establish a scale of relevance and preferences for the selection of indicators for a given sector. In this regard, Sacramento-Rivero (2012) proposed to normalize the indicators according to the following approach: the best value for sustainability development is the ideal sustainability framework (normalized with the value “0″), as this is the maximum value that could theoretically be obtained. In contrast, the critical score is the one representing a “null” sustainable action, which leads the system to collapse (normalized with the value “1″). Accordingly, the degree of sustainability of a biorefinery could be estimated, requiring a not excessive amount of data, which makes the method more suitable for use by stakeholders, investors and policy makers (Sacramento-Rivero, 2012).

2.3. *Standards focused on sustainable practices*

To assess whether the value chain management, process strategies and action plan are sustainable, the use of standardized guidelines is practical and pragmatic. There are several available at global level, focusing on different sectors (i.e., agriculture, forest, fisheries, textile sector, cosmetics, etc.), products and purposes (i.e., product approach, chain of custody, production process, etc.). Its main goal is to ensure the sustainability of production process, some of them are focus only in one pillar of sustainability, i.e., environment, but others compile the criteria required for the three pillars. It is true that, in most cases, these criteria is qualitative, rather than used quantitative values to directly evaluate the sustainability potential or the lack of adequate practices, which could entail certain degree of error for the sustainability assessment (Scarlat et al., 2015). But indeed, those are adequate tools for increasing the community members acceptances of the bio-based products, to remove trade barriers and to increase transparency and reliability. In this regard, the European Commission has developed a standard to set sustainability criteria for bio-based products (EN 16751:2016).

Rationality and harmonization of criteria and indicators should provide a better scenario for the integration of biorefineries into the production sector. In addition, standards should be developed to reduce the barriers that bio-based products face, fostering their potential for market expansion. Furthermore, investments and financial support should prioritize bio-based production schemes over fossil-based ones (OECD Science, T. and I.P.P., 2019). In order to have an international framework on sustainability measurement, different standards need to be developed and adapted in order to provide a coherent and common relationship with the aim of compiling all requirements, both mandatory and recommended, identified in policies and regulations.

Aiming to promote more sustainable actions, certification should be envisioned by companies and stakeholders as a way to gain market share and access, being more competitive with peers and, at the same time, having greater recognition as a sustainable brand by consumers. But in this regard, one of the main problems faced by companies is the cost for its achievement, so government, institutions and policy makers should reduce financial and administrative fees, which reduce the ability of new production schemes to penetrate the market.

But how are these sustainable standards and regulations implemented? The Global Reporting Initiative (GRI) aims to provide information and guidance on the most widely recognized and used sustainability disclosure standard. Its main objective is to allow transparency when it comes to assessing sustainable practices throughout the supply chain. It believes that biorefineries should be approached, developed and assessed according to sustainable and circular approaches. On the other hand, it also advocates that the involvement of auditors, stakeholders, experts and policy makers is necessary to assess the biorefinery commitment with sustainability. Regarding the research reports evaluating the potentiality of biorefineries on the supply chains, Table 4 is depicted, including the sectors applied and the main outcomes achieved by the research reports.

One of the main challenges in developing an accurate and reliable sustainability assessment, is the lack of knowledge on the future implication on economic and societal pillars, especially in the case of social assessment (Silva et al., 2017). This requires the use of tools that attempt to roughly determine future scenarios (in terms of technology evolution, market trends, social demands, production capacity and resource availability).

2.4. Future challenges for biorefineries

When assessing the future of biorefineries, the first thought goes for the feedstock availability, production capacity and economic profitability. But in fact, those are not the only concerns to be overcome, the resources efficiency, the quality of the bioproducts and, for sure, its acceptance by the consumers and community members, is essential to ensure the market penetration and maintenance of biorefineries. In this regard, policies should encourage and promote all these aforementioned issues about bio-based production strategies, and should support and announce the role of biorefinery as key actor on sustainable development is fundamental (Solarte-Toro and Cardona Alzate, 2021).

