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Life-cycle sustainability assessment for the production of bio-based polymers and their post-consumer materials recirculation through industrial symbiosis

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Life-cycle sustainability assessment for the production of bio-based polymers and their post-consumer materials recirculation through industrial symbiosis

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Abstract

Sustainability assessment should be considered as a decision-making framework for the development of circular processes. Techno-economic, environmental and social metrics should be integrated and interrelated (e.g., through life-cycle costing) to achieve sustainable and circular processes. By-products and waste streams from conventional linear value chains can be considered as feedstock for the future sustainable chemical industry. For instance, post-consumer biopolymers could be valorized avoiding the linear production and disposal of biopolymers as waste. This review elaborates on the state-of-the-art sustainability and circularity assessment methodology and indicators focusing on the life-cycle of biopolymer production, including end-of-life alternatives for their post-consumer valorization.

Keywords: sustainability; circular economy; industrial symbiosis; life cycle costing; techno-economic and environmental assessment; biopolymers.

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1. Introduction

The sustainable and circular production of bio-based chemicals and polymers should be verified through the integrated assessment of the three pillars of sustainability, considering the whole life-cycle and the alternative end-of-life (EoL) loops [1–4]. Process design of sustainable technologies using appropriate design software is used to size equipment and estimate material and energy balances, which are required for techno-economic assessment (TEA) [5,6] and life-cycle assessment (LCA). The comparison of alternative EoL routes for the post-consumer bioplastics, considered nowadays as valuable secondary bio-based feedstocks, should be assessed to identify the most sustainable recirculation option. To ensure the sustainability of EoL alternatives, relevant criteria, indicators and metrics of techno-economic, environmental and social sustainability (TEESA) should be used.

The development of sustainable technologies for biopolymer production and post-consumer EoL recirculation routes should meet the criteria of sustainable chemistry [7]. The use of renewable resources, the minimization of environmental loads and the use of efficient conversion technologies should be the main areas of focus when evaluating alternative approaches to biopolymer production and recycling [7]. This review focuses on the scientific progress made in the methodologies and indicators used for the assessment of sustainable circular processes with integrated linear value chains and EoL recirculation scenarios, towards the development of sustainable industrial symbiotic systems.

2. TEA indicators

A TEA study aims to determine the economic feasibility for the production of a specific biopolymer using a specific technology. Process design, equipment sizing and estimation of material and energy balances are used to estimate the TEA indicators (Table 1) [8,9]. This assessment evaluates process feasibility, and it may incorporate the effects of recirculation of

side and post-consumer streams as input feedstocks, as their recycling implies a reduced purchased cost on the input feedstocks, but an additional production cost for their sorting, recycling and conversion.

Table 1. Main indicators for TEA and LCA

TEA		
Metric	Definition ¹	
Fixed capital investment (FCI)	$FCI = (\sum C_{eq})f_L$	
Net present value (NPV)	$NPV = \sum \frac{CF_n}{(1+i)^n}$	
Return on investment (ROI)	ROI= NP/COI	
Cost of manufacture (COM)	$COM = 0.18 \cdot FCI + 2.73 \cdot C_{OL} + 1.23 \cdot (C_{UT} + C_{RM} + C_{WT})$	
Minimum selling price (MSP)	Lowest selling price calculated when NPV = 0 at the end of the plant life cycle	
Payback period	Period required to recover the initial investment	
Minimum feedstock capacity (MFC)	The minimum feedstock requirement to reach economies of scale (minimum cost of manufacture)	
LCA		
Category	Unit	Recommended methodology (ILCD) ¹
Climate change	kg CO ₂ -eq	IPCC 2013 model
Acidification	kg SO ₂ -eq	Accumulated Exceedance model
Eutrophication	kg PO ₄ -eq	ReCiPe 2016 model
Ecotoxicity	CTUe	USEtox model
Ozone depletion	kg CFC11-eq	EDIP model
Resource depletion	kg Sb-eq	CML 2002 model
Land use	m ²	Milà i Canals model

¹ C_{eq} (Purchased equipment cost), f_L (Lang factor), CF (Cash Flows), i (interest rate), n (years of plant operation), NP (Net Profit), COI (Cost of Investment), C_{OL} (Cost of Labor), C_{UT} (Cost of Utilities), C_{RM} (Cost of Raw Materials), C_{WT} (Cost of Waste Treatment), ILCD (International Reference Life Cycle Data System).

