Advancing waste valorization and end-of-life strategies in the bioeconomy through multi-criteria approaches and the safe and sustainable by design framework

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Advancing waste valorization and end-of-life strategies in the bioeconomy through multi-criteria approaches and the safe and sustainable by design framework

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ABSTRACT

Proper waste management is a key element in the transition to a sustainable bioeconomy. Population growth and the demand for food and services have led to an ever-increasing production of biotic waste whose disposal in landfills is no longer considered a sustainable option. For this reason, efforts are being made to find an appropriate management strategy for biotic waste, whose organic content allows it to be considered as a resource for the development of biotechnological and/or biorefinery processes. Assessing the sustainability of alternative options is of paramount importance. To this end, this systematic review researches trends in waste management in terms of technology and sustainability profile according to the life-cycle approach and multi-criteria analysis. The aim is to provide insights into potential resource recovery and waste valorization schemes towards high-value-added products in the marketplace, beyond their direct energy recovery. Our results show that future studies should focus on the development of multi-criteria analysis from an SSbD perspective, so that all pillars of sustainability and risk assessment are properly assessed from an early design stage.

1. Introduction

The impact of industrial and human activities on the quality of the environment, the depletion of fossil resources, the demand for more equitable jobs and the interest in healthy and environmentally friendly products by consumers are elements under the spotlight [1–3]. There is a growing awareness of the need for change, in which the transition of the productive model towards a more responsible and cleaner one is required. This is why new initiatives have been launched to drive this transition, such as the EU Green Deal and the Action Plan for the Circular Economy, among others. In this context, the bioeconomy approach appears as an effective and efficient framework to move further towards a greener and a sustainable transition [4,5].

The bio-based economy is considered necessary to address and solve current global challenges, which encompass food security, efficient use of natural resources, maintenance of ecological limits, economic development and social welfare [6,7]. In this complex panorama, one of the key drivers for this transition is the transformation and adaptation of sustainable food-related value chains [8,9].

The EU Council discussed the challenges of increasing sustainable agricultural production, working on closing nutrient cycles and boosting research and innovation to increase the competitiveness of bio-based products. For this, it is necessary to foster symbiosis between all stakeholders involved in the value chain in order to develop new opportunities to reduce waste, improve the efficient use of resources and increase the sustainability of the food-related sector [10,11].

It is in this context that this systematic review is framed, as it delves into an analysis of biotic waste management and valorization technologies of residual streams related to the agriculture, forestry, and food sector. This systematic review provides an overview of the technologies that have been most extensively assessed and includes the identification of the sustainable and multi-criteria assessments available in the literature to quantify the efficiency and effectiveness of waste management strategies to drive change and resilience. With respect to the sustainability assessment, the articles considered are the ones following the Life Cycle thinking approach, which is a standardized method developed on the international guideline ISO 14040 [12], considering the analysis of all the pillars: environmental [13], economic[14] and social [15,16]. On

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the other hand, also the scope and applicability of the Safe-and-Sustainable by Design (SSbD) framework for a European bioeconomy has also been included. The SSbD is, by nature, a multidimensional framework that encompasses the analysis of health, safety, environment, economics and risk of the target processes. The SSbD framework is a voluntary framework that aims to enhance green and sustainable industrial processing, looking to avoid the use of chemicals and compounds that could entail a hazard on the health and/or on the environment. The assessment under this framework requires the development of five main stages: three concerting the safety dimension (hazard assessment, human health & safety aspects, human health & environmental aspects), environmental dimension (environmental sustainability assessment following the LCA methodology) and social and economic dimension (including the sustainable analysis of those areas of concern) [17].

This systematic review provides information and practical lessons on the technological strategies to enhance and improve the recovery and valorization of residual streams coming from the bioeconomy sectors. It also identifies the bio-products that have been the core of the research analysis in the literature, as well as it develops an analysis on the methodological assessments that have been used to evaluate these valorization processes under a sustainable perspective. This review could be a guidance for the development of future research, technological strategies and actions towards residues valorization. willing to promote a more sustainable, circular and resilient bio-based sector. Furthermore, through the analysis of sustainability-related methodologies, it is expected that the results of the review will bridge the gap between theoretical and practical strategies in the pursuit of successful EoL strategies.

The main novelty of this review is (1) the provision of an integrated assessment: this review is based on the combination of life cycle assessments, economic evaluation, social analysis and circularity approaches, providing a multicriteria and comprehensive analysis of waste valorization strategies. This combined approach provides a nuance deep analysis of the environmental and economic constraints and challenges to waste-to-resources processes, which has not been deeply analyzed in the literature, (2) the systematic analysis developed highlights the previously explored, and unexplored, trade-offs and synergies about waste valorization technologies and assessment trends, which is considered as a crucial analysis for guiding future research on circular and sustainable waste management, (3) the triple analysis between life cycle perspectives, SSbD and technologies offers a global overview and a forward-looking perspective on how the technologies should be further improved or implemented to achieve a more sustainable and circular bioeconomy, and (4) this review discuss, in a very first time, about the integration of SSbD framework on the waste-to-resource valorization technologies and assessments, and this approach is considered as an strategic decision-making in the production sector, currently under development by the European Commission. It has been discussed about how SSbD could be applied, and which challenges and needs are required to enhance its use and to provide a more holistic and comprehensive analysis concerning safety, sustainability and circularity as a whole from early-stages of design. All these aspects could contribute significantly to both academic literature and practical applications in sustainable waste management technologies, fostering a sustainable and efficient bioeconomy.

2. Methodology

In order to assess the waste management and EoL valorization strategies related to the bioeconomy sector, a systematic review on the articles available on the literature that have analyzed this area of research has been developed. According to Grant and Booth[18], this review could be catalogued as systematic as it seeks to select the most relevant research articles on the field in a narrative manner, including also a thorough analysis and discussion on what has been found on the literature, together with a description of the current gaps and future challenges and recommendations.

The aim is to be able to answer the following research questions (RQ) related to the technological development on waste valorization strategies, as well as the analysis of those technologies under a sustainable and/or circular approach, under a life cycle and SSbD frameworks.

- RQ1 What are the most recurrent waste management and EoL valorization technologies that have been analyzed in the last 10 years?
- RQ2 Do the articles available for RQ1 include an environmental sustainability assessment? Do they follow an LCA perspective? Which functional unit and methodology were considered for the assessment? Which environmental impacts were assessed?
- RQ3 Do the articles available for RQ1 include an economic sustainability or techno-economic assessment? Is the valorization strategy economically viable?
- RQ4 Do the articles available for RQ1 include a social sustainability assessment? What methodology is used? How many indicators are provided?
- RQ5 Do the articles available for RQ1 include a circularity assessment? How many indicators are provided? Does the valorization strategy follow a circular economy approach?

To find an answer to the above research questions, PRISMA guidelines, providing an adequate procedure to identify, select and analyze studies, and the SCOPUS database have been used, and considered the combination of the following keywords: **RQ1** *"waste valorization AND technologies AND food OR agriculture OR forestry"* [time frame 2014–2024], **RQ2** *"RQ1 keywords AND life cycle assessment OR LCA"* [time frame 2014–2024], **RQ3** *"RQ1 keywords AND life cycle cost OR LCC OR techno-economic assessment OR TEA* [time frame 2014–2024], **RQ4** *"RQ1 keywords AND social assessment OR analysis"* [time frame 2014–2024], **RQ5** *"RQ1 keywords AND circularity"* [time frame 2014–2024].

The following exclusion criteria were considered: (1) review articles or conference/symposium proceedings or book chapters are not included, only research articles, (2) the articles must be written in English, (3) the articles must be available in Open Access and (4) articles and papers should be in the scope of the topic of analysis. After the application of these exclusion criteria, 206 studies were considered suitable for review.

The PRISMA flowchart, that provides information about the different phases considered for the development of this systematic review, including the maping of the number of records identified and included on each phase, is shown in Fig. 1, ending up with the final research articles selected for analysis.

