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Social life cycle assessment of bio-based products from microbiomes: Additives, bioplastics, pigments and hydrogen

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ABSTRACT

In recent decades, interest in bio-based products from microbiomes has grown significantly, driven by increasing concerns over the sustainability of conventional and chemically derived products. Although significant technical progress has been made, limited awareness and comprehension of their social dimensions persist.

This study aimed to analyse the social performance of the production of 4 bio-based products for both food and non-food applications (i.e. additives (Exopolysacharides (EPS)), bioplastics (Polyhydroxyalkanoates (PHA)), pigments (phycobiliproteins) and hydrogen) by means of novel bio-based routes based on microbiomes, using the Social Life Cycle Assessment (S-LCA) methodology. In total, 9 scenarios were considered, combining the sole or the co-production of different bio-products. The stakeholder groups were: workers, consumers, local community, value chain actors and society.

Results showed that the sole production of bioplastics and hydrogen had the best social performance (total normalised scores up to 2.5 times higher than the other scenarios). It was mainly due to the high acceptance level for consumers and the better performance in terms of public commitment to sustainability issues for society. In particular, the non-food products (bioplastics and hydrogen) seemed to have higher acceptability from consumers and higher interest in terms of regulation and policy development.

On the whole, all the scenarios showed good performance for workers (health and safety), consumers (quality and performance, acceptability) and the local community (number of jobs generated). More efforts should be made to develop specific regulations and policies (especially for additives and pigments) and implementation at full scale should be boosted to cover the technological development gap.

1. Introduction

During the last decades, awareness of bio-based products has increased due to growing concerns about environmentally friendly and sustainable alternatives to chemical-based polymers and energy sources (Sharma et al., 2021). Indeed, bio-based products can replace fossil fuel-derived products, including polymers, additives, pigments, and energy carriers such as hydrogen (H_2). Moreover, in the context of a circular bio-economy, bio-based products can contribute to reducing waste, minimising environmental impact, and promoting resource efficiency (Chrispim et al., 2024).

Bio-based products are materials that can be derived from renewable biological resources or can be synthesised by microorganisms (Rosenboom et al., 2022). Notably, substances produced by microorganisms are of particular interest. Indeed, during the production processes, chemoheterotrophic organisms can extract energy from organic compounds present, for instance, in wastewater, while photoautotrophic organisms can utilise light and CO_2 as energy sources. Both approaches have the potential to support the development of a closed-carbon-loop, fostering a bio-based circular economy (Santagata et al., 2021).

Despite its potential, the examples of industrial production of bio-based products from microorganisms are still limited. Indeed, most processes depend on monoseptic cultivations of production strains, which pose challenges in preventing contamination and avoiding

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evolution away from the desired production phenotype (Mohedano et al., 2022). For instance, Spirulina production, which provides a supplementary protein source (Lafarga et al., 2021), relies on single-strain cultures that require clean feedstocks and are highly susceptible to contamination, increasing production costs.

One way to overcome this limitation is by using microbiomes (i.e. two or more bacterial or microbial groups living symbiotically), also called microbial consortia or mixed cultures. Microbiomes can be divided into natural or synthetic according to their origin. Natural or environmental microbiomes occur naturally in a specific environment (Berg et al., 2020). Conversely, synthetic consortia or microbiomes are human-designed microbial communities composed of microorganisms containing genetic modifications to perform target functions (Johns et al., 2016). Microbiomes can also be classified as photosynthetic or heterotrophic. A photosynthetic microbiome is a microbial community dominated by photosynthetic microorganisms (e.g. cyanobacteria) that obtain energy from photosynthesis (i.e. using sunlight as an energy source and CO_2 as a carbon source). On the other hand, heterotrophic microbiomes are microbial communities dominated by heterotrophic bacteria, which obtain energy and carbon from organic compounds. Finally, according to the target performance needed, individual strains or microorganisms can be extracted from microbiomes, and they are called microbiome isolates (Atlas and Bartha, 2013).

Microbiomes appear functionally robust while maintaining flexibility toward environmental changes, seemingly self-stabilising and reducing susceptibility to contamination from competing microorganisms (Fant et al., 2021). These features offer industrial advantages by addressing strain stability limitations and allowing waste streams to be used as nutrient sources without sterile conditions (Kourmentza et al., 2017).

Currently, the application of microbiomes in industrial settings is mostly limited to specialised communities in food production (e.g. winemaking with yeasts) (Vassilev et al., 2018).

In the past years, significant progress has been made in identifying novel routes for the bio-based production of various materials, including polymers such as bioplastics (i.e. Polyhydroxyalkanoates (PHA)), additives (i.e. Exopolysacharides (EPS)), natural pigments (i.e. phycobiliproteins), and alternative energy sources (i.e. hydrogen) (Arashiro et al., 2020; Altamira-Algarra et al., 2023; Altamira-Algarra et al., 2024a, 2024b, 2024c; Bellver et al., 2024; Lage et al., 2025; Rueda et al., 2022; Rueda et al., 2023; Senatore et al., 2023). These technical advancements have been rigorously analysed from both environmental and economic perspectives, demonstrating their potential environmental sustainability and cost-effectiveness (Arashiro et al., 2018; Arashiro et al., 2022; Rueda et al., 2023). Despite these promising developments, there remains a lack of awareness and understanding regarding the social implications of such bio-based products, which could influence their broader adoption and market penetration. Recently, Social Life Cycle Assessment (S-LCA) has emerged as a reliable methodology to analyse the social performance of different productive schemes with a comprehensive perspective (Huarachi et al., 2020). This method offers several advantages. Unlike traditional social assessment tools (e.g. Social Impact Assessment, Corporate Social Responsibility), which focus solely on direct issues (e.g. on consumers), S-LCA considers both direct and indirect social implications on different stakeholder groups (i.e. workers, consumers, local community, value chain actors and society) (Iofrida et al., 2018). Moreover, it addresses the whole life cycle, including the process of raw material extraction, production, distribution, application, reuse, maintenance, recycling, and final disposal, giving a wider overview of the social implications. Not only has this methodology been under development for application across various sectors, but recent efforts have also focused on its implementation in industrial product development and emerging technologies (Hannouf et al., 2024; Mármol et al., 2023; Padilla-Rivera et al., 2023; van Haaster et al., 2017). Particularly, it has been employed to analyse the social dimensions of the production of different bio-based products, such as bio-based products from short rotation coppice, green methanol in comparison to conventional fossil methanol, or pigments, biofertilizer and bioenergy from microalgae-based systems treating wastewater (Fürtner et al., 2021; Iribarren et al., 2022; Josa and Garfí, 2023).

However, to the best of the authors' knowledge, to date, no studies have been conducted considering the social performance of novel bio-based products produced from microbiomes.

Therefore, this study aimed to analyse, for the first time, the social performance of the production of 4 bio-based products for both food and non-food applications (i.e. additives, bioplastics, pigments and hydrogen) by means of novel bio-based routes based on microbiomes, using the S-LCA methodology. In particular, an existing S-LCA framework has been adapted and applied to this specific case study. Thus, the following research gaps were addressed: (i) What are the most important stakeholders and social aspects to be considered when evaluating the social performance of the production of bio-based products for both food and non-food applications (e.g., additives, bioplastics, pigments, and hydrogen) through novel microbiome-based pathways? (ii) How can the social performance of these products be characterised? (iii) What are the key insights, limitations, recommendations, and policy implications derived from the study? Closing these research gaps is crucial to overcoming the insufficient recognition and understanding of the social implications of bio-based products, which could impede their large-scale adoption and market integration.

2. Materials and methods

2.1. Social life cycle assessment

The S-LCA is a methodology to assess the social impacts or performance of processes and activities throughout their life cycle (UNEP, 2020). It consists of four main steps: 1) goal and scope definition, 2) life cycle inventory, 3) life cycle impact assessment, and 4) interpretation of results. It uses a systematic framework to evaluate the social implications of any activity or process on different stakeholder groups (i.e. workers, consumers, children, local communities, value chain actors and society) (Garfí et al., 2025; Josa and Garfí, 2023; ISO, 2024; UNEP, 2020; Ziegler-Rodriguez et al., 2025). In this study, the social performance, measured at the inventory indicator level, has been analysed using the Reference Scale Approach (UNEP, 2020). The following sections describe the S-LCA steps, which are also depicted in Fig. S1a (Supplementary Material).

2.2. Goal and scope definition

The goal of this S-LCA was to analyse the social performance of the production of 4 bio-based products for both food and non-food applications (i.e. additives, bioplastics, pigments and hydrogen) from microbiomes from an ex-ante perspective. The generation of these products was conceived to be from different arrangements and configurations, in order to obtain different products and acquire the best-performing scenarios from a technical perspective. They were designed considering experimental results obtained in previous studies, as explained in Section 2.1.1. In total, 9 scenarios were considered, combining the sole or the co-production of different bio-products.

Thus, the following scenarios were analysed: i) EPS, pigments and PHA simultaneous obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes); ii) EPS obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes); iii) Pigments obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes); iv) PHA obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes); v) PHA obtention from heterotrophic microbiomes; vi) PHA and EPS obtention from heterotrophic microbiomes; vii) EPS obtention from microbiome isolates; viii) EPS and PHA from microbiome isolates; ix) Hydrogen from synthetic microbiomes.

The selected functional unit was the operation of one plant for one year to produce the bio-based products, and the reference flow for each configuration was 1 kg of each bio-based product produced in each plant (ISO, 2024; UNEP, 2020).

Scenarios and system boundaries are described in the following section.

2.2.1. Bio-based products and scenarios

Additives (i.e. exopolysaccharides - EPS) are complex carbohydrates secreted by cyanobacteria or heterotrophic bacteria. They serve to protect cells from environmental stresses and assist in adhering to surfaces, forming biofilms (Flemming et al., 2016). Due to their unique biological and physicochemical properties, EPS are highly valued in various industries. They are used as additives such as thickeners, stabilisers, and gelling agents in the agri-food, pharmaceutical, and cosmetics sectors (Korcz and Varga, 2021; Waoo et al., 2023). EPS from heterotrophic bacteria or cyanobacteria could replace petroleum-based additives such as plasticisers, thickeners, stabilisers, and surfactants, offering sustainable alternatives that reduce reliance on fossil fuels and synthetic chemicals while also mitigating associated health risks.

Bioplastics (polyhydroxyalkanoates – PHA) are linear polyesters produced in nature by bacterial fermentation of sugar or lipids. PHAs are a diverse group of polyesters naturally produced by various prokaryotic microorganisms, including cyanobacteria and heterotrophic bacteria (Li and Wilkins, 2020). PHAs have a range of mechanical properties, from flexible to rigid, and are well-regarded for their biodegradability, adaptability, and environmental compatibility. As a sustainable alternative to conventional plastics, PHAs hold significant promise for use in plastic production (Naser et al., 2021). Polyhydroxybutyrate (PHB) is a type of PHA that exhibits similar properties to polypropylene (PP). PP is derived from the polymerisation of propylene, a byproduct of petroleum refining. Bio-based plastics like PHAs offer a promising solution to mitigate the environmental impacts associated with traditional plastics, including the detrimental effects of crude oil extraction and the challenges posed by their extremely slow natural degradation (Kumar et al., 2024).

Natural pigments (i.e. phycobilin protein-based pigments) are the proteins responsible for capturing light in photosynthetic organisms such as cyanobacteria. The proteins include phycoerythrin (pink pigment), allophycocyanin (blue-green pigment), and phycocyanin (blue pigment). Phycocyanin is the only natural blue colourant commercially available and has been approved by the Food and Drug Administration (FDA) for use in food colouring (approved in 2013). Synthetic colourants production depends on hydrocarbons and their spill may lead to the pollution of natural ecosystems. Moreover, they have demonstrated adverse effects on human health, posing challenges for their removal from water bodies due to their slow or non-biodegradable nature, and their synthesis relies on hydrocarbons (Tkaczyk et al., 2020).

Biohydrogen (i.e. hydrogen gas biologically produced) can be generated by microorganisms from renewable resources, under a photofermentative regime capturing solar energy and organic substrates (Bozan et al., 2022; Toepel et al., 2023). Hydrogen (H_2) can be produced from a wide range of resources, including fossil fuels or renewable energy sources. However, most of the H_2 production is fossil-based. As of 2022, 96% of hydrogen production came from natural gas, which led to substantial CO_2 emissions, while only 4% was derived from renewable sources, such as electrolysis (EC, 2022c).