Moving forward the classical TEA to the analysis of how the circularity of streams could affect process sustainability, a monetary-based indicator should be used, namely the Economic Recircularity (ER) [10]. The functional unit used in the LCA should be considered for the ER estimation.

$$ER = \frac{MV_R + MV_{RM}}{MV_{RW}} \quad \text{Equation 1}$$

MV_R: monetary value of the recirculated stream “waste as a resource”,

MV_{RM} : economic value of the virgin raw materials

3. Environmental sustainability assessment indicators

The LCA methodology is the most widespread tool for assessing the environmental loads of a particular process/product, considered as a comprehensive method developed within the ISO 14040 and ISO 14044 guidelines [11]. The indicators (Table 1) provided by the LCA study within the different impact categories are accurate when assessing the inputs and main outputs of a linear production process, but accuracy decreases when evaluating the impacts of residual feedstocks including their valorization and recirculation strategies [12]. The effects of circularity could be assessed by two main frameworks:

- the material flow analysis (MFA), associated with the indicator of Circularity Degree (representing the percentage of a material recyclability)
- the LCA methodology, linked with four main assessment indicators: Circular Performance Indicator (CPI), Eco-Efficiency Index (EEI), Eco-efficient Value Ratio (EVR) and Global Resource Indicator (GRI) [13].

The CPI represents the quality of a recycled material to be used as a virgin one, thus avoiding resource depletion. The theoretical base of this indicator relies on the Cumulative Exergy Extraction from the Natural Environment (CEENE). Both EEI and EVR are focused on economic and environmental aspects. The EEI uses a single score LCA value, using the ReCiPe methodology, to which a monetization factor is then applied. The EVR is based on the Best Available Technologies (BATS) to give a monetary score to the environmental loads. The theoretical concept of GRI is totally different, as it is based on three main aspects: scarcity, which assesses the availability of resources and its rate of extraction, geopolitical availability, to represent the geographic distribution of resources, and recyclability, which aims to

demonstrate resource efficiency by taking into account the losses that occur in conventional processing and recirculation routes [13].

One of the most widespread indicators for measuring circularity is the Material Circularity Indicator (MCI). However, this metric is estimated considering conventional plastic products. Razza et al. [14] developed a methodological approach for bio-based and biodegradable plastics based on the MCI principles but including two adaptations: the consideration of the composition of the bio-based recycled material and the bio-based content. With this approach, the bio-based source and the expected end-of-life are taken into account in the assessment of biopolymer production and recirculation.

Many barriers could be considered when looking for sustainability approaches of biopolymer recirculation [15]. Even though a reduction on the global warming potential is achieved (e.g. 30% less CO₂-eq could be obtained by substituting the fossil-based plastic value-chain with bio-based ones in the EU) [16], sustainable agricultural practices should be pursued, aiming for lower water footprint (39 L H₂O per kg biopolymer, EcoInvent® database), nutrients for fertilization (1.8 g/kg biopolymer, EcoInvent® database) and land use (associated with crop productivity) [17,18]. For instance, using cereal crops as feedstocks result in conservative GHG savings when compared to fossil-based plastics [16].

4. Social Life Cycle Assessment (S-LCA) indicators

S-LCA is a methodology based on the analysis of the sociological and social aspects related to a product/process to assess the positive and negative impacts within the entire life cycle [19]. S-LCA indicators consider societal and individual needs, through the development of standardized questionnaires and metrics to analyze the perspective of every stakeholder involved in the value-chain. Primary and secondary sources are considered to quantitatively assess social indicators, which could be classified into labor practices and decent work

(encompassing occupational health and safety, employee welfare and relationship), human rights, society welfare and product responsibility (including customer health and safety and product compliance) [20].

5. Indicators for EoL recirculation of post-consumer materials

The Circular Economy Package (CEP) has been developed by the EU as an Action Plan for the establishment of Circular Economy practices, looking for sustainable industrial symbiosis (IS), economic growth and social benefits. In this framework, the EoL recirculation scenarios are considered a key aspect. The Waste Framework Directive has defined the prioritization of the EoL alternative routes, with mechanical recycling being preferred, then the chemical route and finally the organic recycling (considering both composting and anaerobic digestion, AD) [21]. Given the importance of EoL practices in achieving a sustainable process, a new industrial sector should be developed within industrial symbiotic systems focusing on side streams processing and post-consumer material recirculation, following the principles of sustainable chemistry [22].

According to the EU-28 technical report for raw materials and circular economy policies, the recycling rates of a product could be assessed by the metric “EOL-RIR” (End-of-life Recycling Input Rate), using the data provided by the development of a Material Flows Analysis [24].

$$EOL - RIR = \frac{G11 + G12}{B11 + B12 + C13 + C14 + D13 + G11 + G12} \quad \text{Equation 2}$$

Secondary materials from post-consumers recycling sent to processing (G11) and/or manufacture (G12),