Other requirements for biorefineries development is its necessity to prove that are profitable and that will conquer a position on the market value chain. In this regard, the risk of investment on new emerging biorefineries should be decreased with the development of policies that supports its establishment and expansion. The degree of policy integration should not only be focus on the market penetration and product enhancement, but also on supporting R&D activities, economic incentives and stakeholders' cooperation. The lack of this instruments entails a lengthy progress on biorefineries facilities, as the scale-up from lab and pilot scale to commercial production needs to be perfectly assessed and effectively proven to be endorsed, and this is somehow difficult given the uncertainties of capacity of market penetration and community acceptance, moreover (Mossberg et al., 2021).

Besides the economic issue, and more focused on the environmental one, according to Meramo-Hurtado et al. (2020), the recommended scheme for future biorefineries should be based on the inclusion of green chemistry principles, process optimization and sustainability principles. It is expected that, following these guidelines, the biorefinery model will maximize profits and minimize environmental impact, considering the selection of the appropriate feedstock and an adequate supply chain. It is also encouraged to assess the interrelationship of the SDGs as production facilities, economic trends and societal development should be focused on meeting the targets set by each SDG.

Some negative issues that have been detected, and needed to be solved, when analyzing the suitability and sustainability of biorefineries are the higher impact on water use and availability, as the use of agricultural and forestry feedstocks entails higher quantities of water needs for irrigation and crop harvesting, in comparison to fossil-based resources (Levidow, 2015). This water demand could be considered as a water stress on this natural resource supply, so an appropriate management of the resources should be encourage in all the levels of the supply chain of biorefineries (Otto et al., 2011). Regarding the impact on soil, some negative issues has also been detected, the fact that residual materials are used as feedstock for bio-facilities (as pruning and collection residues, branches, wood, organic and vegetable waste, etc.) imply that those are not tilled back in the soil, thus reducing the

Table 4
Examples on research reports evaluating the sustainable and circular potentiality of biorefineries in the value chains.

Reference	Sector	Main outcome
Yılmaz Balaman et al. (2018)	Waste-to-energy	Efficient supply chain configuration to integrate energetic recovery of biowaste with an optimization methodology that assesses key aspects on design, planning and manufacturing issues. With the methodology it is possible to identify the optimal biorefinery configuration to ensure its profitability in the vale chain.
Abdul Razik et al. (2019)	Biomass-to-bioproducts	According to the model, applied to a real biomass-based company in Ontario (Canada), the success of bio-based process in the market value chain in directly dependent on the selection of the optimal process stages and products and co-products obtained.
Mehta et al. (2021)	Agriculture	Wastewater coming from agricultural activities could be recovered through circular technologies, promoting the depletion of water resources. The article states that the follow up of the Green Chemistry Principles in the design of wastewater treatment strategies is key for ensuring sustainable and circular managements. Also, process integration and innovation is needed, which entails the evaluation of the scenarios with assessment methodologies as LCA, TEA and circularity principles, thus promoting a "Green circularity".
Khoo et al. (2019)	Bio-chemicals	Integration of LCA, supply chain risks factors and Geographical Information System (GIS) to evaluate the potentiality of the bio-production of bio-based levulinic acid coming from various feedstocks: corn stover and rice straw. The integration of GIS allows to determine the optimal location of the bio-facility in order to increase its potentiality on the supply chain and to reduce the environmental loads derived from transportation activities and emissions. Particularly US, UK, Singapore, India and China have been the locations assessed on the research report, concluding that the biorefineries located in US and UK are the ones with the lowest supply chain risk index.
Moktadir et al. (2022)	Textile	The report analyzed seventeen antecedents about circular bioeconomy practices that were identified to have an effect over the sustainability of the bio-facility on the supply chain. The main antecedents that were categorized as major key aspects to be analyzed and optimized to ensure an optimal and continuous presence of textile bio-industries on the market supply chains were the ones related with facility infrastructure, promotion of more sustainable products than it counterparts and ensure efficient technologies by the establishment of threshold levels.
Morales et al. (2022)	Energy crops	Sugar beet to bioethanol scenarios have been assessed in order to evaluated how non-expected events,

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Table 4 (*continued*)