As mentioned above, 9 scenarios were considered for the analysis, which combine the sole or the co-production of the different bio-products, considering novel bio-based routes based on microbiomes. The evaluation of single-production and co-production scenarios was carried out to reflect the different technologically feasible strategies, since these processes were previously experimentally optimised for each configuration (Altamira-Algarra et al., 2024a; Altamira-Algarra et al., 2024b; Altamira-Algarra et al., 2024c; Bellver et al., 2024; Torres et al., 2022; Bozan et al., 2022; Toepel et al., 2023). This approach enabled the comparison of performance and resource efficiency depending on (i) the type of product and (ii) the process configuration. Indeed, co-production may offer advantages such as improved biomass utilisation and integrated system valorisation, while sole production can lead to higher specific yields when the process is optimised for a single product. Thus, for all the scenarios, hypothetical plants for the production of the studied bio-based products were defined based on the experimental results. The scenarios considered were as follows:

1) Scenario 1 (S1): EPS, pigments and PHA simultaneous obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). In this scenario, a photobioreactor (PBR) is used to grow natural cyanobacteria-enriched microbiomes until nutrient depletion. Part of the biomass is used for EPS and pigment extraction, and the other for PHA production. After centrifugation, EPS are extracted from the supernatant via ultrafiltration, as outlined in (Altamira-Algarra et al., 2023; Rueda et al., 2023), while pigments are extracted from the biomass using agitation, as described in Bellver et al. (2024). The remaining biomass is redirected to a PHA accumulation PBR following nutrient depletion. After this phase, the biomass is centrifuged, and the supernatant is combined with the EPS extraction process. The biomass pellets are then subjected to chemical extraction with solvents to obtain PHA (Altamira-Algarra et al., 2024a).

2) Scenario 2: EPS obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). In this scenario, a PBR is used to grow natural cyanobacteria-enriched microbiomes. Following centrifugation of the biomass, the pellets are subjected to sonication to extract cell-bound extracellular polymeric substances (EPS). Both the released EPS from the supernatant and the bound EPS from the pellets are extracted through ultrafiltration, as described in Altamira-Algarra et al. (2024a).

3) Scenario 3 (S3): Pigments obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). In this scenario, a PBR is used for the growth of natural cyanobacteria-enriched microbiomes. After the growth phase, the biomass is centrifuged, and the supernatant is discarded. The pellets containing the biomass undergo extraction with agitation to obtain pigments, as detailed in Bellver et al. (2024).

4) Scenario 4 (S4): PHA obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). In this scenario, a PBR is initially used to grow natural cyanobacteria-enriched microbiomes until nutrient depletion. Once nutrients are depleted, the PBR is switched to the PHA accumulation phase (Altamira-Algarra et al., 2024b; Altamira-Algarra et al., 2024c). The biomass is then centrifuged, and the supernatant is discarded. The resulting biomass pellets are subjected to chemical extraction with solvents to obtain PHA.

5) Scenario 5 (S5): PHA obtention from heterotrophic microbiomes. In Scenario 5, a sequencing batch reactor (SBR) is used for growing natural heterotrophic microbiomes. The biomass is then transferred to an accumulation reactor, as described by Fradinho et al. (2016). Following this, a centrifugation step is performed to collect the biomass pellets, while the supernatant is discarded. PHAs are then extracted from the biomass using solvent extraction methods.

6) Scenario 6 (S6): PHA and EPS obtention from heterotrophic microbiomes. In this scenario, an SBR is employed to cultivate natural heterotrophic microbiomes. Part of the biomass is directed to an accumulation reactor, while the remaining biomass is centrifuged for EPS extraction. For PHA recovery, biomass pellets are collected through centrifugation, and the supernatant is discarded. PHA is

then extracted from the biomass using solvents. For EPS recovery, the supernatant from the SBR is subjected to ultrafiltration to extract EPS, while the cell pellets are combined with those from the accumulation PBR for PHA extraction (Torres et al., 2022).

7) Scenario 7 (S7): EPS obtention from microbiome isolates. In this scenario, a single strain isolated from a natural heterotrophic microbiome is cultured in a SBR for EPS production. The recovery process involves centrifugation to separate the biomass from the supernatant, which is then processed through ultrafiltration to extract EPS. The centrifuge pellets are discharged as residual biomass (Torres et al., 2022).

8) Scenario 8 (S8): EPS and PHA from microbiome isolates. In Scenario 8, a single strain isolated from a natural heterotrophic microbiome is cultured in a SBR to produce both EPS and PHA. EPS are produced and recovered as described in Scenario 7. Following the centrifugation step, PHA is extracted from the residual biomass using solvent extraction methods (Torres et al., 2022).

9) Scenario 9 (S9): Hydrogen from synthetic microbiomes. In this scenario, a synthetic microbiome primarily composed of photosynthetic microorganisms is cultivated in a capillary biofilm reactor. Raw materials are delivered through the capillary biofilm using a peristaltic pump, while light is supplied by a light-emitting diode (LED) system. Hydrogen (H_2) is recovered from the gaseous phase within the capillary, and the biomass is discharged (Bozan et al., 2022; Toepel et al., 2023).

All the described scenarios, including the layout of the hypothetical plants and their system boundaries, are shown in Fig. 1. In particular, the system boundaries were considered to be cradle-to-gate, since they included: i) the acquisition of raw materials (including transportation and supply); ii) microbiome cultivation; iii) downstream separation, extraction, purification and formulation of the bio-based products; iv) management and emissions control. Construction, decommissioning and capital goods of the plants and equipment, the use phase and end-of-life of the products, and off-site infrastructure (roads, pipelines, buildings) have been excluded from this assessment.

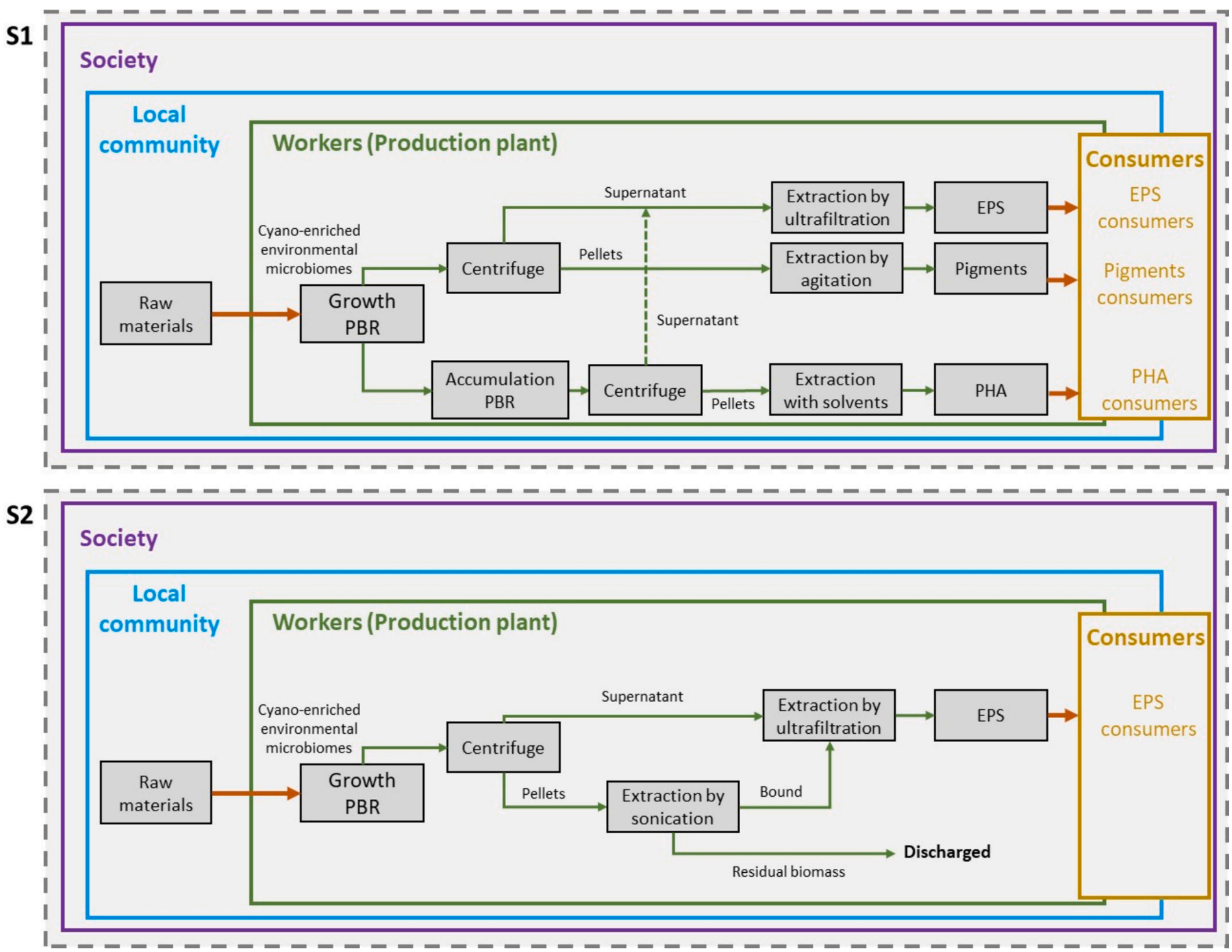


Fig. 1. System boundaries of the analysed scenarios: S1) EPS, pigments and PHA simultaneous obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S2) EPS from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S3) Pigments from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S4) PHA from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S5) PHA from heterotrophic microbiomes. S6) PHA and EPS from heterotrophic microbiomes. S7) EPS from microbiome isolates. S8) EPS and PHA from microbiome isolates. S9) Hydrogen from synthetic microbiomes. Note: EPS: exopolysaccharides (additives); PHA: polyhydroxyalkanoates (bioplastics). PBR stands for photobioreactor, SBR for sequencing batch reactor, and LED for light-emitting diode.

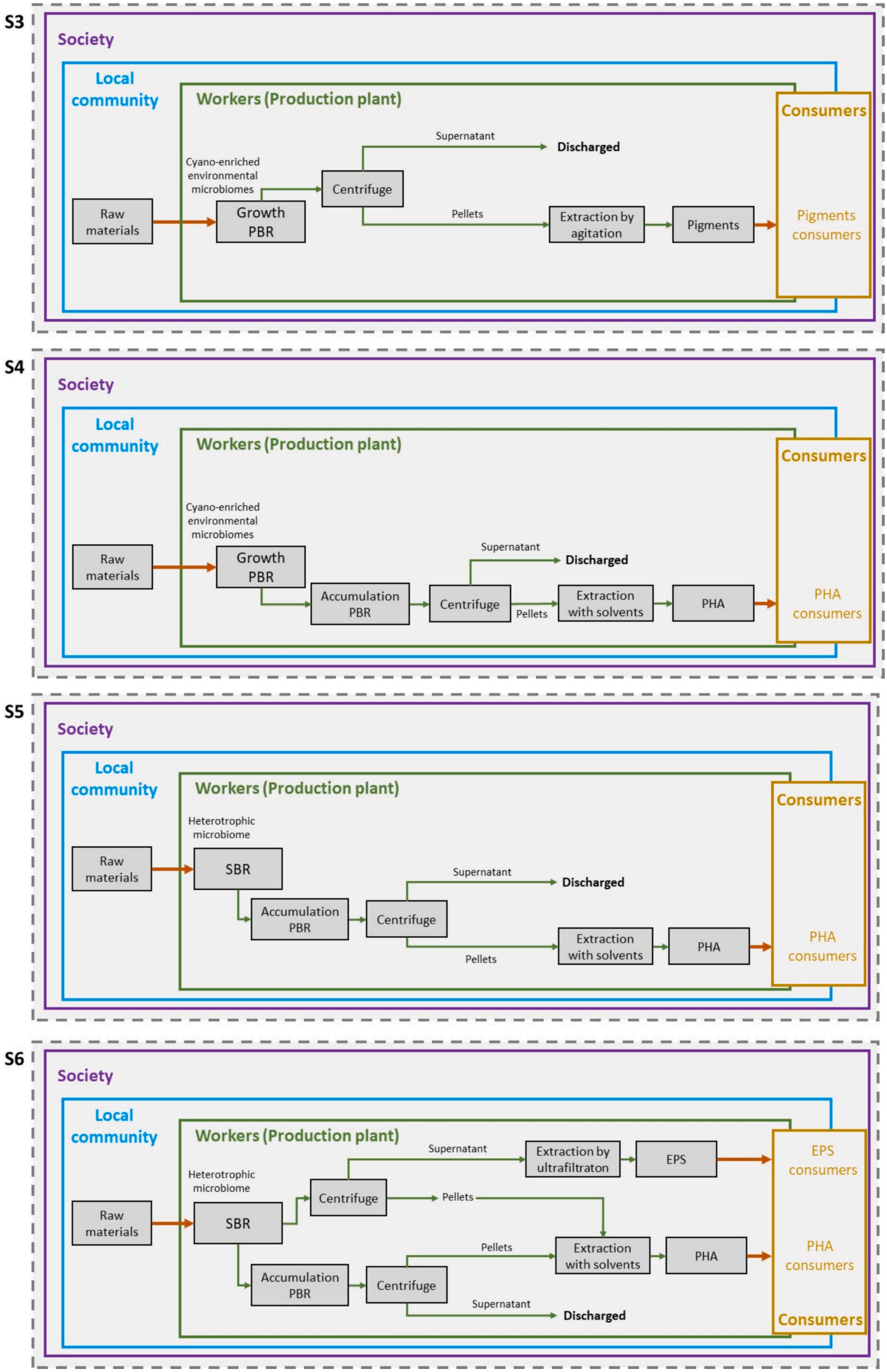

S3
Society
Local community
Workers (Production plant)
Consumers
Raw materials
Cyano-enriched environmental microbiomes
Growth PBR
Centrifuge
Supernatant
Discharged
Pellets
Extraction by agitation
Pigments
Pigments consumers
S4
Society
Local community
Workers (Production plant)
Consumers
Raw materials
Cyano-enriched environmental microbiomes
Growth PBR
Accumulation PBR
Centrifuge
Supernatant
Discharged
Pellets
Extraction with solvents
PHA
PHA consumers
S5
Society
Local community
Workers (Production plant)
Consumers
Raw materials
Heterotrophic microbiome
SBR
Accumulation PBR
Centrifuge
Supernatant
Discharged
Pellets
Extraction with solvents
PHA
PHA consumers
S6
Society
Local community
Workers (Production plant)
Raw materials
Heterotrophic microbiome
SBR
Centrifuge
Supernatant
Extraction by ultrafiltraton
EPS
EPS consumers
Pellets
Accumulation PBR
Centrifuge
Pellets
Extraction with solvents
PHA
PHA consumers
Supernatant
Discharged
Consumers

Fig. 1. (*continued*).

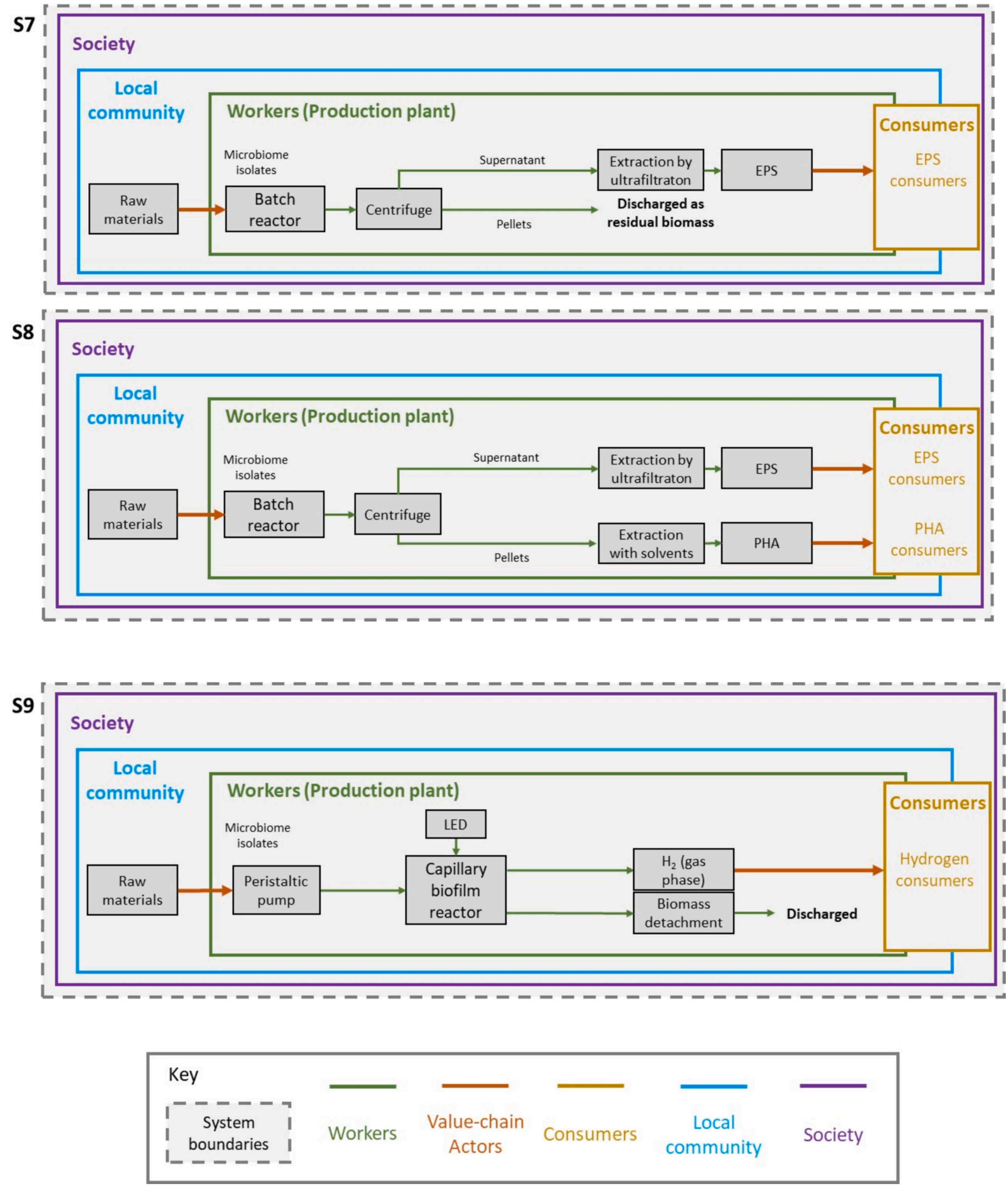


Fig. 1. (*continued*).

2.3. Life cycle inventory

This study collected specific quantitative and qualitative data. These data were directly obtained from interviews, surveys and roundtables performed with stakeholders and experts (n = 50) (see Supplementary Material – S2). All the inventory data was gathered and/or estimated for each plant over one year, and scaled to the functional unit when necessary. In the scenarios producing more than one product, the inventory was first aggregated at the plant-year level and then related to each reference flow (1 kg of each product) by dividing it by the annual output of each product.

The impact categories and related subcategories and indicators were chosen following the recommendations from the UNEP Life Cycle Initiative guidelines and methodological sheets (UNEP, 2020, 2021). The details on the impact categories, impact subcategories, their indicators and how they are assessed are described in the following sections.

Table 1
Summary of stakeholders, impact categories, impact subcategories and impact assessment indicators.

Stakeholders	Description	Stakeholder subcategory	Impact category	Impact subcategory	Indicator	Scales/values	Reference for scale values assignment
Workers	Technicians, heads and administration	–	Working conditions	Health and safety [MI]	Maintenance and operation tasks risks	Hazard (Scale 1 to 5) x Severity (Scale 1 to 4) [QL,N]	Experts' roundtables
Consumers	Consumers of material/ immaterial outputs (i.e. natural pigments, additives, bioplastics and hydrogen)	Pigments consumers	Health and safety	Quality and performance [PI]	Expressive and Instrumental performance	Performance scale (1 to 5) [QL,P]	Survey (experts)
			Human rights	Acceptability [PI]	Acceptance level	Acceptance scale (1 to 5) [QL,P]	Survey (experts and consumers)
		Additives (EPS) consumers	Health and safety	Quality and performance [PI]	Instrumental performance	Performance scale (1 to 5) [QL,P]	Survey (experts)
			Human rights	Acceptability [PI]	Acceptance level	Acceptance scale (1 to 5) [QL,P]	Survey (experts and consumers)
		Bioplastics (PHA) consumers	Health and safety	Quality and performance [PI]	Instrumental performance	Performance scale (1 to 5) [QL,P]	Survey (experts)
			Human rights	Acceptability [PI]	Acceptance level	Acceptance scale (1 to 5) [QL,P]	Survey (experts and consumers)
		Hydrogen consumers	Health and safety	Quality and performance [PI]	Instrumental performance	Performance scale (1 to 5) [QL,P]	Survey (experts)
			Human rights	Acceptability [PI]	Acceptance level	Acceptance scale (1 to 5) [QL,P]	Survey (experts and consumers)
Local community	Community living nearby the plant	–	Socio-economic repercussions	Local employment [MI]	Employment generation	Number of jobs generated [QT,P]	Experts' roundtables
Value chain actors	Actors directly involved in value chain activities (i.e. suppliers, hauliers, retailers)	Actors involved in the production of the bio-based products	Socio-economic repercussions	Promotion of social responsibility [MI]	Regulation implementation level	Scale (1 to 7) [QL,P]	Survey, experts' roundtables
		Actors involved in the transportation of the bio-based products	Socio-economic repercussions	Promotion of social responsibility [MI]	Regulation implementation level	Scale (1 to 7) [QL,P]	Survey, experts' roundtables
Society	Society in general terms	–	Socio-economic repercussions	Public commitment to sustainability issues (additives production and use) [MI]	Presence of documents on sustainability issues	Scale (1 to 7) [QL,P]	Survey, experts' roundtables
				Public commitment to sustainability issues (pigments production and use) [MI]	Presence of documents on sustainability issues	Scale (1 to 7) [QL,P]	Survey, experts' roundtables
				Public commitment to sustainability issues (bioplastics production and use) [MI]	Presence of documents on sustainability issues	Scale (1 to 7) [QL,P]	Survey, experts' roundtables
				Public commitment to sustainability issues (hydrogen production and use) [MI]	Presence of documents on sustainability issues	Scale (1 to 7) [QL,P]	Survey, experts' roundtables
				Technological development (additives production and use) [PI]	Technology readiness level	Scale (1 to 9) [QL,P]	Survey (experts)
				Technological development (pigments production and use) [PI]	Technology readiness level	Scale (1 to 9) [QL,P]	Survey (experts)
				Technological development (bioplastics production and use) [PI]	Technology readiness level	Scale (1 to 9) [QL,P]	Survey (experts)
				Technological development (hydrogen production and use) [PI]	Technology readiness level	Scale (1 to 9) [QL,P]	Survey (experts)

Note: Additives: exopolysaccharides (EPS). Bioplastics: polyhydroxyalkanoates (PHA). MI: company/management-driven impact subcategory. PI: product-driven impact subcategory. QL: qualitative indicator. QT: quantitative indicator. P: the higher, the more positive. N: the higher, the more negative.

2.4. Stakeholders, impact categories and impact assessment

The stakeholder groups and the impact categories and subcategories were selected in order to properly assess the social performance generated by the analysed systems through a materiality assessment (i.e. a procedure to choose relevant issues) (UNEP, 2020). Since this is an ex-ante study, the materiality assessment was nurtured by a comprehensive literature review and a series of brainstorming sessions and roundtable discussions with experts and stakeholders. In particular, the materiality assessment followed a systematic approach for identifying and prioritising stakeholders and relevant impact subcategories, as suggested by UNEP (2020) and Bouillass et al. (2021) (Fig. S1b). Stakeholders were first identified through literature-based screening and then refined through consultations involving experts and stakeholders, which led to the inclusion of additional groups. Subsequently, a preliminary set of impact categories was defined based on existing frameworks (Josa and Garfí, 2023) and refined through a sectoral risk analysis to identify potential social and socio-economic hotspots across the life cycle. A participatory prioritisation process was then applied to finalise the relevant impact subcategories and indicators. Overall, the participatory approach aimed to enhance the representativeness and relevance of the assessment by integrating diverse perspectives on social issues.

The stakeholder groups identified were:

i) Workers: the workers of the bio-based products hypothetical plants, including technicians, heads and administration.
ii) Consumers: the consumers of the bio-based products (i.e. natural pigments, additives, bioplastics and hydrogen).
iii) Local community: people living near the plants producing the bio-based products.
iv) Value chain actors: the actors directly involved in value chain activities (i.e. suppliers, hauliers, retailers).
v) Society: the society in general terms.

Since individuals may simultaneously act as workers and/or members of the local community, while being part of society, interrelations might be present among some of the stakeholder groups (Ziegler-Rodriguez et al., 2025). For instance, consumers can belong to both the local community and society, as depicted in Fig. 1.

In this study, the impact categories considered were: working conditions, health and safety, human rights and socio-economic repercussions (UNEP, 2020).

Table 1 shows the impact categories and subcategories, and the indicators used to assess the social performance of the scenarios analysed. The impact subcategories were classified into two groups (Table 1): i) the company/management-driven issues, which are those attributable to organisational management; ii) technology/product-driven issues, which are those more tightly linked to the nature of the technology or the type of bio-based product. In particular, the former group comprises the health and safety for workers, local employment for the local community, promotion of social responsibility for value chain actors and public commitment to sustainability issues for society. On the other hand, the latter includes quality and performance and acceptability for consumers and technological development for society.

All the indicators were semiqualitative. For all the indicators, the higher the value the better social performance, except for health and safety, where the higher the value the more negative social performance.

As mentioned above, this study employed the Reference Scale Approach (UNEP, 2020). Thus, to assess the social performance and indicators of the selected scenarios, reference scales were defined based on existing literature, established guidelines, and a thorough analysis of the specific sector (Josa and Garfí, 2023; UNEP, 2020). These reference scales were particularly grounded in relevant standards, common and recognised practices. The scales were mainly adapted from the existing literature and sometimes designed ad hoc to reflect varying levels of social performance and compliance by interpreting these norms, practices, goals, and targets (Goedkoop et al., 2018; UNEP, 2020). Once defined, the reference scales were validated during experts' roundtables. All the reference scales are detailed in the following sections for each stakeholder group (Section 2.4.1 to 2.4.5). As mentioned above, all the knowledge required to assess the indicators and assign the reference values to each scenario was gained from interviews, surveys and roundtables specifically developed for this case study and performed with stakeholders and experts ($n = 50$) (see Supplementary Material – S2 and S3).

2.4.1. Workers

Workers were all the employees and personnel of the hypothetical plants producing bio-based products, including heads and administration staff. For this stakeholder group, the impact category considered was working conditions, and the subcategory was health and safety (Table 1).

2.4.1.1. Working conditions

2.4.1.1.1. Health and safety. This impact subcategory measured the effect of the operation and maintenance of the equipment in each hypothetical plant. To evaluate this impact subcategory, two indicators were considered: hazard and severity (Campbell and Smith, 2007; Karakhan and Gambatese, 2018; Josa and Garfí, 2023). These two indicators were multiplied to obtain the risk.

The machinery and processes identified as possible sources of hazard were scenario-dependent, as shown in Fig. 1. They included pumps, centrifuges, reactors (e.g. SBR, PBR), and the use of chemicals (e.g. solvents). For each process/machine, seven different potentially hazardous events were included in the analysis: oxygen deficiency, physical injuries, toxic gases and vapours, infections, fire, explosions, and electrocution (Spellman, 2020; Josa and Garfí, 2023).

Each process/machine was assigned a value for hazard and severity for each event. As mentioned above, the hazard and severity values were multiplied to obtain the risk. Values from hazard and severity were obtained from experts in the field. The scales used to assign hazard and severity values are shown in Tables 2 and 3, respectively.

Afterwards, the risks of each process/machine and event were added to obtain the total risk by considering all the equipment and processes in each scenario.

2.4.2. Consumers

Consumers were considered to be all the people who would consume or use each of the analysed bio-based products. A consumer group for each of the 4 bio-based products was considered (Table 1). The impact categories health and safety and human rights were examined for this stakeholder group. The subcategories were quality and performance, and acceptability, respectively (Table 1).

2.4.2.1. Health and safety

2.4.2.1.1. Quality and performance. For the quality and performance impact subcategory, the scale used by Josa and Garfí (2023) was adapted, as presented in Table 4. This scale follows the logic of a Likert scale, where the higher the value of the scale the better the performance of the product. For natural pigments, the 2 features analysed were expressive performance (e.g. colour) and instrumental performance (e.g.

Table 2
Scale used for the measurement of risk hazard (Josa and Garfí, 2023).

Scale		Description
1	Unlikely	Unexpected, but might occur
2	Seldom	Expected to occur on a rare basis
3	Occasional	Expected to occur occasionally
4	Likely	Probably will occur often
5	Frequent	Probably will occur very often

Table 3
Scale employed for the measurement of risk severity (Josa and Garfí, 2023).

Scale		Description
1	Negligible	Damage probably less than accident or incident levels
2	Moderate	Incident to minor accident damage
3	Critical	Accident level injury and equipment damage
4	Catastrophic	Loss of life, complete equipment loss

Table 4
Scale employed to assess quality and performance (Josa and Garfí, 2023).

Scale		Description
5	Very high quality	Performance of complete quality parameters
4	High quality	Inessential deviations
3	Satisfactory quality	Pronounced deviations, insignificant defects
2	Marginally satisfactory quality	Significant defects
1	Unsatisfactory quality	Serious defects

production process or usage simplicity), while for the other products, only the latter was considered (Haghighat, 2017; Josa and Garfí, 2023). Average values gained from the surveys for each scenario were used.

2.4.2.2. Human rights

2.4.2.2.1. Acceptability. The acceptability impact subcategory was included in the analysis since it is one of the key issues for a successful penetration of the bio-based products in the market (Macht et al., 2023). At the same time, consumer acceptability is considered a human right component since a product should be designed in order to satisfy consumers' needs, especially for food products (Garfí et al., 2025; Morris, 2025).

In this case, the scale applied by Josa and Garfí (2023) was adapted. The measurement of the acceptance indicator was performed with a scale ranging from 5 to 1, where the highest value reflects a totally acceptable product, and the lowest value a totally unacceptable product (Table 5). To assess this indicator, experts and consumers were asked to define their acceptance level for each bio-based product. To obtain the final value, the average of the values assigned to the bio-based products produced in each scenario was calculated.

2.4.3. Local community

For the local community stakeholder group (i.e. people living near the hypothetical plants), the considered impact category was the socio-economic repercussions and the subcategory was local employment (Table 1).

2.4.3.1. Socio-economic repercussions

2.4.3.1.1. Local employment. For the local employment impact subcategory, the indicator used was the employment generation. It was expressed as the number of workers generated by the implementation of the hypothetical plants producing the bio-based products analysed (Padilla-Rivera and Güereca, 2019; Josa and Garfí, 2023). Thus, the number of workers needed in each scenario was calculated based on the required processes, machinery and activities (including technicians, heads and administration).

Table 5
Scale used to evaluate bio-based product acceptance.

Scale	
5	Totally acceptable
4	Slightly acceptable
3	Undecided
2	Slightly unacceptable
1	Totally unacceptable

2.4.4. Value chain actors

The value chain actors were considered to be all the suppliers, hauliers and retailers involved in the bio-based products value chain. In this case, the impact category considered was socio-economic repercussions and the subcategory was the promotion of social responsibility (Table 1).

2.4.4.1. Socio-economic repercussions

2.4.4.1.1. Promotion of social responsibility. In this study, two main stages have been considered in the life cycle of the bio-based products analysed: 1) production of the bio-based products, and 2) transportation and marketing of the bio-based products (Table 1).

The performance was measured by addressing the regulation or legislation implementation level with regard to social responsibility that regulates the actions of the value chain actors considered. Regarding this, a scale from 1 to 7 that considers different regulation implementation levels was adapted (Josa and Garfí, 2023) (Table 6). Scale values were obtained from experts' roundtables and surveys. The final value for each scenario was derived by summing the scale scores assigned to each value chain actor group.

2.4.5. Society

For the society stakeholder group, the socio-economic repercussions impact category was considered. The two impact subcategories accounted for were: i) public commitment to sustainability issues; and ii) technological development (Table 1).

2.4.5.1. Socio-economic repercussions

2.4.5.1.1. Public commitment to sustainability issues. The public commitment to sustainability issues impact subcategory was measured using a scale from 1 to 7 (Josa and Garfí, 2023; U.S. Agency for International Development, 2000) (Table 7). This assessment consisted of the evaluation of the presence of documents related to sustainability issues that regulate each of the bio-based product production processes. Scale values were obtained from experts' roundtables and surveys. The final score was derived by calculating the average of the scores assigned to the different bio-based products produced in each scenario.

2.4.5.1.2. Technological development. The technological development impact subcategory was measured considering the technology readiness level indicator (Dovichi Filho et al., 2021; Josa and Garfí, 2023). A scale from 1 to 9 was used, as shown in Table 8. Average scores from the survey were assigned to each scenario.

2.5. Normalisation

The results of each impact subcategory/indicator were normalised by employing the min/max procedure, where the minimum score obtained is converted to 0, while the maximum is converted to 1. The remaining values are converted to numbers ranging between 0 and 1 (Josa and Borrion, 2025). The formula used is presented in Eq. (1).

Table 6
Scales used for the evaluation of the regulation implementation level (Josa and Garfí, 2023).

Scale	Regulation implementation level
7	New regulations
6	Existing authority
5	Policy
4	Industry standards
3	Guidance
2	Information
1	Knowledge

Table 7
Scales used for the evaluation of the presence of documents on sustainability issues (Josa and Garfí, 2023).

Scale	Description
7	A supportive national policy
6	A strategic plan
5	A National control programme that is highly placed within the government structure
4	A comprehensive programme that addresses all key aspects of prevention, care, and mitigation
3	A comprehensive research programme
2	Adequate funding
1	Sustained monitoring and evaluation

Table 8
Scales applied for the assessment of technological readiness level (Josa and Garfí, 2023).

Scale		Description
9	Deployment	Extensive implementation
8		A few records of implementation
7		First implementation
6	Development	Industrial pilot
5		Demonstration pilot
4		Experimental pilot
3	Research	Concept validation
2		Concept and application formulation
1		Basic principles

$$x_{norm} = \frac{x - min(x)}{max(x) - min(x)} \quad (1)$$

Eq. (1) was used to normalise all the indicators, except for the health and safety impact category (Table 1), whose scale was inverted (i.e. the higher the indicator, the worse). In this case, the maximum score was converted into 0, and the minimum one into 1.

2.6. Monte Carlo analysis

An uncertainty analysis was used to explore the potential outcomes of the model based on inputs variation, aiming to assess the influence of data errors on the final results. Additionally, it accounts for potential uncertainties and biases stemming from the sample size.

It was carried out using the Monte Carlo analysis (Bamber et al., 2020; Lipton et al., 1995). In this method, a random set of input data values is generated from the probability distribution of the dataset. Then, these values are employed to obtain the output of the model. The result is a distribution of the probability of the output variables generated from the variations in the input values. In this study, the input values corresponded to the different indicators, while the output represented the S-LCA results.

Normal probability distribution functions were chosen as a rough approximation for the different variables, given that the real distribution was unknown. Normal probability density functions require the mean and the standard deviation. In instances where the data was constrained within specific values (i.e. survey results ranging from 1 to 5), the boundaries were incorporated into the model.

The mean was defined as the value presented in the results section. The minimum and maximum values were determined by subtracting and adding the standard deviation, respectively. For those cases where standard deviation could not be obtained (i.e. indicators evaluated through experts' roundtables by consensus), a variance percentage was taken into account. This percentage was defined as 10% for those indicators defined through scales (which were most of the indicators in this study) and 5% for the remaining indicators (Josa and Garfí, 2023).

The Monte Carlo analysis was replicated 10,000 times. Once the distribution of each indicator was calculated, they were normalised considering Eq. 1, resulting in a distribution ranging between 0 and 1 for all the indicators. Afterwards, the obtained values were summed to determine the distribution of the total impact for each scenario.

Moreover, two additional runs of the Monte Carlo analysis were performed to test the core assumptions of the assessment: i) lower variance, equal to half of the original percentages (i.e. 5% for indicators defined by scales and 2.5% for the remaining ones), and ii) higher variance, equal to twice the original percentages (i.e. 20% for indicators defined by scales and 10% for the remaining ones). It was assumed that no correlation existed between the indicators.

3. Results and discussion

3.1. Social life cycle assessment

The following sections analyse the results for each of the stakeholder groups, while the inventory results for each subcategory are presented in the Supplementary material (S4).

3.1.1. Workers

The results for the workers stakeholder group are shown in Fig. 2. Scenarios S1 and S6 (co-production of EPS, pigments and PHA from photosynthetic microbiomes, and of PHA and EPS from heterotrophic microbiomes, respectively) showed the worst performance since they present the highest health and safety risks for workers. This was due to the complexity of the systems that produce more than one product simultaneously and, thus, have a higher number of equipment and machinery which increases the probability of hazard events.

On the contrary, Scenarios S2, S7 and S3 (sole production of EPS and pigments) are simpler systems with a lower amount of equipment, which leads to a lower probability of risks for workers.

These results were in accordance with previous studies that evaluated the health and safety of people working in hypothetical microalgae-based systems for the production of natural pigments, bioenergy and biofertilizers with similar methodology (Josa and Garfí, 2023). In particular, the scores obtained for Hazard x Severity were between 100 and 275 for all the scenarios considered in both investigations (Fig. 2). Moreover, both studies used an ex-ante perspective and predicted the hazard and severity values for each equipment by means of experts' roundtables and workshops. On the other hand, ex-post studies estimated this subcategory considering the number of fatal accidents and sick-leave days per year and per employee, but with difficulties in

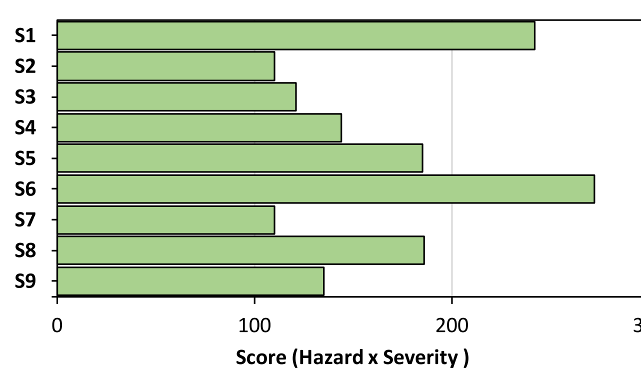


Fig. 2. Results for workers – health and safety impact subcategory (Hazard x Severity). Note that for hazard x severity indicators, the higher the more negative. Scenarios: S1) EPS, pigments and PHA simultaneous obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S2) EPS from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S3) Pigments from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S4) PHA from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S5) PHA from heterotrophic microbiomes. S6) PHA and EPS from heterotrophic microbiomes. S7) EPS from microbiome isolates. S8) EPS and PHA from microbiome isolates. S9) Hydrogen from synthetic microbiomes.

obtaining data from companies (Fürtner et al., 2021; Garfí et al., 2025). This highlights that the used methodology is not only appropriate for evaluating technologies and processes at an early stage of development, but it can also be applied in ex-post studies when data on accidents or sick leave are not available. Moreover, other studies highlighted the increased supply-chain complexity of green systems (e.g. for green fuel production) compared to conventional ones (Iribarren et al., 2022). Additionally, working conditions have been identified as a hotspot of social issues in previous studies assessing the social performance of bioenergy production (Valente et al., 2018; Zhang et al., 2021).

Since this impact subcategory is attributable to organisational management, the social performance of the scenarios considered might be improved by specific measures promoted by the companies, for example, health and safety certification, risk prevention plan, measures to improve mental health (Garfí et al., 2025; Møller et al., 2024). These aspects should be considered in future ex-post studies.

3.1.2. Consumers

Figs. 3 and 4 show the results for the quality and performance, and acceptability impact subcategories for the consumer stakeholder group. Regarding the quality and performance impact subcategory, all the scenarios showed satisfactory results (Table 3). In particular, Scenario S5 showed the highest quality and performance, followed by S3. Both of them are scenarios that produce only one product (PHA and pigments, respectively). Previous studies investigating social issues of bio-based products from a consumer perspective showed that the health and safety impact category was recognised as 'very important,' since it is considered a key determinant for consumers (Falcone and Imbert, 2018). In particular, they emphasised that consumers' willingness to pay is strongly affected by this category (Falcone and Imbert, 2018). This highlights the importance of addressing this social issue when evaluating the social performance of bio-based products.

Regarding the acceptance impact subcategory, all the scenarios obtained high scores, which indicates the high acceptance level of these products by the consumers. These results were in accordance with the literature. Indeed, several authors stated that in general, bio-based products have a positive social acceptance, particularly if they are also functional and environmentally friendly (Sijtsema et al., 2016; Kymäläinen et al., 2022; Ruf et al., 2022). Among the scenarios, the sole production of bioplastics (S4 and S5) and hydrogen (S9) showed the highest scores. The slightly higher acceptance level of bioplastics (PHA) and hydrogen with respect to pigments and additives (EPS) could be explained because of the positive perception of functionality, versatility and safety, which are the most valued qualities by consumers when referring to marketing-related activities of bio-based products (Ruf et al., 2022). Also, usually, consumers are less resistant to novel non-food products than food products. Moreover, Sijtsema et al. (2016) also stated that consumers' perception of bio-based products is directly related to consumer awareness, since it is more accepted when the consumer is aware of its benefits. Since acceptability is a product-related impact subcategory, a broader, ex-post analysis should be conducted to compare these bio-based products with conventional ones once they are commercialised. This research at a consumer-perception level might clarify which aspects influence more consumers' perceptions and possible mixed (positive and negative) feelings toward bio-based products (Kymäläinen et al., 2022).

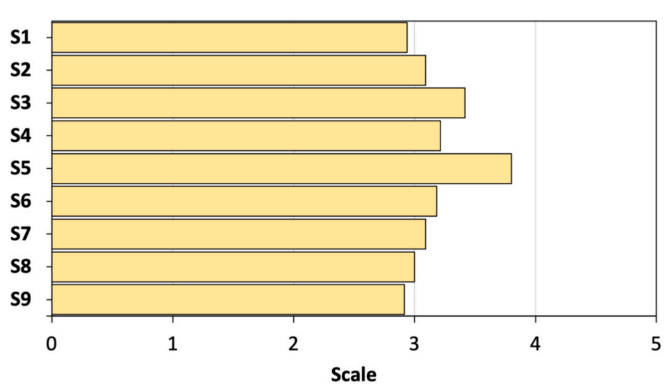


Fig. 3. Results for consumers - quality and performance impact subcategory. Scenarios: S1) EPS, pigments and PHA simultaneous obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S2) EPS from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S3) Pigments from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S4) PHA from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S5) PHA from heterotrophic microbiomes. S6) PHA and EPS from heterotrophic microbiomes. S7) EPS from microbiome isolates. S8) EPS and PHA from microbiome isolates. S9) Hydrogen from synthetic microbiomes.

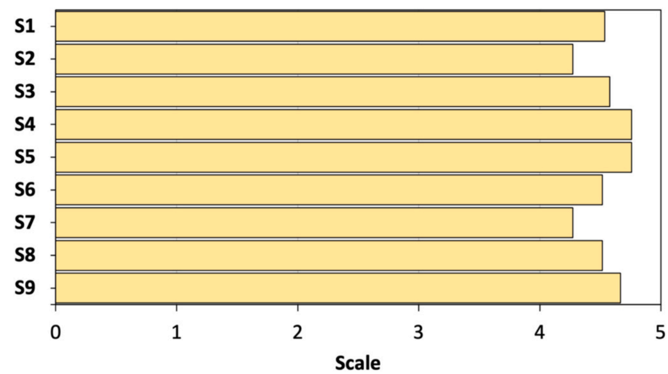


Fig. 4. Results for consumers – acceptability impact subcategory. Scenarios: S1) EPS, pigments and PHA simultaneous obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S2) EPS from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S3) Pigments from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S4) PHA from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S5) PHA from heterotrophic microbiomes. S6) PHA and EPS from heterotrophic microbiomes. S7) EPS from microbiome isolates. S8) EPS and PHA from microbiome isolates. S9) Hydrogen from synthetic microbiomes.

3.1.3. Local community

Concerning the local community, Scenarios S1 and S6 (co-production of EPS, pigments and PHA from photosynthetic microbiomes, and of

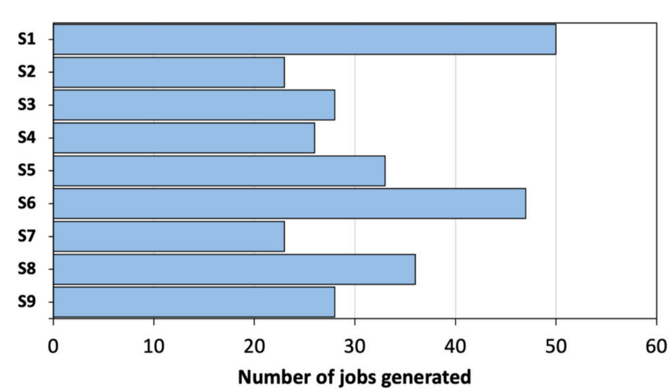


Fig. 5. Results for local community – local employment impact subcategory. Scenarios: S1) EPS, pigments and PHA simultaneous obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S2) EPS from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S3) Pigments from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S4) PHA from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S5) PHA from heterotrophic microbiomes. S6) PHA and EPS from heterotrophic microbiomes. S7) EPS from microbiome isolates. S8) EPS and PHA from microbiome isolates. S9) Hydrogen from synthetic microbiomes.

PHA and EPS from heterotrophic microbiomes, respectively) showed the highest performance in number of jobs generated (Fig. 5). As mentioned above, these scenarios were the most complex and, thus, require a higher number of machinery and workers compared to the other scenarios.

For instance, it was estimated that for Scenario S1, where additives, bioplastics and pigments are simultaneously produced, 50 employees were needed. On the other hand, for the sole production of hydrogen (S9), and additives (S2 and S7), fewer than 30 workers were needed. These results were in accordance with other studies that evaluated the employment generation in hypothetical microalgae-based systems for the production of natural pigments, bioenergy and biofertilizers using similar methodology (Josa and Garfí, 2023). In particular, in both studies, the number of jobs created in the most complex scenarios was approximately 1.5 times higher than in the other scenarios.

However, other S-LCA studies carried out using an ex-post perspective pointed out the difficulties in evaluating this indicator due to the lack of companies' transparency and the information regarding the number of jobs generated in the local community (Garfí et al., 2025).

As noted for other management-driven issues, the social performance of the scenarios analysed in terms of local employment could be enhanced by adopting specific policies such as prioritising local hiring, providing skills training to community members, partnering with local businesses and educational institutions, developing local supply chains, and supporting local economic development initiatives (Bartik, 2020). These aspects require consideration in an ex-post future evaluation.

3.1.4. Value-chain actors

Regarding value chain actors, the regulation implementation level showed to be the same for all the scenarios (Fig. 6). Indeed, existing European legislation on bio-based products (Regulation 1907/2006, 2025; European Commission, 2022a) covers a wide range of areas. In particular, for the evaluation of this impact category, the existing EU Directive on corporate sustainability reporting (Directive 2022/2464, 2025), and the guidelines on corporate social responsibility in transportation (Responsible Trucking, 2021) were considered. According to the employed scale (Table 5), both documents were classified as guidance and information, respectively. It has been considered that procurement activities and complementary services for the assessed scenarios might not differ, as these activities are not as product-specific as the generated goods. It is worth mentioning that the two documents (Directive 2022/2464, 2025; Responsible Trucking, 2021) considered for the evaluation of this indicator are generic documents that do not specifically address social responsibility issues in the value chain of bio-based products. This is in accordance with previous studies carried out in different fields, which found that, despite supply chains having a significant social implication, usually greater than companies' operations, research and regulation regarding the social responsibility of value chain actors is still limited (Garfí et al., 2025; Patil et al., 2022; Wang et al., 2022). Thus, to date, value chain actors have been included in only a few S-LCA studies (Rebolledo-Leiva et al., 2023).

This fact points out the necessity to develop specific regulations or legislation that regulates the actions of the value chain actors involved in the production of bio-based products. It could be promoted at the management and organisational level by assessing suppliers' practices to identify social and environmental risks, and by incentivising compliance with social responsibility standards through measures such as long-term contracts or increased purchase orders.

3.1.5. Society

Figs. 7 and 8 show the results of public commitment to sustainability issues and technology development impact subcategories for society, respectively.

Regarding public commitment to sustainability issues, scenarios S9, S4, and S5 (hydrogen and PHA sole production from photosynthetic and heterotrophic microbiomes, respectively) showed the best performance. As mentioned above, this indicator evaluates the presence of documents that support the commitment to social sustainability issues, which regulate the processes under consideration.

In the last decades, hydrogen has gained attention since it might be an alternative, affordable, secure and sustainable energy solution. In fact, in 2019, the EU published the Hydrogen Roadmap – Europe, a report that stated that achieving the energy transition in the EU will require hydrogen at large scale (Fuel Cells and Hydrogen Joint Undertaking, 2019). Therefore, in 2022, the EU launched REPowerEU plan, an EU strategic plan aimed at reducing Europe's dependence on fossil fuels and accelerating the transition to green energy, promoting, among other supplies, renewable hydrogen as a solution (European Commission, 2022b). In addition, in 2023, the EU also published a supplementing directive to REPowerEU plan to regulate the production of renewable liquid and gaseous transport fuels, with a focus on renewable hydrogen (Commission Delegated Regulation 2023/1184, 2025).

Regarding bioplastics (PHA), in 2022, the EU published the EU

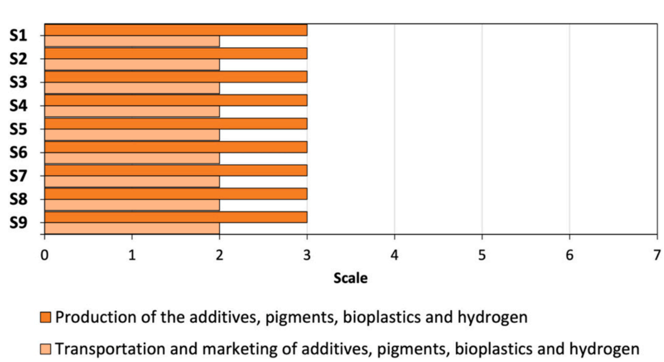
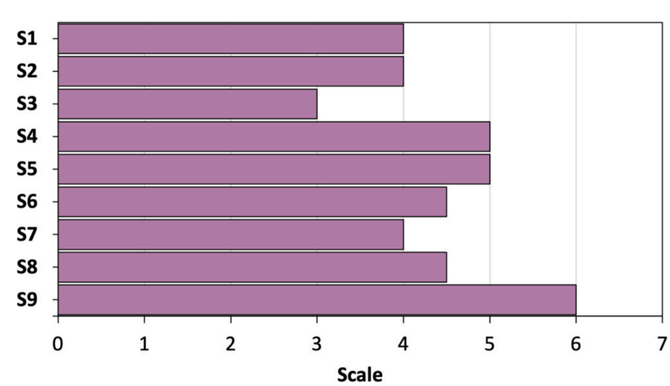


Fig. 6. Results for value chain actors - promotion of social responsibility impact subcategory. Scenarios: S1) EPS, pigments and PHA simultaneous obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S2) EPS from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S3) Pigments from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S4) PHA from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S5) PHA from heterotrophic microbiomes. S6) PHA and EPS from heterotrophic microbiomes. S7) EPS from microbiome isolates. S8) EPS and PHA from microbiome isolates. S9) Hydrogen from synthetic microbiomes.



1. 7. Results for society - public commitment to sustainability issues impact subcategory. Scenarios: S1) EPS, pigments and PHA simultaneous obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S2) EPS from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S3) Pigments from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S4) PHA from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S5) PHA from heterotrophic microbiomes. S6) PHA and EPS from heterotrophic microbiomes. S7) EPS from microbiome isolates. S8) EPS and PHA from microbiome isolates. S9) Hydrogen from synthetic microbiomes.

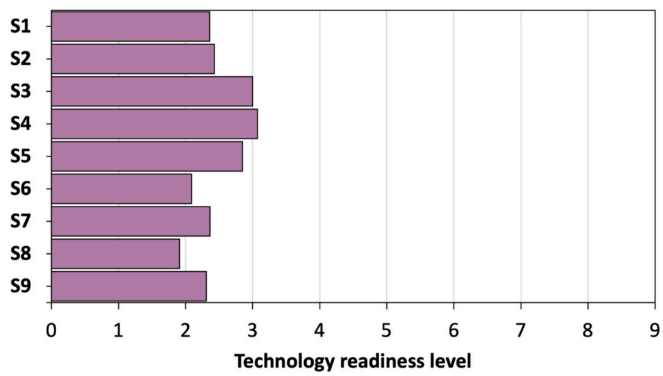


Fig. 8. Results for society - technological development impact subcategory. Scenarios: S1) EPS, pigments and PHA simultaneous obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S2) EPS from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S3) Pigments from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S4) PHA from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S5) PHA from heterotrophic microbiomes. S6) PHA and EPS from heterotrophic microbiomes. S7) EPS from microbiome isolates. S8) EPS and PHA from microbiome isolates. S9) Hydrogen from synthetic microbiomes.

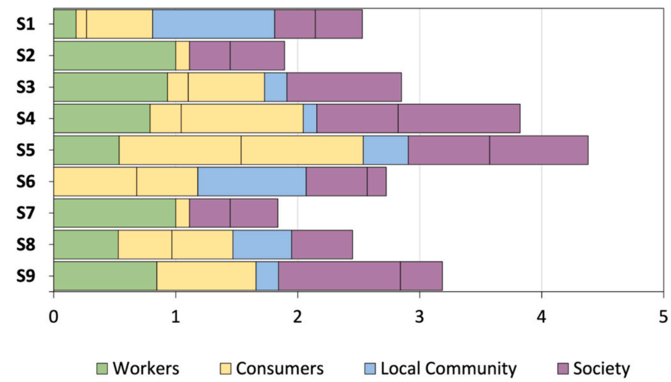


Fig. 9. Total normalised scores for all the scenarios. Scenarios: S1) EPS, pigments and PHA simultaneous obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S2) EPS from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S3) Pigments from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S4) PHA from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S5) PHA from heterotrophic microbiomes. S6) PHA and EPS from heterotrophic microbiomes. S7) EPS from microbiome isolates. S8) EPS and PHA from microbiome isolates. S9) Hydrogen from synthetic microbiomes.

policy framework on bio-based, biodegradable and compostable plastics (EC, 2022a), which can be considered a national control program highly placed within the government structure (Table 6). Moreover, bioplastics have been considered within the Circular Economy Action Plan (EC, 2020a) and the Horizon Europe Research and Innovation Programme (EC, 2020b).

In the case of additives (EPS), the only identified existing document regarding sustainability issues is an EU Commission Regulation on specifications for food additives (Commission Regulation 231/2012, 2025). As it is generic and not specific for bio-based products, it has been classified as a comprehensive program that addresses all key aspects of prevention, care, and mitigation (Table 6).

Finally, even though the Food and Drug Administration (FDA) approved phycocyanin as the only natural blue colourant commercially available for use in food colouring (approved in 2013), pigments production is only indirectly addressed by EU's REACH regulation (i.e. a Regulation on the registration, evaluation, authorisation and restriction of chemicals) (EC, 2006) and research projects (PROMICON, 2023). Thus, pigment production has been considered to be regulated by a comprehensive research programme (Table 6).

In the case of the technological development impact category, all the scenarios obtained similar results. In particular, the production of the bio-based products considered in this study is still in the research stage (Table 7). Indeed, only scenarios S3, S4 and S5 (pigments obtention from photosynthetic microbiomes, PHA obtention from photosynthetic microbiomes and PHA obtention from heterotrophic microbiomes, respectively) are considered to achieve concept validation (Table 7). This means that these technologies and processes still lack maturity and need further research to be suitable for effective development and deployment. However, although applying S-LCA to the early stage of technology development is a highly complicated task, it remains a top priority to ensure proper social conditions when the process is implemented in the bio-product sector (Cadena et al., 2019).

3.1.6. Normalisation

Fig. 9 shows the normalised results. In the normalisation step, the results for value chain actors were not considered, since all the scenarios obtained the same score. Also, it is worth mentioning that, even though individual scores showed slight differences among the scenarios in several impact subcategories (e.g. consumers' acceptability), the normalisation procedure magnifies these differences.

Results showed that Scenario S4 (PHA obtention from photosynthetic microbiomes or cyanobacteria) and Scenario S5 (PHA obtention from heterotrophic microbiomes) had the best social performance, mainly because of the better social implications for the consumers and society stakeholder groups. This indicated that the sole production of bioplastics, from either heterotrophic or photosynthetic microbiomes, had the best overall social performance. It was mainly because of: i) better quality and performance, and higher acceptance level for consumers; ii) better performance in terms of public commitment to sustainability issues and higher technological development for society, compared to the other scenarios.

Hydrogen production from synthetic microbiomes (S9) also showed good social performance. It was mainly due to: i) low risks for health and safety for workers; ii) high acceptance level for consumers; and iii) high performance in terms of public commitment to sustainability issues for society.

Finally, all the scenarios for the production of bio-based products (pigments, additives, bioplastics and hydrogen) showed good performance for workers, consumers, and the local community.

More efforts should be made to develop specific regulations and policies for both the promotion of social responsibility (value chain actors) and the public commitment to sustainability issues (society) in the field of bio-based products (especially for additives and pigments). Moreover, implementation at full scale should be boosted in order to cover the technological development gap.

3.1.7. Monte Carlo analysis

Fig. 10 presents the results of the uncertainty analysis. It shows the probability distribution function and its respective cumulative distribution function for each scenario. It can be observed that scenarios S4, S5 and S9 (PHA obtention from photosynthetic microbiomes, PHA obtention from heterotrophic microbiomes and hydrogen from synthetic microbiomes, respectively) were still the ones with the highest social performance, followed by scenario S3 (pigments obtention from photosynthetic microbiomes).

Moreover, the additional Monte Carlo runs showed that increasing or decreasing uncertainties did not modify the final ranking of the scenarios (Fig. S5 – Supplementary Material). Changes in variance narrowed or widened the distributions. In fact, the resulting probability distributions and cumulative probability distributions showed increased or decreased dispersion, but the final ranking of the scenarios remained unchanged (Fig. S5 – Supplementary Material). Since changing the magnitude of the variance indirectly tests the influence of the

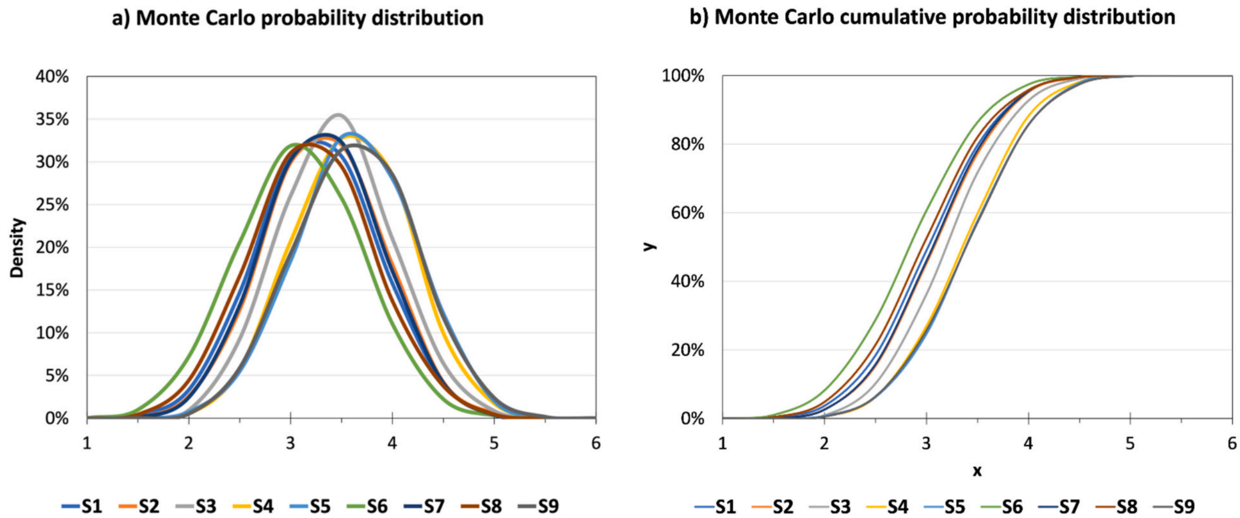


Fig. 10. Results of the Monte Carlo Analysis. Scenarios: a) Probability distribution of Monte Carlo simulation of total normalised values. b) Cumulative probability distribution of Monte Carlo simulation of total normalised values. Scenarios: S1) EPS, pigments and PHA simultaneous obtention from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S2) EPS from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S3) Pigments from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S4) PHA from photosynthetic microbiomes (cyanobacteria-enriched microbiomes). S5) PHA from heterotrophic microbiomes. S6) PHA and EPS from heterotrophic microbiomes. S7) EPS from microbiome isolates. S8) EPS and PHA from microbiome isolates. S9) Hydrogen from synthetic microbiomes.

distribution shape and type (Helton and Davis, 2003), this analysis also proved that the results were not sensitive either to the variance levels or to the use of normal distributions as a modelling assumption.

3.2. Key insights, limitations and policy implications

This study not only provided valuable insights into the social performance of producing bio-based products from microbiomes but also highlighted several limitations and remaining challenges in the field.

Firstly, it demonstrated that the comprehensive frameworks used and applied to this specific case study might serve as guidance for assessing the social performance of novel and developing processes for the production of bio-based products from an ex-ante perspective. It is of utmost importance to promote research on sustainable bio-based products, which should be both environmentally and socially friendly, as a key step toward the transition to a circular bio-economy. However, it has to be mentioned that, even though many of the subcategories and indicators used in this study have a broad applicability, social hotspots, key issues, and relevant stakeholders may differ across case studies. Therefore, each context must be carefully assessed to identify its specific stakeholders, dynamics, and social concerns, particularly in settings marked by emerging technologies, where new systems are to be implemented and no prior knowledge exists about how they will interact with different stakeholders.

Concerning the stakeholder categories, as mentioned above, in this study, they were defined following the UNEP guidelines for S-LCA, which primarily focus on workers, consumers, local communities, value chain actors, and society. Vulnerable groups (i.e. children, the elderly, and indigenous communities) were not explicitly considered, since there is currently limited availability of specific social indicators and data related to these populations in the context of the assessed technologies, and the production systems analysed do not directly involve or target these groups (MacNeil et al., 2021; Pérez-López et al., 2025). Also, the potential social impacts for children identified in UNEP methodological sheets can be considered quite limited in the case of bio-based products production when assuming that activities are performed in the European context (Pérez-López et al., 2025; UNEP, 2021). Moreover, although children are recognised as a vulnerable population, particularly in relation to manufacturing activities as part of the local community and as consumer-related issues, the present study focused exclusively on adults over 18 years of age. This decision was driven by ethical and practical considerations, as research involving minors entails stricter ethical protocols and greater complexity in data collection. Nevertheless, it is acknowledged that the exclusion of such vulnerable groups may underestimate potential negative or positive social performance. Therefore, future ex-post research should explore methods to explicitly incorporate diverse stakeholder perspectives (e.g. children, the elderly, and indigenous communities) by developing context-sensitive indicators and ethically robust protocols to achieve a more comprehensive and socially inclusive sustainability assessment of bio-based products.

A key and well-known challenge in S-LCA is the limited availability of data. In this study, due to its ex-ante nature (i.e. processes still in an early stage of development and low technological readiness level), some information had to be estimated (e.g. the hypothetical plants design, employment generation), and the results were analysed using an uncertainty analysis. In particular, the hypothetical plant design may have had the greatest influence on the final ranking. Moreover, the low technological readiness level of the studied processes mainly affected the company/management-driven subcategories (i.e. health and safety for workers, local employment for the local community, promotion of social responsibility for value chain actors and public commitment to sustainability issues for society). As mentioned above, in these impact subcategories, the social performance of the studied bio-based products might be enhanced by specific measures and policies promoted by the companies. Nevertheless, the results of the uncertainty analysis showed that the outcomes of this study provided a robust overview of the good social performance of bio-based products from microbiomes and highlighted the areas where further research is needed to support their introduction into the market. This analysis should be replicated as an ex-post evaluation to identify social hot-spots to be improved once the bio-based products are already commercialised. It should be carried out considering companies' performance rather than the distinct aspects of the specific products assessed, including both management-driven and product-driven social issues. The ex-post analysis should also include other impact subcategories (e.g. working hours, fair salary) that could not be analysed in the present study because of the lack of data.

Lastly, the findings of this study aim to inform policymakers and provide scientific evidence to support and promote the sustainable production of bio-based products from microbiomes. Indeed, integrating bio-based products from microbiomes into circular economy strategies requires a multidimensional assessment approach that includes social sustainability as a core component of the transition toward resilient and socially responsible biotechnological systems. Accordingly, the results of this study may assist the public sector in formulating policies that encourage the adoption of more sustainable products, similar to those promoted in other industrial sectors. For instance, the EU Cosmetics Regulation (EC) 1223/2009 (EC, 2009), complemented by the cosmetic claims criteria set out in Regulation (EU) 655/2013 and related Commission guidance (EU, 2013), establishes a clear structure to ensure that any product (including the microbiome-related ones) is safe and supported by adequate evidence and communicated in a truthful, transparent, and verifiable manner. In parallel, the EU Fertilising Products Regulation (EU) 2019/1009 explicitly recognises microbial plant biostimulants as a distinct product category, setting specific requirements on safety and efficacy (European Parliament and Council, 2019). These two frameworks illustrate how regulators can balance innovation and consumer protection: by defining product categories, clarifying acceptable claims, and aligning scientific evidence with market access.

Key recommendations to enhance the social performance related to the production, marketing and use of the bio-based products from microbiomes include: i) fostering investment in research and innovation to analyse and enhance the sustainability of these ground-breaking processes; ii) promoting partnership, collaboration and knowledge-sharing among researchers, policymakers, and industry stakeholders to increase interdisciplinary research in this field; iii) boosting implementation at pilot and full-scale to cover the technological development gap and increase awareness through demonstration; iv) developing and strengthening specific regulations and policies (particularly those that promote social responsibility among value chain actors and encourage public commitment to sustainability) that enable safe applications and encourage their use in different sectors; v) creating labels for bio-based products that are both environmentally and socially friendly, focusing on transparency, sustainability, and ethical production; vi) fostering the integration of S-LCA as a requirement in research and innovation calls within the bioeconomy sector, to ensure that projects are not only technically and environmentally viable but also socially responsible; vii) establishing harmonized social indicators at the European level to enable consistent assessment, benchmarking, and future regulation of bio-based products across different sectors and applications.

Finally, the findings of this study also directly contribute to several Sustainable Development Goals (SDGs) and circular economy targets, particularly SDG 7 (Affordable and clean energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), by demonstrating the social viability of bio-based products from microbiomes as sustainable alternatives to chemical-based products and fossil energy sources.

4. Conclusions

The aim of this study was to analyse the social performance of the production of 4 bio-based products (i.e. additives, bioplastics, pigments and hydrogen) by means of novel bio-based routes based on microbiomes, using the Social Life Cycle Assessment methodology.

Results showed that the production of bioplastics and hydrogen had the best social performance. It was mainly due to the high acceptance level for consumers and the better performance in terms of public commitment to sustainability issues for society. In particular, the non-food products (i.e. bioplastics and hydrogen) seemed to have higher acceptability from consumers and higher interest in terms of regulation and policy development.

On the whole, all the scenarios for the production of bio-based products (pigments, additives, bioplastics and hydrogen) showed good performance for workers (health and safety), consumers (quality and performance, acceptability) and the local community (number of jobs generated).

The findings of this study aim to support evidence-based policymaking toward the sustainable production of microbiome-based bio-products. Key recommendations include: i) to foster investment in research and innovation to promote interdisciplinary studies of these ground-breaking processes; ii) to boost implementation at full scale to cover the technological development gap; iii) to develop specific regulations and policies, especially for both the promotion of social responsibility (value chain actors) and the public commitment to sustainability issues (society) in the field of bio-based products (especially for additives and pigments); iv) creating labels for bio-based products that are both environmentally and socially friendly, focusing on transparency, sustainability, and ethical production; v) fostering the integration of S-LCA as a requirement in research and innovation calls within the bioeconomy sector. Specific regulations and policies should enable safe applications and encourage the development, use and marketing of bio-based products from microbiomes in different sectors. Furthermore, this analysis should be replicated as an ex-post evaluation to identify social hot-spots for improvement once the bio-based products are commercialised, in order to overcome the limitations identified in this study.

Finally, the frameworks used in this study may provide a valuable basis for evaluating the social performance of emerging and innovative bio-based production processes from an ex-ante perspective, boosting the transition toward a circular bio-economy.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2026.108333.

Data availability

Data will be made available on request.

References

Altamira-Algarra, B., Rueda, E., Lage, A., San León, D., Martínez-Blanch, J.F., Nogales, J., García, J., Gonzalez-Flo, E., 2023. New strategy for bioplastic and exopolysaccharides production: enrichment of field microbiomes with cyanobacteria. New Biotechnol. 78, 141–149. https://doi.org/10.1016/j.nbt.2023.10.008.

Altamira-Algarra, B., Garcia, J., Torres, C.A.V., Reis, M.A.M., Gonzalez-Flo, E., 2024a. Exploring Simultaneous Production of Polyhydroxybutyrate and Exopolysaccharides in cyanobacteria-Rich Microbiomes (Under revision in New Biotechnology).

Altamira-Algarra, B., Lage, A., García, J., Gonzalez-Flo, E., 2024b. Photosynthetic species composition determines bioplastics production in microbiomes: strategy to enrich cyanobacteria PHB-producers. Algal Res. 103469. https://doi.org/10.1016/j.algal.2024.103469.

Altamira-Algarra, B., Lage, A., Meléndez, A.L., Arnau, M., Gonzalez-Flo, E., García, J., 2024c. Bioplastic production by harnessing cyanobacteria-rich microbiomes for long-term synthesis. Sci. Total Environ. 176136. https://doi.org/10.1016/j.scitotenv.2024.176136.

Arashiro, L.T., Montero, N., Ferrer, I., Acién, F.G., Gómez, C., Garfí, M., 2018. Life cycle assessment of high rate algal ponds for wastewater treatment and resource recovery. Sci. Total Environ. 622–623 (1118–1130).
Arashiro, L.T., Ferrer, I., Pániker, C.C., Gómez-Pinchetti, J.L., Rousseau, D.P.L., Van Hulle, S.W.H., Garfí, M., 2020. Natural pigments and biogas recovery from microalgae grown in wastewater. ACS Sustain. Chem. Eng. 8 (29), 10691–10701. https://doi.org/10.1021/ACSSUSCHEMENG.0C01106.
Arashiro, L.T., Josa, I., Ferrer, I., Van Hulle, S.W.H., Rousseau, D.P.L., Garfí, M., 2022. Life cycle assessment of microalgae systems for wastewater treatment and bioproducts recovery: natural pigments, biofertilizer and biogas. Sci. Total Environ. 847, 157615. https://doi.org/10.1016/J.SCITOTENV.2022.157615.
Atlas, R.M., Bartha, R., 2013. Microbial Ecology: Fundamentals and Applications. Pearson.
Bamber, N., Turner, I., Arulnathan, V., Li, Y., Zargar Ershadi, S., Smart, A., Pelletier, N., 2020. Comparing sources and analysis of uncertainty in consequential and attributional life cycle assessment: review of current practice and recommendations. Int. J. Life Cycle Assess. 25, 168–180.
Bartik, T., 2020. Bringing Jobs To People: Improving Local Economic Development Policies. Upjohn Institute Policy Papers. Policy Paper No. 2020–023. https://doi.org/10.17848/pol2020-023.
Bellver, M., Altamira-Algarra, B., García, J., Ferrer, I., Gonzalez-Flo, E., 2024. Enhancing pigment production with cyanobacteria-rich microbiomes: effect of light quality and exposure time. Algal Res. 83. https://doi.org/10.1016/j.algal.2024.103726.
Berg, G., Rybakova, D., Fischer, D., Cernava, T., Vergès, M.C.C., Charles, T., Chen, X., Cocolin, L., Eversole, K., Corral, G.H., Kazou, M., Kinkel, L., Lange, L., Lima, N., Loy, A., Macklin, J.A., Maguin, E., Mauchline, T., McClure, R., Schloter, M., 2020. Microbiome definition re-visited: old concepts and new challenges. Microbiome 8 (1), 1–22. https://doi.org/10.1186/S40168-020-00875-0/FIGURES/7.
Bouillass, G., Blanc, I., Perez-Lopez, P., 2021. Step-by-step social life cycle assessment framework: a participatory approach for the identification and prioritization of impact subcategories applied to mobility scenarios. Int. J. Life Cycle Assess. 26, 2408–2435.
Bozan, M., Schmid, A., Bühler, K., 2022. Evaluation of self-sustaining cyanobacterial biofilms for technical applications. Biofilm 4. https://doi.org/10.1016/J.BIOFLM.2022.100073.
Cadena, E., Rocca, F., Gutierrez, J.A., Carvalho, A., 2019. Social life cycle assessment methodology for evaluating production process design: biorefinery case study. J. Clean. Prod. 238. https://doi.org/10.1016/j.jclepro.2019.117718.
Campbell, J.M., Smith, S.D., 2007. Safety, hazard and risk identification and management in infrastructure management: a project overview. Management 599, 608.
Chrispim, M.C., Mattsson, M., Ulvenblad, P., 2024. Perception and awareness of circular economy within water-intensive and bio-based sectors: understanding, benefits and barriers. J. Clean. Prod. 464, 142725. https://doi.org/10.1016/J.JCLEPRO.2024.142725.
Commission Delegated Regulation 2023/1184, . Commission Delegated Regulation (EU) 2023/1184 Supplementing Directive (EU) 2018/2001 Establishing a Union Methodology Setting Out Detailed Rules for the Production of Renewable Liquid and Gaseous Transport Fuels of Non-biological Origin. http://data.europa.eu/eli/reg_del/2023/1184/oj.
Commission Regulation 231/2012, 2025. Commission Regulation (EU) No 231/2012 Laying Down Specifications for Food Additives Listed in Annexes II and III to Regulation (EC) No 1333/2008. http://data.europa.eu/eli/reg/2012/231/oj.
Directive 2022/2464, 2025. Directive (EU) 2022/2464 Amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as Regards Corporate Sustainability Reporting. http://data.europa.eu/eli/dir/2022/2464/oj.
Dovichi Filho, F.B., Santiago, Y.C., Lora, E.E.S., Palacio, J.C.E., del Olmo, O.A.A., 2021. Evaluation of the maturity level of biomass electricity generation technologies using the technology readiness level criteria. J. Clean. Prod. 295, 126426.
European Commission (EC), 2006. Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32006R1907.
European Commission (EC), 2009. Regulation (EC) No 1223/2009 of the European Parliament and of the Council of 30 November 2009 on Cosmetic Products. Available at: https://eur-lex.europa.eu/eli/reg/2009/1223/oj/eng.
European Commission (EC), 2020a. A New Circular Economy Action Plan - For a Cleaner and More Competitive Europe. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:98:FIN.
European Commission (EC), 2020b. Research and Innovation - Horizon Europe. *https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en*.
European Commission (EC), 2022a. EU Policy Framework on Biobased, Biodegradable and Compostable Plastics. https://environment.ec.europa.eu/publications/communication-eu-policy-framework-biobased-biodegradable-and-compostable-plastics_en.
European Commission (EC), 2022b. REPowerEU Plan. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2022:230:FIN.
European Commission (EC), 2022c. Hydrogen. https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en.
European Parliament and the Council, 2019. Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 Laying Down Rules on the Making Available on the Market of EU Fertilising Products and Amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and Repealing Regulation (EC) No 2003/2003.
European Union (EU), 2013. Commission Regulation (EU) No 655/2013 of 10 July 2013 Laying Down Common Criteria for the Justification of Claims used in Relation to Cosmetic Products. Available at: https://eur-lex.europa.eu/eli/reg/2013/655/oj/eng.
Falcone, P.M., Imbert, E., 2018. Social life cycle approach as a tool for promoting the market uptake of bio-based products from a consumer perspective. Sustainability 10 (4), 1031. https://doi.org/10.3390/su10041031.
Fant, L., Macocco, I., Grilli, J., 2021. Eco-evolutionary dynamics lead to functionally robust and redundant communities. BioRxiv. https://doi.org/10.1101/2021.04.02.438173, 2021.04.02.438173.
Flemming, H.C., Wingender, J., Szewzyk, U., Steinberg, P., Rice, S.A., Kjelleberg, S., 2016. Biofilms: an emergent form of bacterial life. Nat. Rev. Microbiol. 14 (9), 563–575. https://doi.org/10.1038/nrmicro.2016.94.
Fradinho, J.C., Reis, M.A.M., Oehmen, A., 2016. Beyond feast and famine: selecting a PHA accumulating photosynthetic mixed culture in a permanent feast regime. Water Res. 105, 421–428. https://doi.org/10.1016/j.watres.2016.09.022. Nov 15. (Epub 2016 Sep 15. PMID: 27664543).
Fuel Cells and Hydrogen Joint Undertaking, 2019. Hydrogen Roadmap Europe - A Sustainable Pathway for the European Energy Transition. https://op.europa.eu/en/publication-detail/-/publication/0817d60d-332f-11e9-8d04-01aa75ed71a1/language-en.
Fürtner, D., Ranacher, L., Perdomo Echenique, E.A., Schwarzbauer, P., Hesser, F., 2021. Locating hotspots for the social life cycle assessment of bio-based products from short rotation coppice. Bioenergy Res. 14, 510–533.
Garfí, M., Requejo Castro, D., Villanueva, C.M., 2025. Social life cycle assessment of drinking water choices: tap water, bottled mineral water and tap water treated with domestic filters. Environ. Impact Assess. Rev. 112, 107815.
Goedkoop, M.J., Indrane, D., de Beer, I.M., 2018. Product Social Impact Assessment Handbook.
Haghighat, N., 2017. Airline service quality evaluation: A review on concepts and models. Econ. Manage. Sustain. 2 (2), 31–47.
Hannouf, M.B., Padilla-Rivera, A., Assefa, G., Gates, I., 2024. Social life cycle assessment (S-LCA) of technology systems at different stages of development. Int. J. Life Cycle Assess. 1–16.
Helton, J.C., Davis, F.J., 2003. Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems. Reliab. Eng. Syst. Saf. 81 (1), 23–69.
Huarachi, D.A.R., Piekarski, C.M., Puglieri, F.N., de Francisco, A.C., 2020. Past and future of social life cycle assessment: historical evolution and research trends. J. Clean. Prod. 264, 121506.
Iofrida, N., De Luca, A.I., Strano, A., Gulisano, G., 2018. Can social research paradigms justify the diversity of approaches to social life cycle assessment? Int. J. Life Cycle Assess. 23, 464–480.
Iribarren, D., Calvo-Serrano, R., Martin-Gamboa, M., Galan-Martin, A., Guillen-Gosalbez, G., 2022. Social life cycle assessment of green methanol and benchmarking against conventional fossil methanol. Sci. Total Environ. 824, 153840.
ISO, 2024. ISO 14075 - Environmental Management — Principles and Framework for Social Life Cycle Assessment.
Johns, N.I., Blazejewski, T., Gomes, A.L.C., Wang, H.H., 2016. Principles for designing synthetic microbial communities. Curr. Opin. Microbiol. 31, 146–153. https://doi.org/10.1016/J.MIB.2016.03.010.
Josa, I., Borrion, A., 2025. Rebuilding or retrofitting? An assessment of social impacts using social life cycle assessment. Environ. Impact Assess. Rev. 112, 107794.
Josa, I., Garfí, M., 2023. Social life cycle assessment of microalgae-based systems for wastewater treatment and resource recovery. J. Clean. Prod. 407, 137121.
Karakhan, A., Gambatese, J., 2018. Hazards and risk in construction and the impact of incentives and rewards on safety outcomes. Pract. Period. Struct. Des. Constr. 23 (2), 04018005.
Korcz, E., Varga, L., 2021. Exopolysaccharides from lactic acid bacteria: techno-functional application in the food industry. Trends Food Sci. Technol. 110, 375–384. https://doi.org/10.1016/J.TIFS.2021.02.014.
Kourmentza, C., Plácido, J., Venetsaneas, N., Burniol-Figols, A., Varrone, C., Gavala, H. N., Reis, M.A.M., 2017. Recent advances and challenges towards sustainable Polyhydroxyalkanoate (PHA) production. Bioengineering 4 (2), 55. https://doi.org/10.3390/BIOENGINEERING4020055.
Kumar, R., Lalnundiki, V., Shelare, S.D., Abhishek, G.J., Sharma, S., Sharma, D., Kumar, A., Abbas, M., 2024. An investigation of the environmental implications of bioplastics: recent advancements on the development of environmentally friendly bioplastics solutions. Environ. Res. 244. https://doi.org/10.1016/J.ENVRES.2023.117707.
Kymäläinen, T., Vehmas, K., Kangas, H., Majaniemi, S., Vainio-Kaila, T., 2022. Consumer perspectives on bio-based products and brands—a regional Finnish social study with future consumers. Sustainability 14 (6), 3665.
Lage, A., Berrendero, E., García-Abad, L., Martínez-Gutiérrez, C., García, J., Gonzalez-Flo, E., 2025. Assessment of polyhydroxybutyrate production by cyanobacteria strains isolated from environmental water sources using secondary effluent. ACS ES&T Water. https://pubs.acs.org/doi/10.1021/acsestwater.5c00677.
Lafarga, T., Sánchez-Zurano, A., Villaró, S., Morillas-España, A., Acién, G., 2021. Industrial production of spirulina as a protein source for bioactive peptide generation. Trends Food Sci. Technol. 116, 176–185. https://doi.org/10.1016/J.TIFS.2021.07.018.
Li, M., Wilkins, M.R., 2020. Recent advances in polyhydroxyalkanoate production: feedstocks, strains and process developments. Int. J. Biol. Macromol. 156, 691–703. https://doi.org/10.1016/J.IJBIOMAC.2020.04.082.
Lipton, J., Shaw, W.D., Holmes, J., Patterson, A., 1995. Selecting input distributions for use in Monte Carlo simulations. Regul. Toxicol. Pharmacol. 21 (1), 192–198.

Macht, J., Klink-Lehmann, J., Hartmann, M., 2023. Don't forget the locals: understanding citizens' acceptance of bio-based technologies. Technol. Soc. 74, 102318.
MacNeil, K.S., Daniels-Mayes, S., Akbar, S., Marsh, J., Wik-Karlsson, J., Össbo, A., 2021. Social life cycle assessment used in indigenous contexts: a critical analysis. Sustainability 13 (9), 5158. https://doi.org/10.3390/su13095158.
Mármol, C., Martín-Mariscal, A., Picardo, A., Peralta, E., 2023. Social life cycle assessment for industrial product development: a comprehensive review and analysis. Heliyon. 9 (12), e22861.
Mohedano, M.T., Konzock, O., Chen, Y., 2022. Strategies to increase tolerance and robustness of industrial microorganisms. Synth. Syst. Biotechnol. 7 (1), 533. https://doi.org/10.1016/J.SYNBIO.2021.12.009.
Møller, H., Rydhmer, L., Christensen, T., Poulsen, L.K., Olsen, Hanne Fjerdingby, F.K., 2024. Social life cycle assessment in current and future Norwegian livestock production. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-024-02345-3.
Morris, K., 2025. A forgotten element of the right to adequate food: redressing the normative gap regarding consumer acceptability. Hum. Rights Law Rev. 25 (3).
Naser, A.Z., Deiab, I., Darras, B.M., 2021. Poly(lactic acid) (PLA) and polyhydroxyalkanoates (PHAs), green alternatives to petroleum-based plastics: a review. RSC Adv. 11 (28), 17151–17196. https://doi.org/10.1039/D1RA02390J.
Padilla-Rivera, A., Güereca, L.P., 2019. A proposal metric for sustainability evaluations of wastewater treatment systems (SEWATS). Ecol. Indic. 103, 22–33.
Padilla-Rivera, A., Hannouf, M., Assefa, G., Gates, I., 2023. A systematic literature review on current application of life cycle sustainability assessment: A focus on economic dimension and emerging technologies. Environ. Impact Assess. Rev. 103, 107268.
Patil, A., Madaan, J., Chan, F.T., Charan, P., 2022. Advancement of performance measurement system in the humanitarian supply chain. Expert Syst. Applic. 206, 117844.
Pérez-López, P., Rajaonison, A., Zebian, B., Bouallou, C., González-Fernández, C., Greses, S., Gómez-Serrano, C. Acién, Fernández, F.G., 2025. Exploiting outcomes of life cycle costing to conduct coherent screening social life cycle assessments of emerging systems: a case study of microalgae biorefineries. Int. J. Life Cycle Assess. 2025 (30), 770–791.
PROMICON, 2023. Harnessing the Power of Nature Through PROductive MIcrobial CONsortia in Biotechnology - Measure, Model, Master. https://promicon.eu/.
Rebolledo-Leiva, Ricardo, Moreira, María Teresa, González-García, Sara, 2023. Progress of social assessment in the framework of bioeconomy under a life cycle perspective. Renew. Sust. Energ. Rev. 175.
Regulation 1907/2006, 2025. Regulation (EC) No 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency.
Responsible Trucking, 2021. Truck Transport Social Guidelines- An Initiative of the Collaborative Platform Responsible Trucking. https://www.csreurope.org/responsible-trucking-guidelines.
Rosenboom, J.G., Langer, R., Traverso, G., 2022. Bioplastics for a circular economy. Nature Rev. Mater. 7 (2), 117–137. https://doi.org/10.1038/s41578-021-00407-8.
Rueda, E., Altamira-Algarra, B., García, J., 2022. Process optimization of the polyhydroxybutyrate production in the cyanobacteria Synechocystis sp. and Synechococcus sp. Bioresour. Technol. 356, 127330. https://doi.org/10.1016/J.BIORTECH.2022.127330.
Rueda, E., Senatore, V., Zarra, T., Naddeo, V., García, J., Garfí, M., 2023. Life cycle assessment and economic analysis of bioplastics production from cyanobacteria. Sustain. Mater. Technol. 35. https://doi.org/10.1016/j.susmat.2023.e00579.
Ruf, J., Emberger-Klein, A., Menrad, K., 2022. Consumer response to bio-based products–a systematic review. Sustainable Prod. Consumption 34, 353–370.
Santagata, R., Ripa, M., Genovese, A., Ulgiati, S., 2021. Food waste recovery pathways: challenges and opportunities for an emerging bio-based circular economy. A systematic review and an assessment. J. Clean. Prod. 286, 125490. https://doi.org/10.1016/J.JCLEPRO.2020.125490.
Senatore, V., Rueda, E., Bellver, M., Díez-Montero, R., Ferrer, I., Zarra, T., Naddeo, V., García, J., 2023. Production of phycobiliproteins, bioplastics and lipids by the cyanobacteria Synechocystis sp. treating secondary effluent in a biorefinery approach. Sci. Total Environ. 857, 159343. https://doi.org/10.1016/J.SCITOTENV.2022.159343.
Sharma, P., Gaur, V.K., Sirohi, R., Varjani, S., Hyoun Kim, S., Wong, J.W.C., 2021. Sustainable processing of food waste for production of bio-based products for circular bioeconomy. Bioresour. Technol. 325. https://doi.org/10.1016/J.BIORTECH.2021.124684.
Sijtsema, S.J., Onwezen, M.C., Reinders, M.J., Dagevos, H., Partanen, A., Meeusen, M., 2016. Consumer perception of bio-based products—an exploratory study in 5 European countries. NJAS-Wageningen J. Life Sci. 77, 61–69.
Spellman, F.R., 2020. Handbook of Water and Wastewater Treatment Plant Operations. CRC press.
Tkaczyk, A., Mitrowska, K., Posyniak, A., 2020. Synthetic organic dyes as contaminants of the aquatic environment and their implications for ecosystems: a review. Sci. Total Environ. 717. https://doi.org/10.1016/J.SCITOTENV.2020.137222.
Toepel, J., Karande, R., Bühler, B., Bühler, K., Schmid, A., 2023. Photosynthesis driven continuous hydrogen production by diazotrophic cyanobacteria in high cell density capillary photobiofilm reactors. Bioresour. Technol. 373. https://doi.org/10.1016/J.BIORTECH.2023.128703.
Torres, C.A.V., Catalão, M., Freitas, F., Reis, M.A.M., Gonzalez-Flo, E., Altamira-Algarra, B., Bellver-Catalá, M., Garcia, J., 2022. Collection, Pre-screening and Characterization of Natural Microbiomes (D2.1 – PROMICON Project).
UNEP, 2021. Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA) 2021. United Nations Environment Programme (UNEP.
U.S. Agency for International Development, 2000. Measuring Political Commitment - HIV/AIDS Toolkit.
UNEP, 2020. Guidelines for Social Life Cycle Assessment of Products and Organizations, 138.
Valente, C., Brekke, A., Modahl, I.S., 2018. Testing environmental and social indicators for biorefineries: bioethanol and biochemical production. Int. J. Life Cycle Assess. 23, 581–596. https://doi.org/10.1007/s11367-017-1331-x.
van Haaster, B., Ciroth, A., Fontes, J., Wood, R., Ramirez, A., 2017. Development of a methodological framework for social life-cycle assessment of novel technologies. Int. J. Life Cycle Assess. 22, 423–440.
Vassilev, I., Hernandez, P.A., Batlle-Vilanova, P., Freguia, S., Krömer, J.O., Keller, J., Ledezma, P., Virdis, B., 2018. Microbial electrosynthesis of isobutyric, butyric, caproic acids, and corresponding alcohols from carbon dioxide. ACS Sustain. Chem. Eng. 6 (7), 8485–8493. https://doi.org/10.1021/ACSSUSCHEMENG.8B00739/SUPPL_FILE/SC8B00739_SI_002.XLSX.
Wang, S., Su, D., Wu, T., 2022. Environmental and social life cycle assessments of an industrial LED lighting product. Environ. Impact Assess. Rev. 95, 106804.
Waoo, A.A., Singh, S., Pandey, A., Kant, G., Choure, K., Amesho, K.T.T., Srivastava, S., 2023. Microbial exopolysaccharides in the biomedical and pharmaceutical industries. Heliyon 9 (8), e18613. https://doi.org/10.1016/J.HELIYON.2023.E18613.
Zhang, Y., Li, J., Liu, H., Zhao, G., Tian, Y., Xie, K., 2021. Environmental, social, and economic assessment of energy utilization of crop residue in China. Front. Energy 15 (2), 308–319.
Ziegler-Rodriguez, K., Josa, I., Castro, L., Escalante, H., Muñoz Muñoz, A., Garfí, M., 2025. Social life cycle assessment of low-tech digesters for biogas and biofertiliser production in small-scale farms. Sustainable Prod. Consumption 54, 303–323.