Primary material used as main product (B11) or by-product (B12),

Imports flows of primary (C13), secondary (C14) and processed (D13) materials

Alamerew and Brissaud (2019) considered the three pillars of sustainability to assess the EoL alternative scenarios via three main indicators, the Net Recoverable Value (NRV), an economic indicator based on the study of the recycle costs, the EoL impact (EoLI), assessing the environmental loads, and the social indicator, which qualitatively evaluates the exposure to hazardous materials and the number of employers needed for the EoL scenario.

$$EoLI = \sum IE \cdot W \quad \text{Equation 3}$$

IE: EoL impact (mPt),

W: weight of the material (kg)

6. Sustainable biopolymer production through industrial symbiosis

IS integrates the utilization of industrial side streams as feedstocks in circular processes with the aim of reducing logistics, minimizing waste generation and promoting the production of bio-based products in a sustainable manner [12,26]. IS creates a network of interlinked industrial plants within an entrepreneurial ecosystem that benefits through the circulation of materials/energy produced within the system in order to maximize resource efficiency [27]. CE principles are fulfilled through the utilization of output streams from one process as feedstock in another process within the symbiotic network [28]. Sustainability assessment evaluates the life cycle of the symbiotic system (Figure 1) with the aim of optimizing the circularity of materials and energy. IS produces value-added products from side streams, reduces environmental impact, enhances economic benefits and facilitates the development of circular business models and new market opportunities [29].

Industrial sustainability could be quantitatively determined by a simplified methodology that evaluates the environmental-social-economic nexus through the Industrial Sustainability Index (ISI), represented as the following expression [30]:

$$ISI = \frac{RVA \cdot EMP}{CO_2 \text{ emissions}} \quad \text{Equation 4}$$

RVA: Resource Value Addition (annual economic value of materials and energy: outputs – inputs),

EMP: employees on annual basis,

CO₂ emissions: annual CO₂ emitted by the specific industrial activity (t CO₂/year)

Indicators assessing the sustainability of industrial activities should include the complexity of symbiotic systems. This could be achieved through life-cycle costing approach that jointly assess techno-economic, environmental and social aspects. Key bottlenecks should be identified to optimize resource conversion efficiency and recirculation.

Future IS systems involving biopolymers production should integrate existing linear value chains with appropriate EoL recirculation routes (e.g., mechanical, chemical, biological). Favi et al. (2016) reported case-specific index formulas for assessing alternative EoL recirculation routes.

Mechanical recycling of discarded PLA leads to degradation and reduces thermal stability. However, blending aged PLA with virgin PLA improves its recyclability and reduces the environmental burden of PLA-food-packaging discards [31,32]. Valorization of aged PLA could be achieved through its conversion, using mild operating conditions and a selective organic catalyst, into ethyl lactate as bio-based industrial solvent [33]. Biological recycling has been assessed for PHA conversion into animal feed supplements [34,35]. Combined chemical-biological PHB recycling has been assessed through thermolytic distillation for crotonic acid production followed by bacterial fermentation of crotonic acid for new PHB production [36]. Regarding energy and fertilizer recirculation, AD and composting could be considered as EoL alternatives when material and chemical recycling have reached their limits [37].