Reference	Sector	Main outcome
		as COVID-19 pandemic, could affect over the bio-based industrial symbiosis consortium. A base case bioethanol production has been compared to an alternative scenario in which circular economy strategies are implemented (i.e. risk mitigation, re-design, production changeover, integral use of resources, etc.). The methodology for comparison includes the agricultural yield of production, biofertilization requirements, surface variance, bioethanol productivity, biomass-to-alcohol yield and cropping allocation in order to compare the alternatives. The results obtained showed that the implementation of circular economy strategies ensures the viability of the bioethanol production, the survivability of the biorefinery on the value chain and the adequacy of sugar beet as feedstock for bioethanol production even if extraordinary events are occurring.
Palmeros Parada et al. (2017)	All sectors	The appropriate evaluation of a bio-based production process entails the need of performing an accurate sustainability assessment from an early-stage of design, looking to identify the main drawbacks, challenges and bottlenecks that could be faced in the near future and could entail a failure to foster the inclusion of bio-based process in the value chain. The main outcome of this report is that the evaluation of the sustainability and circular potential of a bio-based process scheme should consider environmental, economic and social pillars from a micro to a macro-level, also considering both multi- and trans-disciplinary levels, with the combination of various methodologies and frameworks.
Cardona Alzate et al. (2023)	Food residues	In this research report is being analyzed which aspects are assessed as key for being assessed in order to ensure an efficient and successful implementation of food residues biorefineries in the food value chain. According to the authors, a multifeedstock assessment should be developed, encompassing environmental, socio-economic and technological evaluations, in which the limiting factors of the food value chain should be defined and analyzed in order to reduce its negative effects and to promote the use of food residues as feedstocks.
Santibañez-Aguilar et al. (2015)	All sectors	The introduction of biorefineries on the supply chain should consider three main key aspects to ensure its adequacy: identification of the appropriate facility location, being aware of the availability of the bio-based feedstocks and promotion of sustainable development through the evaluation of environmental, social and economic issues to enhance the position of biorefineries over the traditional production schemes. In this regard, the as multiple objectives are needed to be achieved, the authors have considered that the development of a mathematical modelling and programming is a necessary tool to achieve an optimal solution for biorefinery development. The main strategy on the mathematical model constructed is the provision of the process parameters that gives the highest net profit, the lowest environmental loads and enhanced social benefits. Besides, while applied, the authors have concluded that the three key areas (environment, economics and society) have a strong impact over the success of bio-based facilities on the value chains.

maintenance of soil health (nutrient composition, chemical and physical properties) and the avoidance of erosion (Smolker et al., 2008).

On the other hand, although this aspect is beyond the scope of this research report, when optimizing or selecting the most beneficial alternative scenario for the development of a biorefinery scheme, the use of machine learning (ML), artificial intelligence (AI) or computer programming platforms could be useful. In this way, it would be possible to evaluate which are the best alternatives to consider from the point of view of process optimization (Meramo-Hurtado et al., 2020).

Another concept that is on the rise is industrial symbiosis, which is based on promoting the circularity of production with a vision of integration of flows between different facilities located in a nearby environment. What is waste from one process is transformed into raw material for another. This is the reason why a synergy between industrial symbiosis and circular bioeconomy would promote a higher degree of development of new biorefinery process schemes and an efficient use of resources (Bijon et al., 2022). In this context, the Bio-based Industries Initiative (BBI) has been developed which includes a series of value chains that should be analyzed in the framework of achieving lower waste production and greater use of resources (OECD Science, T. and I.P. P., 2019).

In order to exemplify the need of implement new sustainable production trends within the biorefinery approach, some research articles on this topic are included and analyzed on Table 5.

As can be seen in Table 5**, several research reports have focused on the evaluation of biorefineries using various methodologies, from the use of LCA or TEA, which has already been mentioned above, to others not as common but as significant for evaluating the potential of biorefineries, such as energy analysis, exergetic evaluation and their combination with environmental and economic evaluations. The justification for their importance in the evaluation of new bioprocesses lies in the current need to build new, more energy-efficient production models, given the detrimental effects that energy consumption has on environmental and economic indicators. The performance of energy and exergy analyses, through the evaluation of process flows under a thermodynamic perspective, is crucial to assess the degree of efficiency in the use of energy. To this end, future research should focus on the integration of sustainability, circularity and energy/exergy assessment to provide an in-depth analysis on the efficiency of a bio-based process scheme**.

2.5. *Next steps: encompassing sustainability with circularity criteria*

The transition to circularity is necessary on the path to resource preservation, waste management and carbon flows, but the declaration of the circularity of a product or technology is not as developed as sustainability certification and monitoring systems. Still, efforts are being made to find new guidelines, standards and product declarations that take into account circularity criteria, which would encourage

Table 5
Some recent articles on which sustainability of biorefineries schemes is evaluated.

Sector	Type of analysis	Indicators	Main results	Reference
Pulp and paper industry	Three-phase Delphi study with a SWOT-Analytic Hierarchy Process	Drivers and barriers factors of the biorefinery	Weakness observed: high investment, limited technology, and difficulties to ensure its potentiality. Strengths detected: high efficiency in resource recovery, increased competitiveness and policy support	(Brunnhofer et al., 2020)
Forest	Bioeconomy business models	Questionnaire to experts considering company's background, business model, value creation and value capture achieving quantitative and qualitative indicators	The circular economy model is still weak for implementation, low expected profitability, increased social and environmental benefits, business models still focused on traditional sustainability approaches	D`Amato et al. (2020)
Global: biorefineries design	Sustainability metrics for biorefinery design	LCA indicators, TEA scores, social indicators and multidimensional factors	Detected subjectivity on the assessments, lack of appropriate social evaluation, identification of the appropriate boundaries to perform the analysis	Palmeros Parada et al. (2017)
Global: bio-based supply chains	Descriptive and content analysis	Supply chain strategic planning, bottlenecks parameters, social indicators, feedstock selection criteria	Encourage the development of socio-technical-ecological studies based on the evaluation of the bio-resource selection as feedstock, the circularity opportunities and the waste hierarchy	(Cerca et al., 2022)
Waste biorefineries	LCA	Feedstock, technologies, products and applications comparison and scores under a LCA perspective	The maximization of energy efficiency, advocating for waste recycling and for the recovery of resources are the most important issues when assessing biorefineries	(Liu et al., 2021)
Bioethanol production	Multi-criteria assessment	Quantitative and qualitative social, environmental, economic and safety indicators	The selection of the appropriate biorefinery production route should be based on a depth multicriteria analysis to select the most attractive option from the three pillars of sustainability	(Posada et al., 2013)
Forest	Thematic analysis method with interviews to representatives of the sector	Qualitative indicators	Achieving environmental sustainability is an important driver to the business models of forestry sector, the lack of systematic approaches to adequately evaluate the sustainable potential of biorefineries is a clear bottleneck, definition of high and low impact criteria for defining a preliminary environmental assessment.	(Näyhä and Horn, 2012)
Bio-chemicals	Exergetic, techno-economic and sensitivity assessments	Quantitative indicators based on economic features: minimum selling price, return on investment, production capacity, raw material cost and energy flows	The performance of sensitivity analysis at an early stage of development of a biorefinery approach is essential to select the most adequate production scheme, type of feedstock used and technology	(Meramo-Hurtado et al., 2020)
Global: biorefineries evaluation	Integrated life cycle sustainability assessment (LCSA)	Environmental quantitative indicators through LCA, economic scores obtained with life cycle costing analysis (LCC) and social aspects through S-LCA (social-LCA)	The development of integrated LCSA provides a ex-ante decision making framework that enables to identify the main bottlenecks to be faced, the main barriers that could be encountered and a benchmarking on the opportunities of the biorefinery process under assessment	(Keller et al., 2015)
Lignocellulosic biorefinery	Multi-criteria analysis	Techno-economic scores and sustainability indicators based on health index, risks, feedstock availability, market size, environmental safety and economic constraints	The assessment of a systematic methodology for the evaluation of the adequacy of a lignocellulosic biorefinery is useful to identify the upgrade of the process scheme through the maximization of the profits, the reduction on environmental and the detection of the risk and uncertainties for a long-term production horizon	(Cheali et al., 2015)
Bio-chemicals	Environmental and social assessments	Identification of the required product category rules for the environmental indicators, considering various impact assessment methods. Use of the Social Hotspots Database for the selection of the social indicators	Lack of establishment and identification of the appropriate indicators to evaluate the biorefineries for the production of bio-chemicals in a deep approach, being more important this lack of for the social assessment. Further development of the indicators and methodologies is required for the assessment of biorefinery process schemes through a more appropriate analysis.	(Valente et al., 2018)
Lignocellulosic wood residues	Integrated techno-economic assessment (TEA)	Cumulative discounted revenues, operational costs, net present value, capacity levels, Monte-Carlo sensitivity evaluation, estimation of end-product prices and discounted rates	The availability of the wood residues together with the location for the implementation of the biorefinery has been identified as the main bottlenecks of the biorefinery, but the authors concluded that the use of wood as feedstock is promising but for being profitable those aspects should be analyzed carefully.	(Tschulkow et al., 2020)
Lignocellulosic wood residues	TEA	Production rates, energy consumption, operation and capital costs and return on investment.	The results obtained showed that an increase on the production capacity has a positive effect over the economic profitability and technology potential. However, this effectiveness could be affected by the feedstock supply and the	Giwa et al. (2023)

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Table 5 (*continued*)

Sector	Type of analysis	Indicators	Main results	Reference
			transportation distance, so those aspects should be analyzed through sensitivity assessment to ensure that they do not affect badly to the biorefinery potentiality.	
Food waste	TEA	Mass and energy balances, operational costs, capital expenditures and expected incomes.	The factors that affect the most over the economic profitability of the biorefinery are the minimum selling price of the products, in this case polyphenols and energy, together with the production capacity.	Orive et al. (2021)
Lignocellulosic	Energetic analysis combined with LCA and TEA	Energy requirements evaluated through: fraction of energy consumed and GHG emissions per MJ of energy needed	The authors concluded that the production capacity of the biorefinery, which is in line with the amount of feedstock processed, is a key aspect for a positivity energetic analysis as the most favorable scenario is the one for small biorefineries, given the fact the energy required for transportation is reduced and because of the reduction on the equipment sizes of the facility.	Geissler and Maravelias (2021)
Agricultural	Exergy analysis	Chemical and physical exergy rate, exergy efficiencies and exergy destruction rates.	The exergy analysis of the cascade production of lactic acid, electricity and steam has been assessed in this research report, concluding that the production of steam is the one that implies the higher exergy destruction, that could be reduced by designing a heat exchanger network On the other hand, the higher exergy efficiency is obtained for the feedstock pretreatment unit.	Aghbashlo et al. (2018)
Macroalgae	Exergy analysis	Evaluation of the thermodynamic properties of the process streams.	The assessment of three alternative valorization scenarios has been assessed: I. Without algae pretreatment, II. With algae pretreatment and III. With electricity production. The results showed that the pretreatment unit provides benefits for both energy requirements and production efficiency, as lower amount of feedstock is required per product obtained, while opting for energy production entails the most promising alternative, as the with it the biorefinery is self-electricity-sufficient.	Chung et al. (2022)
Agricultural	Energy, economic and environmental assessment	LCA scores, under a cradle-to-gate approach, energy performance using the 1st law indicators and economic feasibility with investment indexes	Palm and sugarcane residues have been used as feedstock for the production of biodiesel and bioethanol, respectively. Two scenarios are compared, one considering the use of each feedstock separately, and the other by performing an integrated biorefinery in which a simultaneous culture of both feedstocks is developed. This last scenario is the one showing the best results, given the increased efficiency, by a 3.82%, and the excess on electricity production, amounting to 106.32 kWh/ton feedstock, thus being more environmental sustainable and more energetically efficient.	Ocampo Batlle et al. (2021)
Agricultural	Exergoeconomic and environmental evaluation	Exergy destruction, exergetic efficiency, cost of production, monetary costs and global warming potential	Palm oil has been used as feedstock for producing bio-jet fuel by. The results obtained showed that a high energy demand is required for the biorefinery, which implies high production costs, and thus reduced expected revenues and increased minimum selling prices of the bio-jet-fuel, significantly higher to the ones on the market. Given the outcomes obtained, the authors have concluded that it is better to assess the production of jet bio-fuels using alternative vegetables oils rather than palm oil.	Julio et al. (2021)
Agricultural and livestock	Environmental and exergetic sustainability assessment	Total cumulative exergy loss (TCExL)	The indicator TCExL encompasses the depletion and scarcity of resources with the cumulative exergy loss characteristic of the biorefinery process, based in this case on comparing power generation using various feedstock: verge grass and pig manure. The results obtained showed that the anaerobic digestion of manure has the lowest exergetic sustainability potential, while bioethanol production by using verge grass is the most promising scenario.	Stougie et al. (2018)
Food and agriculture	Energy, exergy and economic analysis	Exergy efficiencies and irreversibilities, operation costs and expected revenues	Two recovery alternatives are evaluated for the energy recovery of vinasse: incineration and anaerobic digestion. Regarding the energy and exergy analysis, the results showed that the anaerobic digestion provides the highest	Palacios-Bereche et al. (2020)

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Table 5 (*continued*)

Sector	Type of analysis	Indicators	Main results	Reference
			electricity production capacity and exergy efficiency, 11% higher in comparison to incineration process. On the other hand, regarding the economic evaluation, anaerobic digestion is the scenario with the higher capital costs but also with the higher revenues, being economically feasible.	

entrepreneurs and stakeholders to engage more intensively in the transition from linear to circular production.

In this approach, the European Environment Agency (EEA) and the Italian Institute for Environmental Protection and Research (ISPRA) developed the “Bellagio Declaration”, under the guidelines of the Environmental Protection Agency network. In this declaration, seven principles were developed that are considered key to developing a circularity monitoring system. Firstly, all stages of the production process, from the extraction of raw materials to end-of-life, should be monitored, also assessing how the transition to circular production affects the three pillars of sustainability. Moreover, it includes the statement based on the encouragement of the exploitation of databases that contribute to a more generic monitoring framework, as well as policies and regulations related to the circular economy. Once the system has been monitored, sufficient data will be available to be able to define a set of circularity indicators. These indicators should at least cover material and waste flows, carbon footprint, economic and social impacts, as well as effects on key policies and sectors.

Furthermore, the choice of these criteria should be based on the RACER (Relevant-Accepted-Credible-Easy to monitor-Robust) criterion. Once the indicators have been defined, the remaining principles concern their applicability and validity, and they should be useable to ensure monitoring at various levels of the economy (i.e. public and private sector, at the governance level or at different scales (national, regional, local), at the meso, micro and macro level, etc.) to focus on the goals and objectives set by policies, and be used in a transparent way.

3. Conclusions

This manuscript allows to deepen the knowledge of the methodologies available to assess the potential of biorefineries under a sustainable and circular perspective, both in current and future scenarios. It has also provided a discussion and analysis of the available certification programs, to improve the potentiality of biorefineries through official recognitions, policy implications, which should be based on the improvement of supply chains in terms of sustainability and circular actions, and also how sustainable, circular and policy actions should be aligned to build more attractive value chains for the integration of biorefinery models. In this sense, this report shows a monitoring of the current status of biorefineries and their future trends, and how they should be evaluated, from an early design stage to a more developed one, in order to promote their sustainability, circularity and techno-economic potential. On the other hand, it also provides guidance for the development of future strategies, policies and guidelines for the proper evaluation of biorefineries. The main result that can be drawn from the development of this research report is that the adequacy of a biorefinery model should be assessed as comprehensively as possible, considering the use of different methodologies that refer to sustainability, circularity, economic viability and energy efficiency, key aspects in the development of process models that comply with the SDGs. On the other hand, the support of governments, institutions, policies and action plans is essential, as well as orienting the market value chain towards a position that offers a greater opportunity for bio-based production processes.

CRediT authorship contribution statement

Ana Arias: Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Gumersindo Feijoo:** Methodology, Investigation, Supervision. **María Teresa Moreira:** Conceptualization, Validation, Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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