3. Results

This section is divided into a first analysis of the most relevant valorization strategies in the literature, from a technological point of view (Section 3.1.1), to continue with the evaluation of the waste streams that have been most studied from the perspective of their valorization (Section 3.1.2). In addition to the technological aspect and the typology of wastes used as raw material for the development of biorefinery models, the type of bioproducts obtained from these valorization schemes has also been evaluated (Section 3.1.3), as well as the combination of all these aspects, i.e. the correlation between technology-waste-product (Section 3.1.4). On the other hand, in the pursuit for the transition to the bioeconomy, it is not only important to develop more circular production models, but also to advocate for the more sustainable ones. The fact that a process is bio-based does not mean that it is more sustainable than its chemical counterpart, which is why the use of assessment methodologies is essential. In this regard, Section 3.2 includes an analysis of the research articles that have considered an evaluation using a life cycle approach, both from an

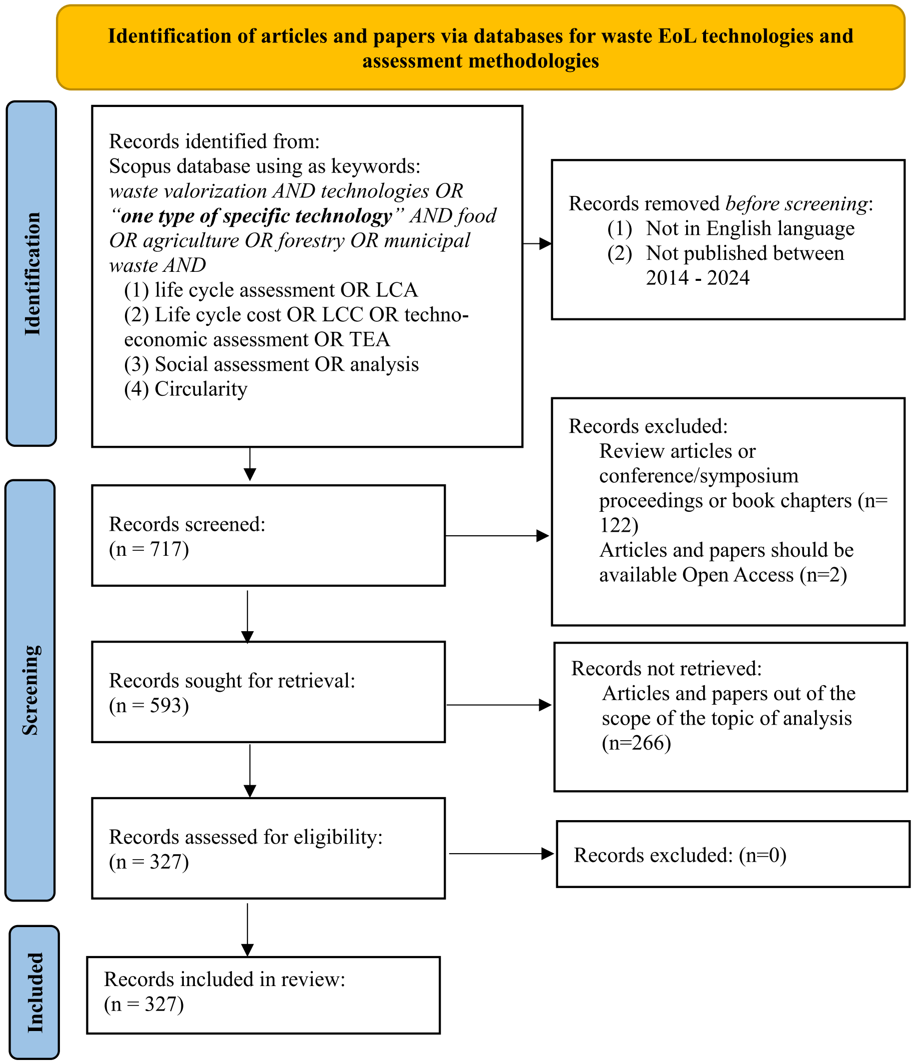

Fig. 1. Methodological approach for the selection of articles to be further analyzed considering PRISMA guidelines.

environmental and economic point of view (Section 3.2.1), as well as from a social perspective (Section 3.2.2), which are the three pillars of sustainability. In addition, it has been appreciated that other authors have considered to evaluate biorefinery models from a multi-criteria perspective, which is discussed in Section 3.2.3. Finally, the link between biorefineries and the SSbD framework is argued
in Section 3.4.

3.1. State-of-the-art on waste-based biorefinery models

3.1.1. Most relevant valorization strategies

Once the evaluation of the 327 research manuscripts was completed, it has been proceeded with classifying the reviewed articles according to the type of technology used for the valorization of waste from the industrial, food, agricultural, domestic and municipal sectors.

As can be seen in Fig. 2, there are a large number of waste valorization technologies, as well as combinations between them, although the ones that stand out are technologies based on heat recovery, that indeed are valorization strategies but on a lower level of interest, as the calorific value of the waste streams is the target value, and anaerobic digestion for the production of biogas, as well as liquid and solid digestates, which can be used as biofertilizers.

In the case of the biotechnological treatment, fermentation is widely studied, given the possibility of the valorization of the fermentable sugars for the formulation of culture media for diverse microbial strains.

The recovery of high-value compounds from waste is also a focus of research, using a variety of extraction and separation techniques. Solvent extraction is one of the most traditional methods to recover valuable compounds from waste although the consumption of large quantities of chemical solvents is an issue to take into account. For this reason, the use of less chemical-intensive extraction technologies has been investigated in recent years, although their large-scale application is still under development. Among these, ultrasound-assisted extraction is based on the disruption of cell walls by the application of high-frequency sound waves, thus increasing the surface area available for extraction. Extraction yields are usually higher and extraction times shorter compared to solvent extraction, which as shown in Fig. 3. Moreover, it requires virtually no chemical solvents for the process and requires mild operating conditions, which avoids degradation of the compounds due to high temperature. In addition to ultrasound, microwave and supercritical fluid extraction technologies stand out. This technology implies the use of microwave energy to heat the extraction solvent in contact with the solid matrix, making it a less useful technology for heat-sensitive bioactive compounds. Regarding the use of supercritical fluid extraction, the use of carbon dioxide is the most widely used, usually in combination with ethanol to improve the yield of the process. The use of supercritical fluid extraction relies on the use of CO_2 in combination with ethanol under high-pressure conditions. It is characterized by high selectivity, efficiency and short extraction time, and is usually coupled with a condenser to recover 100 % of the

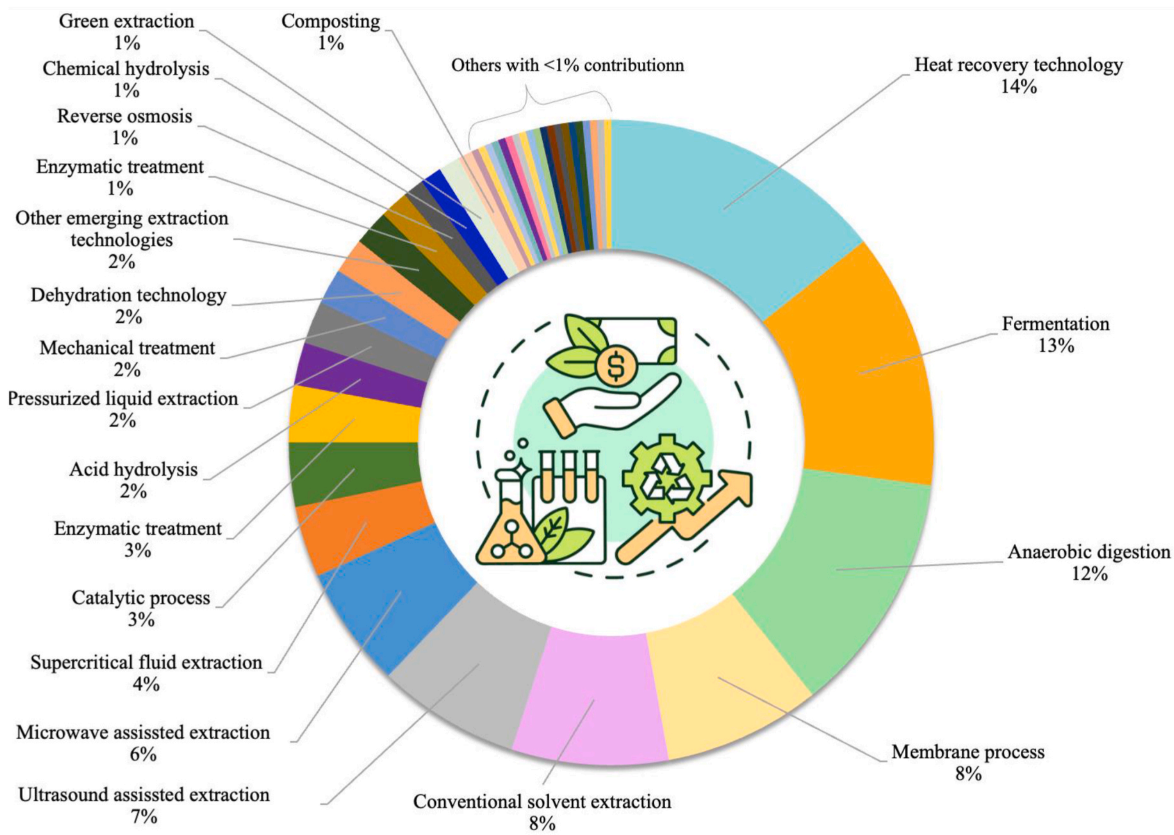

Fig. 2. Most relevant technologies used for waste valorization found on research articles from 2014 until 2024.

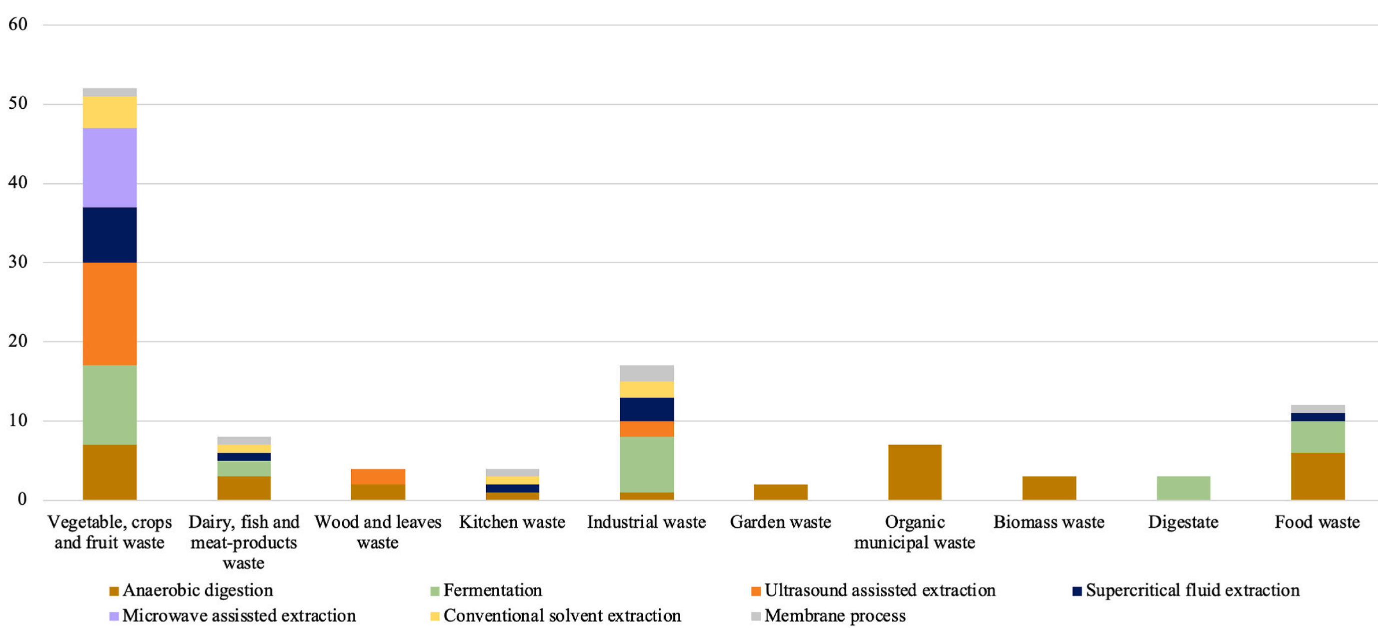

Fig. 3. Analogy between type of waste and type of technology used for waste valorization strategy.

supercritical fluid and solvent used for extraction.

Another technology that also stands out is the use of membranes, mainly nanofiltration, ultrafiltration and reverse osmosis, to recover and concentrate nutrients, bioactive compounds and other inorganic and organic products. It is mostly used in combination with other valorization technologies. The exclusive use of membrane technologies for waste valorization could pose several problems, from high energy consumption, leading to high environmental burdens and associated production costs, to fouling of membranes or reduced selectivity, among others, so coupling with other technologies is considered the best alternative.

3.1.2. Most relevant waste streams to be valorized

In addition to assessing and categorizing the type of technology used for waste recovery, it could also be classified regarding the type of waste valorized in the assessed literature, which include vegetable, fruit and crop waste. In this case, the technologies that have been most extensively studied in the literature have been selected, as can be seen in Fig. 3. As for the type of technology that stands out most in their valorization, it is extraction, specifically ultrasound-assisted extraction, followed by microwave-assisted extraction, although fermentation also plays an important role.

In addition to agricultural residues, there are also industrial residues associated with the agri-food sector, as for example olive mill waste [19,20], or fruit industrial processing waste [21–23], and food waste from household [24]. For both of these, the extraction technology is no longer a priority, since their content of bioactive compounds is not as high compared to those present in vegetable, crop and fruit residues. The use of agro-food waste as a carbon source for fermentative processes is the most studied option in the literature, without ruling out recovery through anaerobic digestion, especially for domestic waste [25–28].

Finally, for garden waste, organic municipal waste and general biomass waste, anaerobic digestion is the outstanding valorization strategy that has been evaluated in the literature [29–32], while for dairy, fish and meat waste or kitchen waste, i.e. oils, anaerobic digestion processes [33,34], membrane processes[35] and supercritical fluid extraction [36] have also been considered.

3.1.3. Most relevant bio-products valorized

Considering the type of product, three stand out by far, with the extraction of bioactive compounds being the most prominent, specifically by means of ultrasound-assisted extraction technology, with a significant share of microwave-assisted extraction and conventional solvent extraction. Bioactive compounds include antioxidants, peptides, proteins, carotenoids, linolenic acid, omega 3, among others (see Fig. 4).

Products related to bioenergy and biofuel are obtained through anaerobic digestion and fermentation technology. The anaerobic digestion process results in the production of biogas, which can be converted into thermal energy and electricity through a coupled cogeneration system. This has been the approach analyzed by [37], based on the valorization of the bio-waste fraction of the municipal solid waste of Madeira and Porto Santo Island through anaerobic digestion coupled with a combined heat and power system, achieving conversion values that amounts to the production of 7.54 GWh of electricity and 12.14 GWh of heat by valorizing 64 ktons of biowaste. The use of biowaste has also been studied by Gross et al. [38], concretely the biowaste fraction of Indian municipalities, but also in combination with manure and crop residues, and concluded that its energy valorization with anaerobic digestion could be able to substitute around 60 % of the total energy used in households of villages, and around 10 % in chase of households in cities, which could help on achieving more circular towns and cities [38]. Besides, it has also been evaluated the option of having centralized or decentralized anaerobic digestion systems for the valorization of organic waste, as analyzed by [39], as the location of the facility could have a significant effect on the advantage of using the electricity and heat produced in the surrounding communities. The analysis done, considering various scenarios, highlighted the environmental benefits of using anaerobic digestion technologies rather than incineration of the organic waste, as well as those decentralized facilities, focused on biogas production, are the ones saving higher quantity of GHG emissions and energy, thus being more sustainable. On the other hand, even though agricultural and municipal waste are the residual raw materials preferred to develop anaerobic digestion, also dairy waste has been studied as a possible material for energy recovery. The assessment has shown that by the valorization of 1 L of dairy manure per day with an anaerobic digestion system combined with hydrothermal liquefaction unit, it is possible to get 1.03 kWh of electricity, 275 L of biocrude and 198 kg of hydrochar, thus being a cascade process with high added value compounds obtained [40].

On the other hand, the fermentation process is commonly used to produce biofuels such as bioethanol or biohydrogen, which requires dark fermentation. The production of bioethanol has been articleed by, for example [41], using mango and orange peel wastes fermented by a mixed culture of various bacteria strains (*Enterobacter cloacae,*

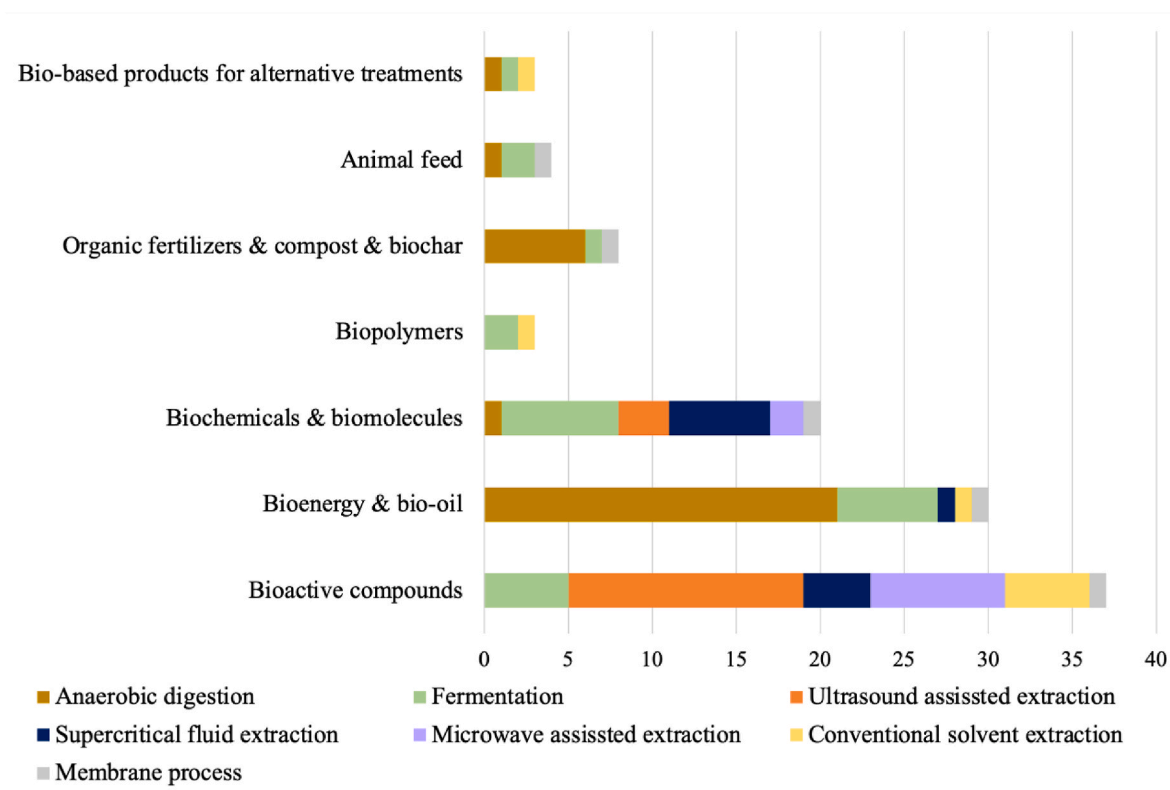

Fig. 4. Analogy between type of bio-product and type of technology used for its production.

Pseudomonas aeruginosa and Bacillus cereus), and providing a yield on bioethanol production that amounts to 32 % after 72 h of batch fermentation process. It has also been articleed the use of the digestate coming from the anaerobic digestion process, in order to achieve a more circular energy recovery strategy, achieving a bioethanol yield that amounts to 37 g/kg of total solid content on the digestate, and thus providing an extra electricity production of 8483 kWh per day [42].

Biochemicals and biomolecules also have an important weight in the literature, obtained mainly by fermentation processes, but also by extraction processes, with supercritical fluid extraction standing out, followed by ultrasound-assisted extraction. Some of the products included in this category are lactic acid (obtained by the fermentation of mixed bakery waste [43], fruit waste [44], potato waste [45] and/or food waste [46]) ferulic acid (produced by an enzymatic extraction process using as raw material industrial residues as brewers spent grains [47]), xylooligosaccharides (mainly using agrowaste and considering enzymatic conversion or hydrothermal treatment for its production [48, 49]), or enzymes such as alpha amylase, produced by the fermentation of rice by-products [50], or β-1,4-endoxylanase, obtained by the enzymatic hydrolysis of wheat straw [51].

In the context of anaerobic digestion, it is very common to use digestate to produce organic fertilizers or biochar [52], as its high organic content makes it an ideal composition to improve the quality and nutrient balance of agricultural soils. Other less relevant products in the literature are animal feed [53], given their low economic benefit compared to bioactive compounds, and also biological products used for other treatments, such as use in bioremediation, as adsorbents [54] or for vermicomposting [55], and those were considered as "bio-based products for alternative treatments".

3.1.4. *Correlation between technologies, waste streams and bio-products*

The relationship between the type of technologies most prominent in the literature, the type of waste used as a resource to be valorized and the category of bioproduct obtained is presented in Table 1. It is worth mentioning that, although a trend has been observed between the type of waste stream and the technology used for its valorization, our assessment shows that several studies have chosen to analyze different typologies of technologies in order to assess which of them is more suitable for the biorefinery or biotechnology model. For example, studies tend to associate the anaerobic digestion technology with municipal and agricultural waste, mainly for obtaining bioenergy and bio-oil, although there is also a strong tendency to valorize the digestate obtained for the production of organic fertilizers and biochar.

In the case of extraction technologies, whether conventional, ultrasonic, supercritical fluid or microwave, there is a clear trend towards the use of agricultural waste. Regarding the type of product, it is also clear that the main objective of valorization is to obtain bioactive and biochemical compounds or biomolecules.

As for fermentation, there is no clear focus on the type of waste used, although industrial and agricultural waste have been studied to a greater extent, but on the type of bioproducts obtained: bioenergy and bio-oil, as well as biomolecules and biochemicals. As for membrane technology, it is undoubtedly the one in which the development of a smaller number of valorization strategies has been considered, and a great variety of target bioproducts has been observed. The main reason for this result may be due to the fact that this technology is usually coupled with other waste valorization techniques, whereby its main consideration is to increase the purity of the value-added bioproducts and thus improve their quality.

3.2. *Biorefineries assessed under a life-cycle approach*

3.2.1. *Life cycle assessments of valorization of biotic waste with biorefineries*

Some of the studies evaluated include a combination of Life Cycle Assessment (LCA) and economic analysis, using different methodologies

Table 1
Relation between type of technology, type of waste to be valorized and type of bio-product obtained.

Technology	Residue	BP1[a]	BP2[a]	BP3[a]	BP4[a]	BP5[a]	BP6[a]	BP7[a]
Anaerobic digestion	Biomass waste	1				1		1
	Dairy, fish and meat-products waste	3				1		
	Food waste	3					1	
	Garden waste	2						
	Industrial waste	1						
	Kitchen waste	1						
	Organic municipal waste	6	1			3		
	Vegetable, crops and fruit waste	7				1		
	Wood and leaves waste	1				1		
Conventional solvent extraction	Dairy, fish and meat-products waste							1
	Industrial waste				1			
	Kitchen waste				1			
	Vegetable, crops and fruit waste	1		1	3			
Fermentation	Dairy, fish and meat-products waste				2		1	
	Digestate	1	2					
	Food waste		1	1				1
	Industrial waste	2	5		1			
	Vegetable, crops and fruit waste	5	1	1	3	1	1	
Membrane process	Dairy, fish and meat-products waste					1	1	
	Industrial waste		1		1			
	Kitchen waste		1					
	Vegetable, crops and fruit waste	1						
Microwave assisted extraction	Vegetable, crops and fruit waste		2		8			
Supercritical fluid extraction	Dairy, fish and meat-products waste		1					
	Food waste		1					
	Industrial waste		2		1			
	Kitchen waste		1					
	Vegetable, crops and fruit waste	1	3		3			
Ultrasound assisted extraction	Industrial waste				2			
	Vegetable, crops and fruit waste		3		10			
	Wood and leaves waste				2			

[a] Acronyms: BP1: Bioenergy & bio-oil, BP2: Biochemicals & biomolecules, BP3: Biopolymers, BP4: Bioactive compounds, BP5: Organic fertilizers & compost & biochar, BP6: Animal feed and BP7: Bio-based products for alternative treatments.

(i.e. Life Cycle Cost (LCC), Techno-economic assessment (TEA), cost and benefit analysis (CBA), etc.), while others are more focused on a single pillar of sustainability, environmental or economic, rather than performing a combination between those. Given this, for all the life cycle-based found in literature covering environmental and economic aspects, those have been analyzed specifying the methodological details considered for its development.

To this end, with respect to the environmental pillar, a classification has been made according to the functional units as follows: "input" (I) based, i.e. the quantity or input of waste into the production system, or "product" (P) based, related to the output or target product(s) of the recovery system. This classification allows assessing a wide variety of products and wastes. It is worth mentioning that when two or more outputs are obtained, it is common to select the input as the functional unit, as this is simpler and would also allow the development of an allocation of environmental impacts, which could be either a mass allocation or an economic allocation.

In 62 % of the manuscripts, the mass or volume of the inflow to the system was considered as the functional unit (Table 2), e.g. "1 m^3 of food waste" [56], "1 ton of municipal solid waste" [57–60], "total mass of residues produced in one year" [56,61–63] or "1 ton of food waste" [64–67]. Regarding the "product" base functional unit, some examples are "1 MJ of bioethanol" [68,69], "1 kg of extracted compound" [70,71], "1 kWh of power" [72,73] or "antioxidant capacity" [69,74].

Regarding the methodologies used to characterize the environmental impacts of the considered valorization schemes, the use of the impact assessment method ReCiPe stands out in 45 % of the articles analyzed [156], followed by the following methodologies: CML [157] with 25 %, IPCC [158] with 17 % (specially for the calculation of the Carbon Footprint), and the Environmental Footprint (EF), which was considered in 13 % of the articles analyzed (Table 2).

For the studies applying ReCiPe, most of thems use the ReCiPe MidPoint approach, characterized by the provision of a total of 18 midpoint impact categories, from ecotoxicity to eutrophication, impact on human health, carbon footprint or depletion of fossil resources, among others. While some of them assessed all 18 impact categories [72,103,120], others focused on the evaluation of eutrophication, toxicity, photochemical oxidation and global warming [140], on water footprint and eutrophication [155], or on the consumption of mineral and fossil resources, particulate matter formation, global warming and land use [108].

The CML method considers 11 mid-point impact categories, such as three ecotoxicity categories (terrestrial, marine and freshwater ecotoxicity), two related to eutrophication (marine and freshwater eutrophication), one assessing resource depletion, namely "Abiotic resource use", and also it scores human toxicity. As was the case with studies applying ReCiPe, some papers cover all CML impact categories [65,154,86], while others consider e.g. only global warming potential [109,123], sometimes in combination with the eutrophication and acidification potential [121].

For studies referring to the IPCC, the only impact category covered is global warming [85,90,105,144]. In the case of alternative methodologies to score the environmental effects of waste recovery strategies, it has been used in combination with ReCiPe, CML, Chemical Energy Demand (CED), USEtox and Accumulated Exceedance, to assess the impact categories of acidification, eutrophication, fossil resources depletion, human toxicity, ozone depletion, primary and renewable energy demand, and abiotic resource depletion [63,66,125,77].

The EF method has only been used in a few research articles, namely using food waste and agricultural waste as resources for bioenergy and bio-oil using anaerobic digestion/hydrothermal carbonization technologies [61,113], and biochemicals & biomolecules, and biochemicals and biomolecules, namely volatile fatty acids and essential oils and citric acid, using assisted extraction technologies [137,79]. In addition, also not-as-common methodologies have been used apart for the aforementioned ones, such as the EASETECH model [60,141,106], GREET model [69,91,92], TRACI [81,93] and cumulative energy demand (CED) [70,125,122], among others.

Another aspect analyzed is the relationship between the LCA and the type of waste, the technology used for recovery and the bioproduct obtained. In this respect, the classification considered is analogous to that used in the previous section. With regard to the type of waste, three types of waste stand out for which the LCA has been used for studying the environmental impacs of their treatment: food waste, which represents 30 % of the total number of studies analyzed, followed by forestry waste (wood and leaf waste) with 29 %, and agricultural waste (vegetables, crops and fruit) with 28 %. For the remaining waste types, the development of environmental assessment in the literature is reduced to ranges between 1 and 5%.

3.2.2. *Economic assessments for analyzing waste valorization strategies under a biorefinery approach*

With regard to the economic assessments, the parameters analyzed in the selected research articles were also evaluated, as shown in Table 3. As can be seen, both LCC and techno-economic evaluation (TEA), more generic economic analyses, cost-benefit analyses (CBA) and, to a lesser extent, the use of material flow cost accounting (MFCA, a method used to improve material efficiency, standardized on ISO 14501) are used. In general, when a TEA is chosen as the economic assessment methodology, the valorization process has also been simulated; therefore, these studies also assess the suitability of the equipment used, identifying volumes, production capacities and energy requirements, among others. On the other hand, the use of the LCC methodology follows the guidelines of the ISO 15686 standard, where CAPEX (Capital Expenditure), OPEX (Operational Expenditure) and NPV (Net Present Value) are estimated to assess the economic viability of the valorization process.

On the other hand, more general economic analyses usually also include the calculation of the Minimum Selling Price (MSP) of the desired product, which allows to assess its market potential. Only one research study articleed the use of the analysis of the costs associated with carbon fees, thus limiting it to assessing the environmental costs [153].

In addition to the economic parameters mentioned above, the calculation of Return on Investment (ROI) [88], Internal Rate of Return (IRR) [154,90,139], Payback Value [139,111] or Levelized Cost of Energy (LCOE) [91,111] was also conducted. While the first three are common parameters in cost analysis, providing complementary values to CAPEX, OPEX and NPV, under the same function of analyzing the economic viability of the valorization process, the LCOE is not so common. It is defined as the average cost required to produce 1 kWh of energy and is calculated as the ratio between the total annualized cost and the total amount of energy produced [160].

Regarding the relationship between economic valuation, the type of waste, the valorization technology and the type of bioproduct, there is a clear trend towards the use of food waste (33 % of the articles studied), municipal organic waste (28 %) and agricultural waste (26 %). In terms of technology, anaerobic digestion and fermentation are the main areas, with a percentage of importance of 49 % and 21 %, respectively. It has been observed that many research articles evaluate different technologies. While it is true that there is a tendency to opt for more innovative recovery models, seeking greater benefits in terms of quality and added value of the product obtained, there is a fairly widespread tendency to opt for the energy recovery of waste, both because of its greater simplicity and lower cost compared to other technologies.

Accordingly, as found in the context of the analysis of environmental LCA studies, the production of bioenergy and bio-oil is the most interesting topic in the literature, accounting for 51 % of the articles evaluated, followed by the production of bioactive compounds, accounting for 29 %.

3.2.3. *Valorization of biotic streams and social assessment*

The number of research articles covering the social pillar of

Table 2
Analysis of the available environmental and economic assessment articles on the aforementioned waste resources, technologies and bio-products.

Ref.	Methodology		FU		Methodology					Raw material									Product type					Technology								
	LCA	LCC/ others	I	P	ReCiPe	CML	IPCC	EF	Other	1	2	3	4	5	6	7	8	9	P1	P2	P3	P4	P5	T1	T2	T3	T4	T5	T6	T7	T8	T9
[58]	Y	N	X			X			EcoIndicator99							X			X			X		X								
[75]	Y	EA	X		X							X							X			X				X						
[76]	Y	N	X						Impact2002+								X	X			X		X		X							
[77]	Y	N	X		X	X	X										X			X			X			X						
[78]	Y	N		X	X							X								X						X						
[68]	Y	EA		X			X									X			X					X		X						
[79]	Y	N	X					X									X									X		X				
[80]	Y	N		X					GHG equations								X					X										X
[69]	Y	TEA		X					GREET model								X		X				X	X		X	X					
[57]	Y	N	X						Impact2002+							X			X					X								
[81]	Y	LCC	X						TRACI			X							X			X		X								
[65]	Y	N	X			X						X							X			X		X							X	
[82]	Y	N	X					X				X							X					X								
[83]	Y	N	X		X										X				X					X								X
[84]	Y	N	X						EcoIndicator99							X			X			X		X								
[85]	Y	N	X				X					X							X			X		X		X	X					
[86]	Y	N	X			X									X				X			X		X							X	
[87]	Y	N		X				X	Impact2002+									X	X					X								
[88]	Y	EA	X				X										X		X			X		X								X
[64]	Y	N	X			X										X			X			X		X								
[89]	Y	N		X	X												X		X			X		X								
[90]	Y	LCC		X			X					X							X			X		X							X	
[91]	Y	TEA		X					GREET model			X							X					X								
[92]	Y	TEA		X					GREET model			X							X					X								
[73]	Y	N		X		X			EcoIndicator99							X			X					X								
[93]	Y	N	X						TRACI									X	X			X		X								X
[94]	Y	N	X		X									X					X			X						X				X
[56]	Y	LCC	X		X		X		TRACI			X							X			X		X								
[95]	Y	MFCA		X	X												X				X									X		
[96]	Y	EA	X		X											X			X			X		X							X	
[97]	Y	LCC	X		X											X			X			X		X							X	
[66]	Y	N	X		X	X	X		AE, USETox			X							X			X	X	X							X	
[98]	Y	N		X	X							X										X	X	X								
[63]	Y	N	X			X	X		AE, USETox								X			X					X							
[99]	Y	N		X				X								X			X			X		X								
[59]	Y	N	X		X											X			X					X		X						X
[60]	Y	N	X						EASETECH model							X			X			X		X								
[100]	Y	N	X			X			CED							X			X			X		X								
[61]	Y	N	X					X								X			X			X										X
[101]	Y	N	X		X							X					X		X			X		X								
[102]	Y	N	X		X			X				X							X			X	X	X								
[72]	Y	N		X	X							X							X					X								
[103]	Y	N		X	X												X		X			X		X								X
[104]	Y	CBA	X		X												X		X			X		X								
[105]	Y	EA		X			X					X				X			X			X		X		X						
[106]	Y	TEA	X						EASETECH model								X		X							X						
[107]	Y	N		X	X											X			X	X				X								X
[71]	Y	N		X		X						X							X					X								
[62]	Y	N	X						Characterization								X				X	X		X					X			
[108]	Y	N	X		X							X	X						X			X		X								
[109]	Y	N	X			X								X					X			X		X								

(continued on next page)

Table 2 (*continued*)

Ref.	Methodology		FU		Methodology					Raw material									Product type					Technology								
	LCA	LCC/ others	I	P	ReCiPe	CML	IPCC	EF	Other	1	2	3	4	5	6	7	8	9	P1	P2	P3	P4	P5	T1	T2	T3	T4	T5	T6	T7	T8	T9
[110]	Y	N	X		X							X				X			X			X		X								
[70]	Y	N		X			X		CED			X							X			X		X								X
[111]	Y	EA	X		X		X	X				X								X						X						
[112]	Y	CC		X												X						X										
[113]	Y	N	X					X				X							X	X				X		X						
[114]	Y	N	X			X						X							X			X		X								X
[115]	Y	N		X				X				X								X						X						
[116]	Y	N		X													X		X							X						
[117]	Y	N	X		X											X			X					X							X	X
[118]	Y	N	X		X							X							X					X								X
[119]	Y	N	X			X											X		X			X		X							X	
[120]	Y	N	X						ImpactWorld+							X			X			X		X								X
[121]	Y	N		X	X													X			X				X					X		
[122]	Y	N	X			X										X			X			X		X								
[123]	Y	N	X			X			CED								X		X					X								
[124]	Y	N		X		X										X			X							X						X
[125]	Y	N		X	X											X		X	X					X							X	X
[126]	Y	N		X			X		CED								X				X									X		
[127]	Y	N	X		X				CED								X		X			X		X		X					X	
[128]	Y	N		X					ILCD2011								X				X				X			X				
[129]	Y	LCC	X						GREET model							X			X			X		X								
[130]	Y	TEA		X	X												X			X	X					X						
[74]	Y	N	X					X									X		X					X								
[131]	N	EA												X					X					X								
[132]	Y	CBS	X			X					X								X			X		X								
[133]	Y	TEA		X	X	X											X		X							X						
[134]	Y	N		X		X						X							X					X		X						
[135]	Y	N		X			X		Primary ED							X			X							X						
[136]	Y	N		X		X						X								X					X							
[137]	Y	TEA		X				X				X								X				X								
[138]	Y	LCC	X				X									X			X					X							X	X
[139]	Y	TEA		X	X												X			X						X						
[140]	Y	N	X		X											X			X					X								
[141]	Y	LCC	X						EASETECH model			X							X			X		X		X					X	
[142]	Y	N	X		X											X			X			X									X	X
[143]	Y	N	X		X												X		X			X		X								X
[144]	Y	EA		X			X										X		X			X		X			X					
[145]	Y	TEA	X		X												X		X	X				X								
[146]	Y	N	X						KPIs			X							X					X								
[147]	Y	N	X						EASETECH model							X			X			X		X							X	
[148]	Y	N		X	X												X			X						X						
[67]	Y	N	X			X						X							X			X		X							X	
[149]	Y	EA	X		X												X															
[150]	Y	CBA	X		X											X			X			X		X								X
[151]	Y	N	X		X												X		X		X	X			X							
[152]	Y	N	X						ILCD2011					X									X					X				
[153]	Y	Tax C	X						EASETECH model			X							X			X	X	X							X	
[154]	Y	LCC	X			X								X		X			X					X								
[155]	Y	N	X		X				AWARE			X							X					X								

*Raw material: 1-Biomass waste, 2-Dairy, fish and meat-products waste, 3-Food waste, 4-Garden waste, 5-Industrial waste, 6-Kitchen waste, 7- Organic municipal waste, 8-Vegetable, crops and fruit waste, 9-Wood and leaves waste. Product type: P1: Bioenergy & bio-oil, P2: Biochemicals & biomolecules, P3: Biopolymers, P4: Bioactive compounds, P5: Organic fertilizers & compost & biochar, P6: Animal feed, P7: Bio-based products for alternative treatments. Technology: T1-anaerobic digestion, T2-conventional solvent extraction, T3-fermentation, T4-membrane process, T5-microwave assisted extraction, T6-supercritical fluid extraction, T7-ultrasound assisted extraction, T8-incineration, T9-gasification, pyrolysis, combustion, hydrothermal carbonization, mechanical treatment.

Table 3
Analysis of the economic parameters assessed on available articles considering the aforementioned waste resources, technologies and bio-products.

Ref.	Methodology		Economic parameters						Raw material									Product type					Technology								
	LCA	LCC/others	CAPEX	OPEX	NPV	MSP	EC	Other	1	2	3	4	5	6	7	8	9	P1	P2	P3	P4	P5	T1	T2	T3	T4	T5	T6	T7	T8	T9
[159]	Y	EA	X	X		X					X							X			X				X						
[68]	Y	EA	X	X	X	X									X			X					X		X						
[69]	Y	TEA				X					X					X		X				X	X		X	X					
[81]	Y	LCC	X	X							X	X						X			X		X								
[88]	Y	EA	X	X				ROI							X	X		X			X		X								X
[90]	Y	LCC	X	X	X			IRR, LCOE			X							X			X		X							X	X
[91]	Y	TEA	X	X		X					X					X		X					X								
[92]	Y	TEA	X	X							X							X					X								
[56]	Y	LCC			X						X							X			X		X								
[95]	Y	MFCA	X	X												X				X									X		
[96]	Y	EA	X	X	X										X			X			X		X							X	
[97]	Y	LCC		X							X							X			X		X							X	
[104]	Y	CBA	X	X	X						X				X			X			X		X		X						
[104]	Y	EA				X										X		X							X						
[105]	Y	TEA	X		X			PB, LCOE							X			X	X				X								X
[106]	Y	EA		X											X						X										X
[111]	Y	CC									X							X	X				X		X						
[112]	Y	LCC	X	X											X			X			X		X								
[128]	Y	TEA	X	X			X									X			X	X					X						
[129]	N	EA			X								X					X					X								
[132]	Y	CA	X	X						X					X			X			X		X								
[133]	Y	TEA	X	X	X	X				X						X		X							X						
[137]	Y	TEA	X	X	X						X								X				X								
[138]	Y	LCC	X	X	X			IRR, LCOE, PB							X			X					X							X	X
[139]	Y	TEA	X	X	X	X										X			X						X						
[141]	Y	LCC	X	X				OELEX			X							X			X		X		X					X	
[145]	Y	TEA	X	X												X		X	X				X								
[149]	Y	EA	X	X			X									X															
[150]	Y	CBA	X	X		X									X			X			X		X								X
[153]	Y	Tax C									X							X			X	X	X							X	
[154]	Y	LCC			X			IRR					X		X			X					X								

*Raw material: 1-Biomass waste, 2-Dairy, fish and meat-products waste, 3-Food waste, 4-Garden waste, 5-Industrial waste, 6-Kitchen waste, 7- Organic municipal waste, 8-Vegetable, crops and fruit waste, 9-Wood and leaves waste. Product type: P1: Bioenergy & bio-oil, P2: Biochemicals & biomolecules, P3: Biopolymers, P4: Bioactive compounds, P5: Organic fertilizers & compost & biochar, P6: Animal feed, P7: Bio-based products for alternative treatments. Technology: T1-anaerobic digestion, T2-conventional solvent extraction, T3-fermentation, T4-membrane process, T5-microwave assisted extraction, T6-supercritical fluid extraction, T7-ultrasound assisted extraction, T8-incineration, T9-gasification, pyrolysis, combustion, hydrothermal carbonization, mechanical treatment.

sustainability is relatively small; Table 4 lists the papers assessing social indicators related recovery systems for biotic waste.

As can be seen in Table 4, job creation is the most common indicator for assessing the social perspective, as it is also indicative of economic growth, since both aspects are often interrelated: the better the economy, the greater the employment opportunities. On the other hand, when assessing new production models and also alternative bio-based products, it is important to be aware of their social acceptability. The analysis of market demand, as well as the willingness of consumers to buy bio-based products instead of chemical-based products, is a key factor in ensuring the profitability and productivity of biorefineries. The fact that waste is used as a resource for a product that could be used, for example, in the pharmaceutical or food sector, could lead to a negative reaction from consumers, which is why it is extremely important to disseminate and raise awareness of production models based on waste recovery, as well as to demonstrate that the products obtained do not pose any risk to health or social wellbeing.

Indeed, a successful transition to a bioeconomy context with waste-to-product strategies requires the involvement of all stakeholders associated with the value chain in order to improve social acceptability [168]. These aspects are not being addressed or analyzed in the literature when considering waste valorization strategies or biorefinery development, most research articles are based on the technical aspects and expected sustainability scores, but not on the actual success of the bio-based products obtained in the market value chains [169].

A good synthesis on consumer acceptance of recycled products has been developed by [170], in which several variables have been considered to describe the purchase intention of consumers: product quality, product image, sustainability and environmental benefits and safety. To evaluate and score these variables, surveys were developed in which, for each of the statements associated with the variables, a 5-point level of agreement could be scored, with 1 being "strongly disagree" and 5 being "strongly agree". The results obtained by the authors showed that consumers' decision on whether or not to purchase a bio-based product from a waste recovery strategy depends to a large extent on the safety of the product and its image in the market, while environmental or sustainability benefits are the variables of least concern to consumers.

In this sense, in order to improve the perception and positive attitude of consumers towards organic and recovered products, some key factors have been selected. Firstly, the identification of the drivers that increase product acceptance, which should be critically assessed for each type of valorized product and also for the social community and specific market trends. Secondly, the analysis of barriers that slow down the integration of these bio-based products into market value chains and, thirdly, communication and awareness raising about production processes, product quality and the benefits of buying bio-based products instead of traditional ones [171,172].

3.2.4. Circularity indicators for measuring bio-based process

Some articles about waste valorization strategies and biorefineries found in the literature indicate or assume an assessment of circularity or circular economy simply because of the fact that waste resources are used as inputs for the development of biotechnological or biorefinery processes. But in reality, a circularity analysis implies the use of indicators to determine that, effectively, a circular model is being used and that, in turn, opting for resource recovery does not imply a higher impact than managing them in other more conventional methods, such as incineration, landfill management or energy recovery.

There are several articles or institutions, such as the Ellen McArthur Foundation, which have developed a series of indicators that evaluate in a critical and focused way the degree of circularity of a specific scenario. In fact, there is also a Standard, *BS 8001:2017 Framework for implementing the principles of the circular economy in organizations* and a new ISO, *ISO 59004:2024: Circular economy – Vocabulary, principles and guidance for implementation*, that provides a framework to implement the principles of the circular economy, which could be very useful for the implementation of bio-based processes in a real large-scale industrial process and to take actions and decisions on how to deal with circularity in the institutions. The European Commission has also developed a recent action plan on circular economy, providing a set of Eco Innovation indicators encompassing resource efficiency criteria, as material productivity, energy productivity or GHG emissions, and socio-economic outcomes, evaluating both employment in environmental protection & resource management, value added of eco-industries and exports of eco-products [173]. Also the World Business Council for Sustainable Development (WBCSD) has developed a framework including a list of circularity transition indicators and metrics to mesure climate and nature impact in terms of circular development.

There are not many articles in the literature that apply circularity indicators to assess the potential of emerging biorefinery scenarios or biotechnological processes, and this is something that should be considered in the future as a necessary assessment to ensure the adequacy of waste valorization scenarios. However, there are some authors who have reflected on this aspect of assessing circularity with indicators, such as the research article by [174], which used circularity indicators to evaluate various circular economy strategies in the treatment of food waste.

Regarding the valorization process, the article proposed the use of three circularity indicators: nitrogen recycling rate, phosphorus fertilizer consumption, emissions to water bodies and renewable energy production capacity. For the first three indicators, the objective is to identify the potential benefits of using digestate as fertilizer instead of chemical fertilizers, while for the fourth indicator, the idea was to evaluate the productive capacity in terms of energy. On the other hand, other authors have also proposed another indicator to assess the implications of using bread waste as animal feed instead of energy recovery, which is the land use ratio [174]. The idea was to compare the effect on

Table 4
Analysis of the social parameters assessed on available articles considering the aforementioned waste resources (WR), technologies (T) and bio-products (BP).

Ref.	WR	BP	T	Social parameters						
				Social acceptance	Job creation	Child labour	Force labour	Gender equality	Health expenditure	Contribution to economic growth
[161]	8	1	1,3,9	X						
[162]	7	1	3,8,9		X					X
[163]	7	1	1,8	X	X					
[164]	7	1	1,8,9		X					
[165]	7	1	1,8	X						
[166]	7	1	1,8	X	X					
[167]	3	1	9			X	X	X	X	X

*WR (waste resources): 1-Biomass waste, 2-Dairy, fish and meat-products waste, 3-Food waste, 4-Garden waste, 5-Industrial waste, 6-Kitchen waste, 7- Organic municipal waste, 8-Vegetable, crops and fruit waste, 9-Wood and leaves waste. Product type (BP): P1: Bioenergy & bio-oil, P2: Biochemicals & biomolecules, P3: Biopolymers, P4: Bioactive compounds, P5: Organic fertilizers & compost & biochar, P6: Animal feed, P7: Bio-based products for alternative treatments. Technology (T): T1-anaerobic digestion, T2-conventional solvent extraction, T3-fermentation, T4-membrane process, T5-microwave assisted extraction, T6-supercritical fluid extraction, T7-ultrasound assisted extraction, T8-incineration, T9-gasification, pyrolysis, combustion, hydrothermal carbonization, mechanical treatment.

land use of avoiding the production of feed from crops commonly used for animal feed.

A combination of various indicators have been used to evaluate a decentralized valorization strategy for urban garden and food waste based on alternative processes considering composting, vermiculture, anaerobic digestion and struvite recovery [175]. In terms of circularity indicators, the authors have used three different ones: the self-sufficiency index, which aims to score the availability of nutrient demands (i.e. nitrogen and phosphorus) due to their recovery, the resource export index, which represents the excess supply of nutrients at the municipal level due to their recovery, and the waste outflow index, which indicates the extent to which the amount of exported waste is reduced due to the implementation of recovery strategies at the household level.

Performance indicators could also be useful to assess the circularity potential of a valorization scenario, for example for a municipal organic waste valorization strategy for the recovery and production of compost, digestate, struvite and ammonium sulphate, which are subsequently used as fertilizers for the maize crop. In this case, two indicators focused on the amount of N available and recovered from the organic waste: (1) the amount of N recovered per kg of N available on the organic waste and (2) the uptake of the N by the crop, which is calculated by considering the fraction of N uptake compared to the available N at soil [176].

Table 5
Analysis of the multi-criteria assessments (MCA). Acronyms: MILP (Mixed-integer linear programming), MCDA (Multi-criteria decision analysis), AIJ (Aggreggation of Individual Judgements), MAUT (multi-attribute utility theory).

MCA method	Scenarios under analysis	Goal of analysis	Methodology	Data acquisition	Main outcomes	Reference
MILP combined with LCA	Analysis of various waste management strategies (anaerobic digestion, composting, open or sanitary landfilling)	Assess which of the scenarios simultaneously minimizes costs, human health and ecosystem damage, using a three-dimensional Pareto diagram.	Functional unit selected: 1 ton of food waste, system boundaries: "bin-to-cradle"	EcoInvent database, surveys, national documents and other articles	The most promising valorization treatment is anaerobic digestion with electricity production, while open landfill and drying are the worst	[159]
MCDA using PROMETHE II	Production of bioethanol, syrup, electricity or C-molasses sugar sugarcane as input resource	Outranking the four biorefinery systems by scoring: energy security, job creation, price volatility, climate change, fossil fuel depletion, freshwater and chemicals use indicators	Definition of sustainability metrics, using weight factors and socio-economic and environmental indicators.	Existing processing facility data and modelling data	Ethanol distillery for biofuel production is the sugar cane recovery waste management alternative with the highest sustainability performance	[177]
MCDA	Management alterantives for wheat silage: biofertilizer production and/or anaerobic digestion with heat and energy recovery.	Scoring 18 indicators related with 8 key areas: energy & environmental performance, economic, technical, organization and instutional feasibility, geographical and physical suitability, public and market acceptability and risk avoidance	Definition of the most important criteria and key areas to select the best management strategy	Literature studies and companies	The production of biogas fuel using a local biogas plant or the use of wheat silage as fodder are the most suitable management strategies	[178]
FUZZY AHP method and AIJ combined with LCA	Alternative cropping and harvesting systems for maize grain production	Assess which cropping system is the most adequate considering CML-IA impact categories and socio-economic indicators (profitability, subsidy independency, economic efficiency, contribution to local employment, work difficulty and health risk	Use of criteria weightings and AIJ for scoring a geometric average. Functional unit: 1 kg of maize grain	Surveys, data provided by Agricultural Advisory centers and literature	No tillage maize monoculture production is the most favorable with the exception on the indicator of grain yield, in which conventional tillage peforms better	[179]
DEXiPM model, based on ENDURE and DEXi software	Different pest management scenarios for maize-based cropping systems, toguether with analysis of cropping systems	Scoring of indicators: considering environmental, social and economic perspectives	Combination of environmental, social and economic perspectives by using individual and aggregated indicators.	Expert-based surveys	Innovative pest management and rotatory cropping systems implies increased sustainability performance that conventional cropping systems	[180]
SYNOPS model and SALCA method	Comparison between conventional apple production system and organic harvesting with no plant protection products	Evaluating of how the reduction on the use of plant protection products on apple production could be beneficial under a social, environmental and economic perspective	Scoring of environmental impacts using a LCA perspective, analysis of nutrient cycles, farmers hourly wage and invested capital-labor.	EcoInvent database, Agri-Environmental indicatros farm-network data	The scenarios evaluated differ on better performance depending on the approach considered, thus not being able to select the one that performs better.	[181]
MAUT method	Biorefinery strategy for the production of poly-lactic acid using triticale, which is a hybrid crop of rice and wheat.	Scoring the selected attributes: competitive access to biomass, production costs and margin under price volatility, internal rate of return, supply market uncertainty, GHG emissions, non-renewable resources consumed or saved, land occupation and human health effects.	Use of attributes that considered a utility function (representing the overall sustainability performance) and a relative importance (weighting factor) of each decision criterion.	Not available	The most sustainable altertives are increasing product purification with an ultrafiltration stage and opting for simultaneous saccharification and fermentation to enhance sugars availability.	[182]

3.3. The need of applying a multi-criteria framework

From the former section one can conclude a comprehensive assessment of valorization of biotic waste with biorefineries will easily results in a dozen or more scores on environmental, economic and social indicators. A form of multi-criteria assessment (MCA) hence has to be applied to analyze trade-offs. In the literature for biorefineries, the articles found are depicted on Table 5. It should be mentioned that there are also some articles that, even not directly focused on the technological performance, use a MCA for background processes, such as the harvesting stages of feedstocks used as resources in biorefineries.

Considering the articles analyzed, it could be discussed how MCA could help in the development of new waste valorization strategies following a biorefinery approach, as it offers a comprehensive and holistic analysis of the performance of valorization schemes, including environmental, social and techno-economic aspects. This combined analysis could help decision makers on where to focus in order to improve process performance and increase the penetration of new valorization models in market value chains. On the other hand, MCA also offers great flexibility in terms of analysis preferences and helps in the identification of trade-offs to improve the understanding of bio-based valorization strategies. Nevertheless, even the robust framework that MCA offer, it also present some challenges on its use as a methodological approach, mostly its complexity, as it implies dealing with quite significant amount of data and with certainly complex methods for analysis, as exposed on Table 5. But also the difficulty of collecting all the data required for the analysis, that if not available, the interpretation of the results and the degree of subjectivity on the analysis, are seeing as the main challenges and gaps of MCA.

To this end, when developing an MCA, it is important to be aware of what data are available, to be conscious in choosing what type of method and what criteria should definitely be analyzed, and to avoid as much as possible the subjectivity in interpreting the results obtained. Future research should be focused on 1) how to deal with data acquisition problems, 2) developing guidelines to ensure results scoring and interpretation and 3) reducing the complexity of methods to enhance the use of MCA for analyzing new valorization processes.

4. Future challenges and perspectives

4.1. Focusing on waste valorization strategies

The critical analysis of the studiess available in the literature on recovery schemes and waste flow technologies has shown that there is a strong research interest in the pursuit of more sustainable and circular production models for biotic materials. Nevertheless, there is a considerable focus on direct energy recovery models, both for the production of electricity and thermal energy, rather than on the recovery of resources with higher added value on the market, such as antioxidant compounds, biochemical products or even biopolymers, like polylactic acid. Opting for the recovery of these compounds does not avoid the use of biomass as an energy resource, since these bioproducts generally represent only a small fraction of the total waste used as a raw material, thus also allowing its energy recovery. Therefore, future research should focus on the development of technologies that are more focused on obtaining both energy but also high value-added products on the market, since this not only helps to avoid landfilling or other management methods with high environmental impact and zero economic profitability, but also encourages more circular production practices and avoids the depletion of other resources, such as fossil ones.

On the other hand, although most of the articles analyzed focus on the development on technological performance, there is also a clear trend, to integrate environmental sustainability studies, through the methodology of life cycle assessment, and economic feasibility evaluation, where the use of LCC methodology is not as widespread as the use of techno-economic assessments. Regarding social assessment, very little number of articles have being found. In order to develop an accurate social LCA analysis, it is necessary to have primary data, to conduct interviews with workers, employers, interest groups, communities and consumers, and these data are not easy to obtain or analyze, which is the probable reason for the lack of studies on this pillar of sustainability.

The integration of these three evaluation frameworks, corresponding to the three pillars of sustainability, should be ideal for the future assessment of new production models based on the valorization of resources. The use of a multi-criteria approach that allows a comprehensive evaluation of the advantages and disadvantages of the valorization model for each of the pillars of sustainability, is the key to enhance efficient and sustainable production strategies. In addition, another aspect that should become a priority are the risk analysis, in terms of how fluctuations in value chains and changes in demand by producers and consumers can affect the economic viability of these new production models, and of course from a social approach, especially when new products are developed, focusing on the analysis of their potential health risks, as well as possible toxicological effects.

4.2. A step forward on assessment methodologies: the use of SSbD framework

In order to avoid the shortcomings of the previous mentioned individual assessments, and in the search for holistic and dynamic evaluation methodologies that consider all the pillars of sustainability and risk aspects, the use of the SSbD (Safe-and-Sustainable-by-Design) should be considered in the future studies as an effective framework for the evaluation of new treatment, valorization and large-scale production systems. This framework could be seen as a guideline for stakeholders, entrepenerus, researchers and policy makers, for decision-making in both early design phases and well-developed production schemes.

Although this SSbD approach provides a holistic assessment of the different aspects of sustainability and risk analysis, and therefore could be considered as a suitable methodology in the approach to the development of biotechnological and biorefinery processes, no results were found in the literature regarding its use, mostly because it is more related with the chemical sector, rather than on the bio-based one. But, even though this methodology has been developed to a greater extent for the assessment of "chemical-based" and "conventional production" schemes (the fossil-based and linear production ones), it could and it should be applied to the bio-based sector.

To prove this, the analogy between the SSbD and what is found in the literature is included herein: the environmental and economic analyses well developed in the literature could be framed in three steps of the SSbD framework, namely in Step 3 ″Human health and environmental aspects", Step 4 ″Environmental sustainability assessment" and to some extent also in Step 5 ″Social and economic sustainability assessment". However, for Step 5, as noted above, the application of social assessments is not abundant in the literature. The difficulty in finding accurate data and the lack of participation of stakeholders, social communities or entrepreneurs of the production models implies a significant lack of social data, which is equally important when it comes to measuring the sustainable potential of a process.

On the other hand, as far as the "human health" aspect is concerned, although it could be evaluated to a certain extent thanks to the methodologies available within life cycle analysis, as is the case with the impact categories of human health toxicity potential, human carcinogenic potential, or human non-carcinogenic potential, it would really be necessary to go a step further. When promoting new production models, such as biorefineries or biotechnological processes based on the valorization of waste resources, it is important to take into account the degree of actual and future impact on human health. Product quality standards, as well as potential risks associated with the implementation of new processes or product designs, should be a key element in the decision-making process for bio-based production models.

Human health also includes quality of life, so aspects such as odor emissions, effects on soil quality, which may affect crops and thus the entire food chain, or noise emissions, for example resulting from the installation of a waste treatment plant in the vicinity of social communities, need to be taken into account in the SSbD framework approach.

About the other two steps of the framework, namely Step 1 ″Hazard assessment of the chemical/material" and Step 2 ″Human health and safety aspects in the production and processing phase of the chemical/material", the lack of guidelines on how to deal with this assessment for bio-based processes and products is evident. This is also reflected in the literature, where the development of risk and safety analyses in valorization schemes, bio-based models, bioenergy or bio-products is not common. In fact, no article was found on these aspects. To some extent, the assessment of the degree of health and safety impact of a bio-product or bioprocess would require the prior compilation of laboratory data where, among other matters, toxicological aspects should be studied.

On the other hand, looking at risk from an economic perspective, it seems more plausible to introduce it for biological production models, since it would be analogous to carrying out a sensitivity analysis on economic parameters such as variation in sales price, variation in raw material prices or operating costs. However, it is more difficult to perform a risk analysis on the demand for the bio-product because there is lack of social analysis, historical data, and no knowledge of the level of acceptance of the bio-product in the early stages of design. For this reason, these analyses can be difficult to perform for bio-based models, and therefore their presence in the literature is practically non-existent.

As final global conclusion, the future framework towards a more sustainable model of biotic resource recovery should be based on combining environmental, economic, and social (life cycle) assessments and on the encouragement of valorization technologies, in order to facilitate the pathway towards a more sustainable and resilient future. It is important to recognize the need for a comprehensive understanding, a "design-thinking" of the impact of production systems on all the pillars of sustainability, on economic prosperity and on the quality of life of social communities.

CRediT authorship contribution statement

Ana Arias: Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Gumersindo Feijoo:** Supervision, Writing – review & editing. **Maria Teresa Moreira:** Supervision, Writing – review & editing. **Arnold Tukker:** Supervision, Writing – review & editing. **Stefano Cucurachi:** Methodology, Formal analysis, 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

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

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Appendix A. Supplementary data

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