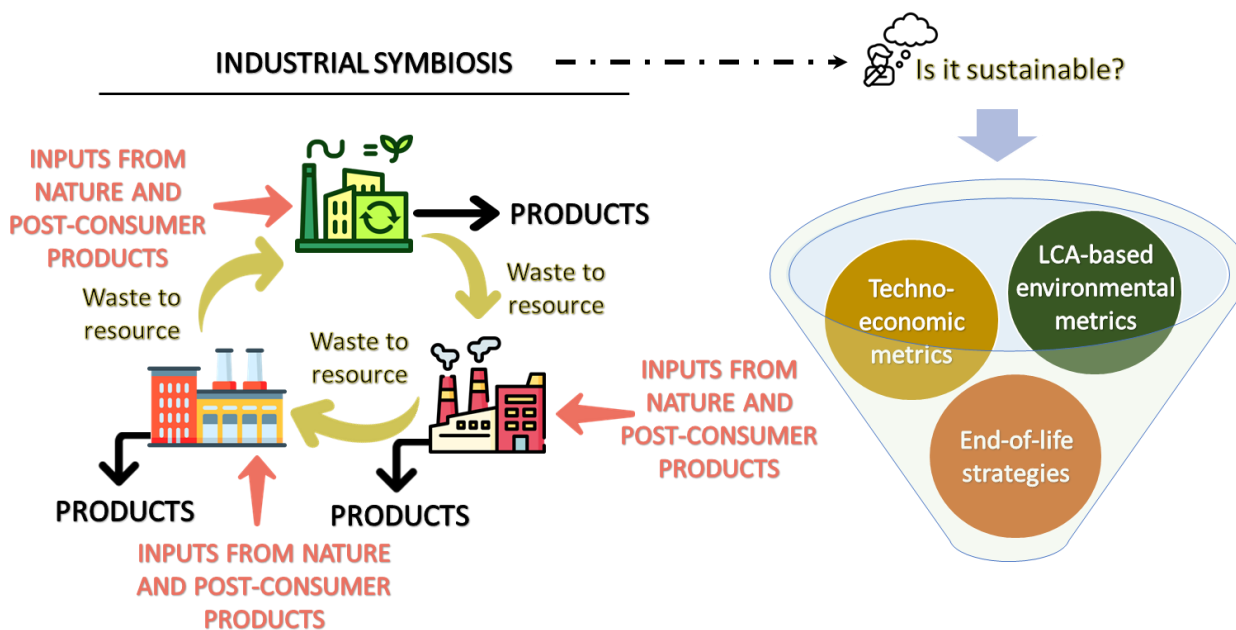


Figure 1. Sustainability assessment of industrial symbiotic systems

7. Future targets

Future targets should be in line with sustainable IS and must be addressed by considering techno-economic, environmental and social metrics as a whole. EoL comprises a stage of the circular value loop, with reuse, reduce and recycling considered as core targets for evaluating sustainable process alternatives (Table 2).

Table 2. Targets, objectives and criteria-indicators related to sustainable chemistry

Target 1	Circular vs. mostly linear processes [38–41]	
Objective	Enabling non-toxic circularity Technology innovations to enable sustainable circular material flows and supply	
Criteria-indicators	Material recycling	Recirculation of materials via EoL alternatives
	Organic recycling	Closing the biogenic carbon loop efficiency through composting of post-consumer biodegradable bio-based plastics
Target 2	Renewable vs. Fossil feedstocks [38–41]	
Objective	Sustainable sourcing of inputs Use sustainably sourced resources, materials and feedstocks without negative trade-offs	

Criteria- indicators	Material recycling	Material recirculation through industrial symbiosis
	Organic recycling	Biodegradability/Compliance with standards
Target 3		Sustainable and recyclable solvents, chemical reagents and products vs. conventional solvents, toxic chemical reagents and products [38–41]
Objective		Minimize chemical hazards Design of chemicals with minimized hazard properties (“benign by design”)
		Develop sustainable solutions Technology innovation to address sustainability challenges (e.g. low toxicity, recyclable solvents) Avoid unsuitable alternatives Develop safe and sustainable alternative chemicals without negative trade-offs
Criteria- indicators	Material recycling	Health protection Safeguard the health of workers, consumers and vulnerable groups
	Organic recycling	Use sustainable additives/solvents/reagents to facilitate bioplastic recycling. Additional requirements apply when used as food contact material [42]
		Use sustainable additives in bioplastics to ensure no negative effect on the production of safe fertilization products, via industrial composting and AD, complying with relevant regulation [43]
Target 4		Catalysis using abundant metals, enzymes, photons or electrons vs. Catalysis using rare metals [40,41]
Objective		Advanced product sustainability Technology innovation to create sustainable products and minimize chemical hazard
Criteria- indicators	Material recycling	Reagents and catalysts used in chemical recycling
	Organic recycling	-
Target 5		Self-separating systems vs. Material- and energy-intensive purification [40,41]
Objective		Advanced product sustainability Technology innovations to create sustainable products and minimise chemical hazard
Criteria- indicators	Material recycling	Sustainable processes for chemical/biological recycling
	Organic recycling	-
Target 6		“Waste” utilization vs. “Waste” treatment [38,40,41]
Objective		Enabling non-toxic circularity Technology innovations to enable sustainable circular material flows and supply
Criteria- indicators	Material recycling	Waste utilization as feedstocks through their recirculation
	Organic recycling	-
Target 7		Maximize function/profit/sustainability & minimize health hazards vs. maximize function/profit [38–41]
Objective		Advanced process sustainability Sustainable chemistry innovation to improve resource efficiency, pollution prevention and waste minimization

		Health protection
		Safeguard the health of workers, consumers and vulnerable groups
Criteria- indicators	Material recycling	Recyclate and recycled chemical recovery efficiency, waste–emissions impact on sustainability
	Organic recycling	Resource efficiency–waste–emissions impact on organic recycling

CRedit authorship contribution statement

D.B.: Methodology, Formal analysis, Investigation. A.P.: Conceptualization, Investigation. M.H.: Conceptualization, Investigation. A.A: Writing-original draft, Formal Analysis, Investigation. MT. M.: Supervision, Writing-review & editing. SM. I.: Writing-original draft. Conceptualization, Investigation. D.L.: Conceptualization, Investigation. A.K.: Methodology, Formal analysis, Investigation, 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.

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*** When assessing where to focus in the future, it is necessary to bear in mind the guidelines developed by established organizations, such as the UNEP, so special interest could be determined for this reference.**

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Declaration of interests

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.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: