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Challenges and limitations of the method when applied to resource recovery systems

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DOI
10.1007/s11367-024-02370-2

Publication date
2024

Document Version
Final published version

Published in
International Journal of Life Cycle Assessment

Citation (APA)
Kokubo Roche, A., Tsalidis, G. A., Blanco, C. F., Dias, D. F. C., & Posada, J. A. (2024). Generic and site-specific social life cycle assessment of municipal wastewater treatment systems in Spain: Challenges and limitations of the method when applied to resource recovery systems. *International Journal of Life Cycle Assessment*, *30*(6), 1480-1504. https://doi.org/10.1007/s11367-024-02370-2

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The International Journal of Life Cycle Assessment (2025) 30:1480–1504
https://doi.org/10.1007/s11367-024-02370-2

SOCIETAL LCA

Generic and site-specific social life cycle assessment of municipal wastewater treatment systems in Spain: challenges and limitations of the method when applied to resource recovery systems

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Received: 24 December 2023 / Accepted: 2 September 2024 / Published online: 2 October 2024
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Abstract

Purpose This work aims to provide insights on the application of social life cycle assessment (S-LCA) in evaluating the social impacts associated with municipal wastewater treatment (WWT). The study assesses the social risks and social performance of two municipal WWT systems in Catalonia, Spain: a conventional wastewater treatment plant (WWTP) (Reference System) and a novel system that recovers water and other valuable resources (Novel System).

Methods S-LCA was conducted at Generic and Site-Specific levels using 1 m^3 of wastewater treatment as the functional unit (FU). The Generic assessment was conducted via the Product Social Impact Life Cycle Assessment (PSILCA) database, while the Site-Specific assessment employed the Subcategory Assessment Method (SAM) with four-level reference scales to assess the social performance of the WWTP operator and its first-tier suppliers. Furthermore, activity variables were calculated based on organizations' shares in the total costs per FU, and the Novel System's multifunctionality was solved through economic allocation. Results were aggregated by *(i)* assigning equal weights to organizations and *(ii)* factoring in organizations' weights and the allocation factor, leading to results per FU.

Results and discussion The Generic analysis results indicated that the Novel System entailed fewer social risks than the Reference System. Most social risks in both systems occurred in the subcategories "Access to material resources," "Fair salary," "Freedom of association and collective bargaining," "Contribution to economic development," and "Corruption." In the Site-Specific assessment, the Novel System presented better social performance than the Reference System per 1 m^3 of wastewater treatment. The latter's performance per FU did not meet the basic requirement in four out of eleven subcategories, mainly due to the performance and weight of a chemical supplier. Allocation greatly benefitted the Novel System's results per FU compared to the results obtained when equal weights were applied.

Conclusions Activity variables were used to connect organizations' conduct with particular WWT systems, and multifunctionality was solved. This approach allowed for obtaining results per FU at both assessment levels. However, social performance was also evaluated by calculating the average social performance of each system without considering activity variables and the FU, leading to different results. The social performance of the Novel System per FU was satisfactory across all subcategories but required improvement in four subcategories based on the average results. Given the limitations of using activity variables and allocation in S-LCA, further research is necessary to appropriately evaluate and compare the social effects of novel resource recovery systems.

Keywords S-LCA · Generic assessment · Site-Specific assessment · Multifunctionality · PSILCA · Reference Scale Impact Assessment approach · Municipal wastewater treatment · Resource recovery systems

1 Introduction

As the global population grows and moves to cities, water scarcity will continue to be aggravated by climate change (Richter et al. 2013; He et al. 2021). Some solutions to urban water scarcity are obtaining water from unconventional water resources and implementing measures for its more efficient use (e.g., by reusing urban and industrial water) (He

Communicated by M. Traverso .

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et al. 2021; Karimidastenaei et al. 2022). However, as these solutions have an impact on the environment, economy, and society (He et al. 2021), it must be ensured that they truly contribute to sustainable development.

Social life cycle assessment (S-LCA) is a framework that both facilitates measuring the social performance of products and services along their life cycles and avoids shifting social problems from one process, location, or point in time to another (Mazzi 2020). Some authors argue that the social impacts of wastewater treatment (WWT) systems are often overlooked, and the use of S-LCA is minimal (Muhammad Anwar et al. 2021; Serreli et al. 2021), particularly, in assessments of resource recovery technologies (Foglia et al. 2021). Therefore, the social impacts of WWT systems, particularly of those that promote treated wastewater reuse, must be further analyzed.

This work mainly aimed at assessing the potential social impacts related to the treatment of municipal wastewater by applying the S-LCA framework described in the S-LCA Guidelines (UNEP 2020) and Methodological Sheets (UNEP 2021). Two wastewater treatment systems in Catalonia, Spain, were analyzed and compared: one was a conventional wastewater treatment plant (WWTP), and the other was an innovative system that not only reclaimed water for reuse but also recovered other valuable materials.

The social risks and the social performance of both systems were assessed through Generic and Site-Specific analyses. The Generic analysis was based on the Product Social Impact Life Cycle Assessment (PSILCA) database and method (Maister et al. 2020), enabling the evaluation of social risks along entire value chains. In contrast, the Site-Specific assessment employed higher resolution data but limited the scope of the assessment to focus specifically on the behavior of the WWTP operator and its first-tier suppliers.

The article is structured as follows. Section 1.1 introduces a brief discussion of some of the main general barriers to S-LCA application. Section 1.2 presents relevant studies in order to learn about the main pitfalls of S-LCA application in the water sector and overcome them in the rest of this work. In Section 2, the WWT systems and the first three stages of S-LCA are described. Next, the Generic and Site-Specific analysis results are presented and discussed in Sections 3 and 4, respectively. Finally, the main conclusions of this study and further research recommendations are suggested in Section 5.

1.1 Brief overview of challenges in S-LCA application

S-LCA employs a mix of methods, representation models, and data on the product system and its social impacts (UNEP 2020; Huertas-Valdivia et al. 2020). S-LCA guidelines were published in 2009 and updated in 2020 (UNEP/SETAC 2009; UNEP 2020). Additionally, impact subcategory descriptions and sets of social indicators were published in the Methodological Sheets in 2013 and updated in 2021 (UNEP/SETAC 2013; UNEP 2021). Despite ongoing efforts to homogenize S-LCA methods, research in the field is still highly fragmented and many limitations persist, e.g., difficulty in accessing data and incorporating social indicators of a more qualitative nature (Mesa Alvarez and Ligthart 2021; Life Cycle Initiative, Social Life Cycle Alliance 2022). The following subsections briefly describe the main challenges of the goal and scope definition phase. A thorough description of S-LCA and its challenges is presented in Kokubo Roche (2022).

1.1.1 Product system and system boundaries

Social impacts can originate due to a project or policy, the technologies themselves, the conduct of organizations, and socioeconomic processes (Lehmann et al. 2011; Zamagni et al. 2011), which suggests that social stressors are mainly created in the Sociosphere. The Sociosphere aims to represent the social aspect of the triple bottom line (the "people" element); hence, it concerns human society and social networks (Irimie et al. 2014; Frederick 2018). Consequently, social impacts have an organizational or "social" nature instead of a strictly technical one (Parent et al. 2010). Therefore, an assessment at a process level is less reasonable in S-LCA as the physical conditions of the processes are not the main cause of impacts on people (except for some direct health impacts) (Dreyer et al. 2006).

In turn, delineating a product system requires careful deliberation (Dreyer et al. 2006). Given the lack of consensus on how this should be done (Zanchi et al. 2018), a combination of a technology-oriented approach with an organization-oriented approach would be ideal as all the technological unit processes and the individual organizations responsible for them would be included (Zanchi et al. 2018).

Furthermore, the system boundaries should also share the product system's dual nature by including an effect-oriented approach and a technology-oriented approach (Zanchi et al. 2018). A double-layer system boundary is relevant for identifying and including all the stakeholders and the unit processes linked to the product system.

1.1.2 Functional unit

As many of the S-LCAs conducted to date indicate, social impacts are mostly analyzed at the organizational level instead of the process level. However, due to the difficulty of linking an organization's conduct with the product under study, the connection between the impacts and the product and its function is somewhat lost (Dreyer et al. 2006). Thus, conflict arises when applying both the functional unit and an organizational perspective in one framework, raising the question of whether the same application of the functional unit in LCA is suitable in S-LCA, which fundamentally aims at improving the *social* aspects of a product system (Zamagni et al. 2011). Consequently, linking social inventory data (e.g., information about an organization's behavior) with the product system presents a challenge (Zamagni et al. 2011).

Generally, to make the results proportional to the product system, practitioners can relate the elementary flows or social stressors to process outputs (like in environmental LCA, E-LCA) or use activity variables to scale the contributions to social impacts from each process in the product system (Parent et al. 2010; Zanchi et al. 2018). Whereas the former implies applying the impact pathway impact assessment (IA) approach, the latter is applicable to the reference scale (RS) IA approach. Since the reference scale approach is often based on an organizational perspective, using activity variables generates results that are representative of each organization's weight relative to the product system (Parent et al. 2010). Nevertheless, it is still questioned whether there are other meaningful ways to represent the social aspects of a product's function, apart from trying to quantitatively link the indicator results with the functional unit (Parent et al. 2010).

1.2 Literature review of S-LCA in the water sector

Relevant S-LCA studies in the water sector were reviewed to determine the use of functional units, the methods applied, and the commonly assessed stakeholder categories and impact subcategories (Kokubo Roche 2022, Online Resource 1, Table S1).

Functional units were defined in most research articles, but, if considered, the results were only implicitly presented in relation to them (e.g., Tsalidis and Korevaar 2019; Serreli et al. 2021). Some authors acknowledged the difficulty of using functional units in S-LCA (Shemfe et al. 2018). For example, Shemfe et al. (2018, p. 3) defined two "ornamental" functional units: 1 kg of copper recovered and 1 kg of formic acid produced. Although the authors' goal was not to compare the social risks across the supply chains of bioelectrochemical systems components, but rather to assess the social hotspots along them, the results were based on the components' import values. As expected, the commodity with the highest import value showed the greatest social risks. Additionally, since the bioelectrochemical systems perform the same function of treating organic wastewater, those functional units could be adjusted and described as reference flows. A similar example is that of Serreli et al. (2021), who defined a functional unit composed of three parts, each representing a different line of wastewater treatment at an electronics and semiconductor company. Given that each line treated different amounts of wastewater, it was unsurprising that the line treating the largest volume (line 1) exhibited the highest social risks.

Discussions about the selection of stakeholder categories and impact subcategories were often missing. When discussed, such selections were based on findings from previous studies (Opher et al. 2018; García-Sánchez and Güereca 2019).

All studies implemented the RS approach for impact assessment, yet various impact assessment methods were applied. Some authors used existing methods (e.g., the Subcategory Assessment Method by Ramirez et al. (2014)) and databases, others applied a combination of approaches (Do Amaral et al. 2019; García-Sánchez and Güereca 2019), and some applied other methods to S-LCA (Opher et al. 2018; Muhammad Anwar et al. 2021). Furthermore, the reference scales and how the scoring was performed were not reported transparently in many studies, which hampers understanding how the results were produced (see Padilla-Rivera et al. 2016; Do Amaral et al. 2019; García-Sánchez and Güereca 2019; Foglia et al. 2021).

Finally, not all studies presented the four stages of S-LCA, and the interpretation phase was found to be often implicitly discussed or entirely omitted (Padilla-Rivera et al. 2016; Shemfe et al. 2018; Do Amaral et al. 2019; García-Sánchez and Güereca 2019; Tsalidis et al. 2020; Serreli et al. 2021; Foglia et al. 2021). From the number of articles found, it is evident that research on the social implications of WWT systems is still limited; hence, the application of S-LCA in more case studies is encouraged.

2 Methods

2.1 Studied wastewater treatment systems

Two WWT systems located in Catalonia, Spain, were assessed: a WWTP based on conventional activated sludge (hereinafter referred to as the "Reference System") and a novel system comprising an anaerobic membrane bioreactor, a partial nitrification-anammox system, new phosphorous recovery technologies, and a reverse osmosis unit (hereinafter referred to as the "Novel System").

The effluent from the Reference System is directly discharged into the local river without reuse. Conversely, in the Novel System, water for agriculture and industries as well as vivianite are recovered. Additionally, biogas is recovered and fully reused in both systems.

It is worth noting that the Novel System is currently operating at a pilot plant scale. Nevertheless, this study considers data pertaining to its full-scale operation, derived from models, simulations, and literature.

2.2 Social life cycle assessment

S-LCA was employed to assess both the broader social effects of wastewater treatment systems along their supply chains and the specific performance of the organizations involved in these systems. The Generic and Site-Specific assessments play complementary roles in providing a comprehensive overview of these potential social impacts. The following sections detail each phase of the S-LCA process as applied in both the Generic and Site-specific assessments.

2.2.1 Generic assessment

Goal and scope definition

As stated above, part of this study's goal involved evaluating the social risks along the value chains of the Reference and Novel Systems. Additionally, another goal was to identify parts of the value chain that were exposed to higher social risks and where addressing them would be beneficial. To achieve these goals, a generic analysis was conducted using the PSILCA database. This database includes social data on different economic sectors across various countries and provides approximate supply chain configurations for these country-specific sectors (CSS).

- Function and functional unit

The primary function of the studied systems was to treat municipal wastewater so that it meets environmental standards before being reused or discharged into the receiving water bodies. While acknowledging the limitations of linking social impacts to the functional unit in S-LCA (Section 1.1.2), defining a functional unit was deemed relevant in this work as it assisted in comparing two WWT systems. Therefore, the functional unit of both the Novel and Reference Systems was the treatment of 1 m^3 of municipal wastewater. Furthermore, the Novel System's multifunctionality was solved through economic allocation (Section 2.2.2).

- Product system definition

It can be noted that product systems in PSILCA are delineated based on a double-layer approach (Section 1.1.1). Accordingly, Fig. 1 provides a general graphical representation of the studied product systems for the Generic analysis. In Fig. 1, the red and blue main rectangles represent the Sociosphere and the Technosphere, respectively. Thus, the affected stakeholders (Sociosphere) and economic sectors comprising the systems' value chains (Techno- and Sociosphere) were identified.

- System boundaries and cut-off criteria

The use of a social database like PSILCA facilitates the inclusion of a product's or service's entire supply chain. Thus, the scope of the Generic analysis included all the economic sectors since the beginning of the supply chain up until the treatment of wastewater. The coproducts generated were cut-off (Section 2.2.2), and the construction of facilities, maintenance, transportation, and equipment used were excluded from this study.

- Activity variable

In the Generic analysis, the activity variables used were worker hours, which were essential for the calculation of social risks in the PSILCA database. The calculation of activity variables is presented below.

- Stakeholder categories, impact subcategories, and social indicators

In the Generic and Site-Specific assessments (Section 2.2.2), all the stakeholder categories suggested in the Guidelines were addressed (UNEP 2020). Moreover, since the stakeholder group Consumers is excluded from PSILCA (version 3), it was omitted from the Generic analysis.

Likewise, all the subcategories and indicators from the PSILCA database were included, except for those related to "Environmental footprints" and "GHG footprints" which, in our view, are better assessed with an E-LCA.

Social life cycle inventory (S-LCI)

- Data requirements: data sources and data collection strategy

Table 1 summarizes the data needs and sources for the Generic and Site-Specific assessments. All the data required for the Generic analysis was sourced from the WWTP operator. Furthermore, Table 2 lists inputs for the Reference and Novel Systems, their country of origin and their corresponding CSS.

- Activity variables calculation

The worker hours of the processes representing the WWT step in the Reference and Novel Systems (foreground processes) were calculated based on Eq. (1):

$$\text{Worker hour} = \frac{\text{Unit labor cost}}{\text{Mean hourly labor cost}} \tag{1}$$

In Eq. (1), the unit labor costs were calculated from the average salary paid by the WWTP operator, the cost of treating 1 m^3 of wastewater (Online Resource 1, Table S3 and Table S4), and the total amount of wastewater treated in 2021. The mean hourly salary was derived from the annual average salary paid by the WWTP operator, considering that a year has 52 work weeks, and employees work 40 hours per week. All the current prices and salaries were adjusted for

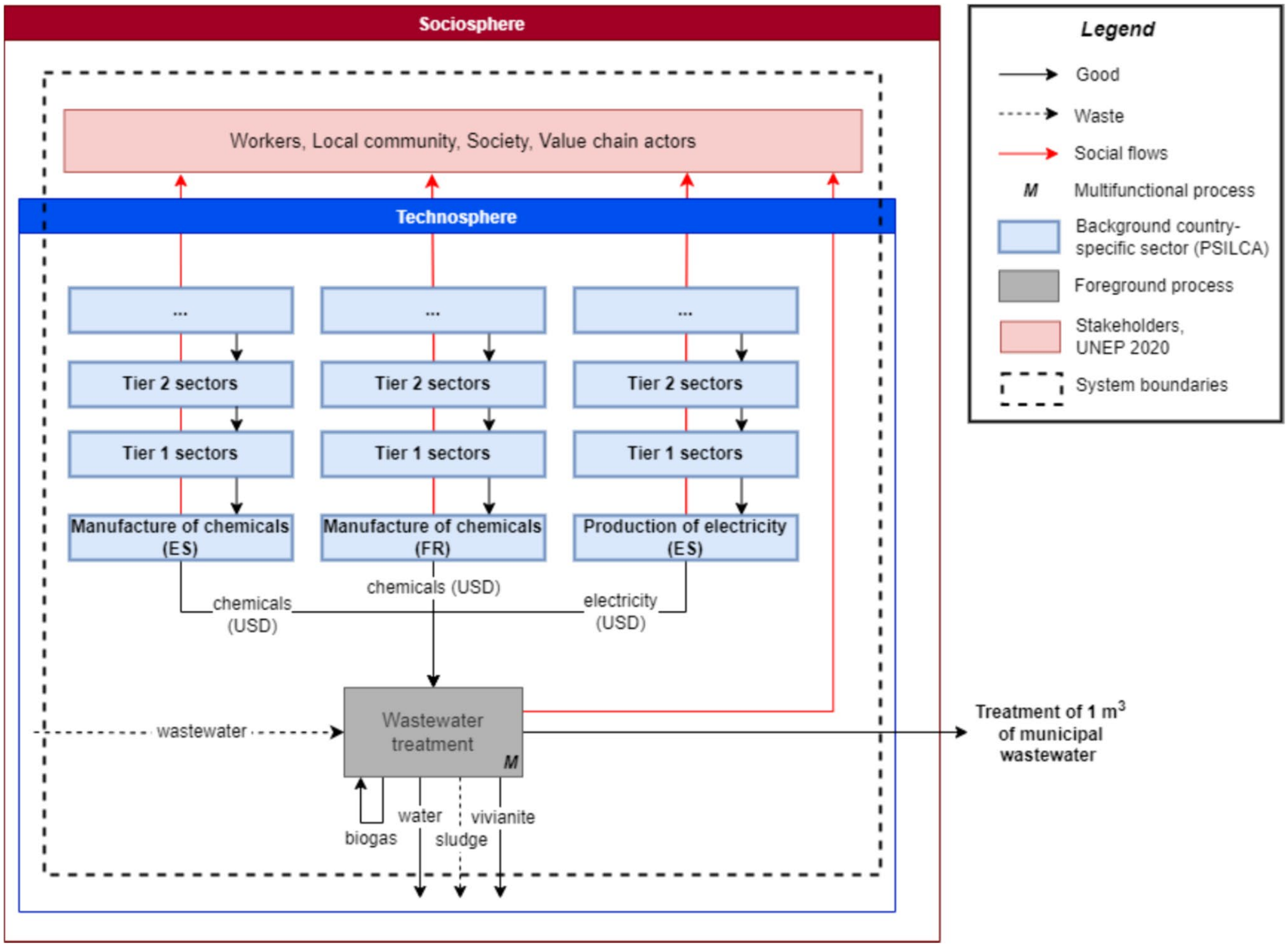

Fig. 1 General representation of a product system in the Generic analysis with PSILCA

inflation and converted to USD, the exchange rate of 2015, which is used in PSILCA.

Table 3 shows the worker hour results for both systems, while detailed calculations can be found in Online Resource 2.

- Multifunctionality and allocation

The WWT process in each product system was defined as multifunctional based on the three-step procedure proposed by Guinée et al. (2021) (Online Resource 1, Table S5). Economic allocation was considered the most suitable multifunctionality solution in this S-LCA since some social flows may have a stronger connection to the economic value created rather than the physical quantity of products generated or waste treated. Furthermore, the coproducts generated in the Novel System (e.g., vivianite) are valuable resources.

It is worth noting that the Reference System's biogas coproduct is used internally, representing an example of a closed-loop recycling system. How allocation is performed in closed-loop recycling systems does not particularly impact the results (Guinée et al. 2021). Thus, economic allocation factors for the Novel System were calculated and are presented in Table 4.

Social life cycle impact assessment (S-LCIA)

- PSILCA database and social risks calculation in PSILCA

PSILCA is based on Eora, a multi-regional input-output database (Huertas-Valdivia et al. 2020). PSILCA contains social data specific to 189 countries and approximately 15,000 economic sectors (Maister et al. 2020). Four stakeholder categories are included, for which there are 25 impact subcategories and 69 qualitative and quantitative indicators (Maister et al. 2020). Furthermore, the stakeholder categories and impact subcategories in PSILCA are aligned with those proposed in the S-LCA Methodological Sheets.

The social indicators included in the database carry contextual information since they are risk-assessed or "characterized" by being assigned a level of risk (Benoît-Norris

Table 1 Data requirements and data sources for the Generic and Site-Specific assessments

Data need	Application	Data source (primary or secondary)
Generic assessment		
Data on the physical flows of the product systems (quantities, costs, country of origin)	Selection of CSSs Generic assessment using PSILCA	WWTP operator As for the country of origin of chemicals: - WWTP operator or chemical suppliers - Online databases, such as the Observatory of Economic Complexity (Simoes and Hidalgo 2011) and BACI (Gaulier and Zignago 2010)
Data on social flows of the Reference and Novel Systems	Generic assessment using PSILCA	PSILCA database. Replicated from the "Market sewage and refuse disposal, sanitation and similar activities" CSS in Spain (Online Resource 1, Table S2)
Data for the calculation of the activity variable (worker hours)*		- WWTP operator - WWTP operator's sustainability report and website
Site-Specific assessment		
Data on the physical flows of the product systems (quantities, costs, first-tier suppliers of WWTP operator)	Calculation of activity variable and (economic) allocation factors	WWTP operator
Data on the basic requirements (BRs)	Establishment of reference scales	Standards and conventions from international organizations such as the International Labor Organization, Organization for Economic Cooperation and Development, Social Accountability International, International Finance Corporation, and the International Organization for Standardization (ISO 2010; OECD 2011; IFC 2012; SAI 2014; ILO 2015)
Data on the social flows of each organization in the product systems	Site-Specific social life cycle impact assessment (S-LCIA)	- WWTP operator and its first-tier suppliers employees - Organizations' sustainability reports and websites, online news articles, online articles from non-governmental organizations (NGOs)
Context data (situation in country or sector, and/or behavior of peers)	Site-Specific S-LCIA; assessment of levels 3 and 4	Peers' sustainability reports and websites, online news articles, online articles from NGOs, and online databases such as Spain's National Statistics Agency (INE) and ILOSTAT

*Includes data on the number of hours worked by employees in the Reference and Novel Systems, the total output of the systems in monetary terms, and the average wage of employees

Table 2 Inputs, country of origin, and EORA sector category of the Reference and Novel Systems

Inputs	Eora sector (country of origin)
Reference System	
Wastewater	Waste flow (Spain)
Sodium hypochlorite	Manufacture of chemicals and chemical products (Spain)
Polyaluminum chloride	
Antifoaming	
Polymer for sludge conditioning	Manufacture of chemicals and chemical products (France)
Electricity	Production and distribution of electricity (Spain)
Novel System	
Wastewater	Waste flow (Spain)
Sodium hypochlorite	Manufacture of chemicals and chemical products (Spain)
Sodium bicarbonate	
Ferrous chloride tetrahydrate	
Hydrochloric acid	
Sodium hydroxide	
Electricity	Production and distribution of electricity (Spain)

Table 3 Worker hour results of the Reference and Novel Systems, based on Eq. (1)

Calculation of worker hours	Reference System	Novel System
Unit labor costs (USD/USD)	0.1327	0.0935
Mean hourly salary (USD/h)	10.8585	10.8585
Worker hours (h/USD)	**0.0122**	**0.0086**

Table 4 Economic allocation factors for the WWT process of the Novel System

Functional flow	Quantity	Price (€/unit)	Allocation factor (%)
Municipal wastewater (m^3)	−1.0000[a]	−0.1948[b]	33.62
Vivianite (kg)	0.0294[a]	10.0000[c]	50.69
Water for agriculture (m^3)	0.6713[a]	0.0740[d]	8.57
Water for industries (m^3)	0.0688[a]	0.6000[e]	7.12

[a]Data provided by WWTP operator.

[b]See Table S4 (Online Resource 1)

[c]Wu et al. 2019

[d]Villar-García 2016

[e]Estimated based on the unit cost of deionized water produced in one case study of the Zero Brine project in Spain and from Pérez et al. (2022)

2014). For each indicator, an ordinal level is assigned to the observed indicator value. On a negative (risk) scale, there are six levels between very low to very high risk (Maister et al. 2020). Alternatively, for indicators that indicate positive social aspects (i.e., "Contribution of the sector to economic development"), an opportunity scale is used (Maister et al. 2020).

The impact assessment method used in PSILCA is the "Social Impacts Weighting Method." This method assigns weights (i.e., impact factors or characterization factors) to different risk or opportunity levels (Online Resource 1, Table S6). Therefore, the indicator results are calculated by multiplying the characterization factor by the worker hours. The results are expressed in "medium risk hours" (mrh). As for the social risks along the whole supply chain, the indicator results are scaled according to the price and quantity of economic inputs, worker hours per unit of output, and characterization factors (Maister et al. 2020). Therefore, the results obtained are very comprehensive top-down results but with reduced granularity compared with process-level data (Benoît-Norris 2014).

PSILCA (version 3) (Maister et al. 2020) and openLCA (openLCA 2022) were used for the Generic assessment. The inputs added to the foreground processes representing the Reference and Novel Systems were in relation to the treatment of wastewater for the amount of 1 USD, which was essential for consistency with the worker hours. Additionally, the wastewater inflow matched the unit of the functional unit (m^3) and was equivalent to 1 USD.

The unit costs (Online Resource 1, Tables S3-4) of the chemicals and electricity used in each product system were adjusted for inflation and then converted to USD2015. Data from online tools were used for inflation adjustment and exchange rate calculation (Inflation Tool 2022; XE.com Inc. 2022).

2.2.2 Site-Specific assessment

Goal and scope definition

The goal of this study also included assessing the social performance of the Reference and Novel Systems. Additionally, areas for potential improvement in social performance among participating organizations (mostly suppliers) were

identified. To this end, a site-specific assessment was conducted to evaluate the presence of potential social impacts resulting from the activities of the organizations involved in the life cycle of municipal wastewater treatment.
The functional unit was the same as the one defined in the Generic assessment.

- Product system definition

Based on the double-layer approach (Section 1.1.1), the product systems represented in Fig. 2 included considerations of the Sociosphere and the Technosphere. Accordingly, all the organizations (light blue boxes in Fig. 2) associated with WWT were identified.

Organizations are part of the Sociosphere since they are formed by, interact with, and affect people. Thus, the red arrows representing social stressors are generated in the Sociosphere (mainly by the conduct of organizations) and affect different groups of stakeholders (red box). Furthermore, organizations are also considered a part of the Technosphere because they operate technical processes for the provision of goods and services. This dual nature is illustrated by the presence of a blue box (e.g., WWTP operator) containing a gray or white box representing a technological process (e.g., wastewater treatment) in Fig. 2.

- System boundaries and cut-off criteria

Considering the WWT systems and the goals of this S-LCA, the only life cycle stage of the urban water cycle included in the product system was that of waste treatment. Furthermore, since two product systems were compared, the identical processes that occurred before WWT were omitted.

In this study, the availability of resources was the primary factor determining the inclusion or exclusion of processes and organizations within the system boundaries. Accessibility and availability of site-specific data is essential for any Site-Specific analysis. As the WWTP operator ran the WWTP, it had some influence on its immediate suppliers, which facilitated access to data from these organizations. Thus, the focal organization and its first-tier suppliers were included within the system boundaries (Fig. 2), as well as the stakeholder groups that they might have affected.

The coproducts of the Novel System were cut-off. While the main consumer groups of the recovered materials in the Novel System have been identified (e.g., metal factories, vineyards, wineries, local municipality, and public utility), these have not yet been defined since the system is still operating at a pilot scale; hence, consumers were excluded. Similarly, the Novel System's chemical suppliers have not yet been defined with certainty. Therefore, a proxy was selected based on the experience of the WWTP operator and the availability and accessibility of site-specific data. As in the Generic assessment, the construction phase, maintenance, transportation, and machinery used were excluded.

- Activity variables

Activity variables were used in this work to assist in the calculation of results per functional unit. In the Site-Specific analysis, the activity variables represented the importance of each unit process (represented by an organization) in each product system, which was indicated by its share in the total costs of treating 1 m^3 of wastewater.

- Stakeholder categories, impact subcategories, and social indicators

Since the studied organizations mainly performed business-to-business operations, they did not directly affect the Children stakeholder category. Thus, this stakeholder category was excluded, although it was indirectly accounted for in the Local Community and Society stakeholder categories.

The selection of impact subcategories was based on a literature review, a screening generic assessment using PSILCA, and desk research to assess the context in Spain. These steps are further described in Online Resource 1.

The social indicators in each impact subcategory were mainly derived from the Methodological Sheets (UNEP 2021). Furthermore, in alignment with the RS method selected (see below), indicators that reflected organizations' engagement with social issues through policies and management systems and actions were included. As the Methodological Sheets provide limited indicators for some subcategories, new indicators were added based on previous studies. Additionally, to measure proactive behavior, relevant social indicators from other studies (Goedkoop et al. 2018, 2020a, b; UNEP 2021; Life Cycle Initiative, Social Life Cycle Alliance 2022) were considered.

- Impact assessment approach and method

Based on this study's goals, the IA approach selected was the RS approach. Although a wide variety of RS methods exist, the most widely used is the Subcategory Assessment Method (SAM) proposed by Ramirez et al. (2014) (Ramos Huarachi et al. 2020). This method is based on the subcategories defined in the Guidelines and Methodological Sheets and allows for the evaluation of the social performance of organizations in a uniform and consistent manner.

Another relevant characteristic of SAM is the inclusion of context considerations in the assessment, which is an essential social dimension that will be preserved even if results are aggregated (Chhipi-Shrestha et al. 2015). Considering the context is crucial in this study as the organizations involved operate in different locations.

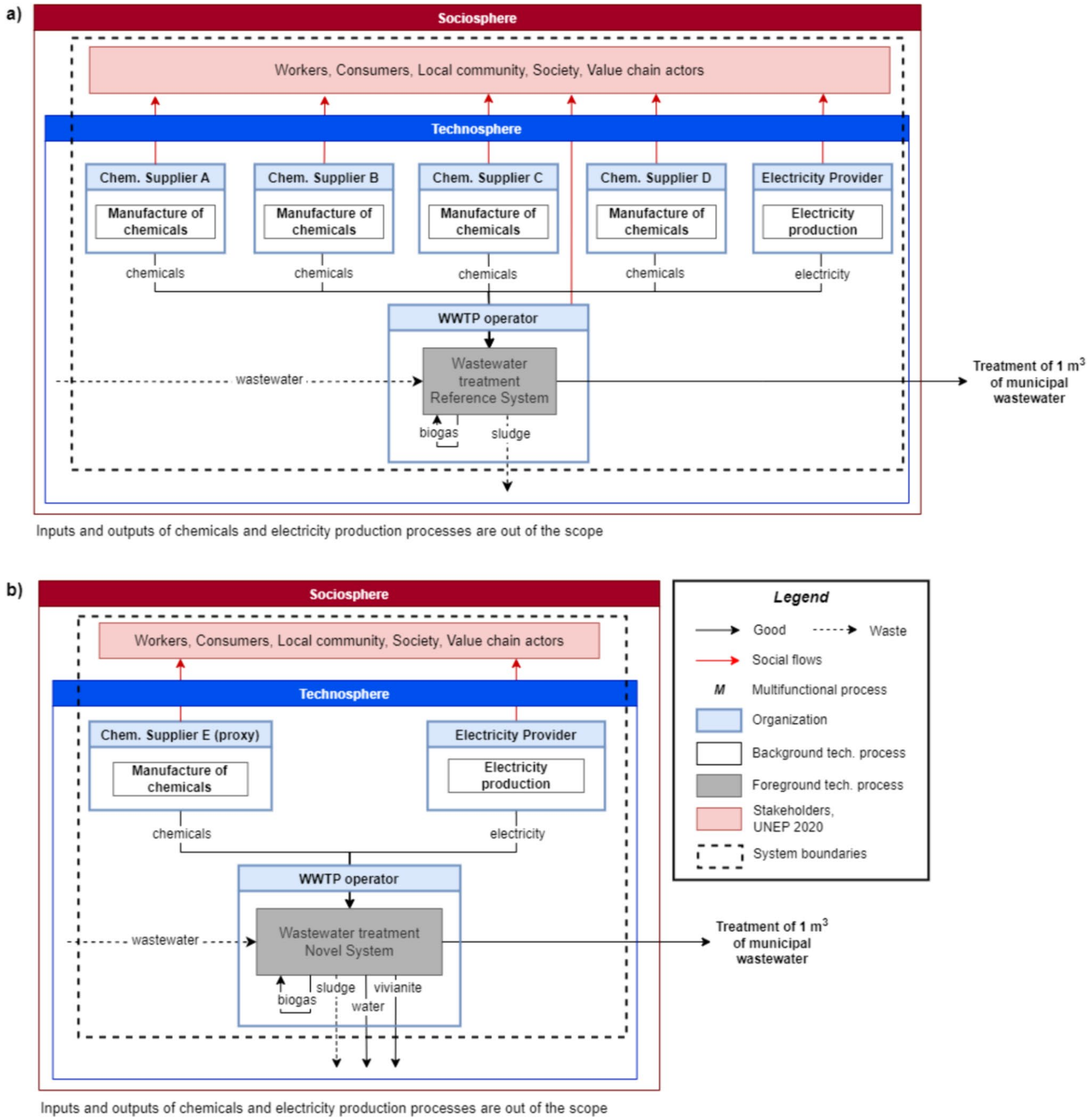

Fig. 2 Flowcharts representing the product systems and system boundaries of the **a** Reference System and the **b** Novel System in the Site-Specific assessment

Another advantage of this method is that it has a semi-quantitative character. It allows for converting qualitative data into quantitative information; hence, there is no restriction on the collected data type. For these reasons, SAM was applied to this study.

Social life cycle inventory (S-LCI)

The preparation of reference scales starts in the S-LCI phase, when data for the BRs must be collected (UNEP 2020). However, before establishing reference scales based on SAM, SAM is first introduced and modifications to it are hereafter explained.

- Reference scale method and modifications applied

Based on SAM, the reference scales of each subcategory are elaborated following the same approach. Each

Table 5 General representation of reference scales (adapted from Ramirez et al. (2014))

1	Proactive behavior
2	Compliance level
3	Noncompliance and negative context OR No data and positive context
4	Noncompliance and positive context OR No data and negative context

subcategory's reference scale is divided into four levels (A to D) based on a so-called "basic requirement" (BR). A BR for an impact subcategory is constructed from the indicators suggested in the Methodological Sheets. For all the subcategories that do not provide practical examples of social indicators, SAM uses the presence of a management system or policy as the BR.

An organization reaches level B if it fulfills the BR or level A if it demonstrates proactive behavior by encouraging the fulfillment of the BR along the value chain. Conversely, failure to meet the BR leads to levels C or D, depending on the context.

Most BRs defined by Ramirez et al. (2014) are based on management indicators while others relate to organizations' performance, which is inconsistent (Hannouf and Assefa 2018; de Santo 2019). The approach employed in this work addressed SAM's inconsistency by separating the BRs from the social indicators, and by assessing compliance with the normative BRs via commitment indicators (policies or management systems) and performance indicators (actions and evidence thereof). To achieve the first, instead of using a social indicator as the BR or formulating a BR based on the indicators from the Methodological Sheets, the BR for each subcategory was directly drawn from international standards or norms of conduct for organizations (International Organization for Standardization [ISO], 2010; Organisation for Economic Cooperation and Development [OECD], 2011; International Finance Corporation [IFC], 2012; Social Accountability International [SAI], 2014; International Labour Organization [ILO], 2015). This enabled the evaluation of the fulfillment of the BR by considering indicators that measured both management efforts and actual performance in the considered social aspect.

Another element of SAM that needed adaptation was the "proactive behavior" level of the reference scale, which overlapped with the subcategory "Promoting social responsibility." In this work, the "proactive behavior" level was granted when organizations undertook activities that went beyond the compliance level (level B).

- Establishment of reference scales

The reference scales adopted in this work had four levels (Table 5), which were associated with numbers to facilitate the presentation and aggregation of results.

The reference scales were developed through the following steps:

1. BR identification: The first step involved identifying BRs that aligned with subcategory descriptions. The BRs were based on international standards or norms of conduct.
2. Inclusion of social indicators: Social indicators from the Methodological Sheets were incorporated, and at the same time, the inclusion of commitment and performance indicators was ensured. One particular instance was the subcategory "Access to material resources," which only included one commitment indicator ("presence of an environmental management system"). In order to address this, the evaluation included ISO 14000 certification, which reflected organizations' actions to address environmental impacts.
3. Coverage of social indicators by the BR: The social indicators must align with the BR.
   a. If more than one indicator measured the same BR and covered the same aspect (e.g., "freedom of association and collective bargaining are included in policies" and "percentage of employees covered by a collective bargaining agreement"), they were combined into one reference scale (see FACB1[1] in Online Resource 1).
   b. If social indicators measured alignment with the same BR in different ways, different reference scales were built. For example, the BR of the subcategory "Equal opportunities/discrimination" established that organizations shall not engage in or support discrimination (Social Accountability International 2014, p. 11). This could be assessed by the "presence of policies on equal opportunities and established procedures to address discrimination issues" and "announcements of job positions through channels open to the general public." As these indicators measured the same BR, yet were different, separate reference scales were established (Online Resource 1).

[1] This is the name of a reference scale. All reference scales are detailed in Online Resource 1 (Tables S8-29).

c. When multiple BRs were considered relevant for a subcategory, reference scales were built accordingly to measure compliance. For example, the subcategory "Local employment" involved having a preference for hiring locally and working with local suppliers. Accordingly, two BRs, each covering one of these aspects, were identified, and thus, two reference scales were built.

4. Context consideration: In addition to considering the context when level 2 was not met, the context was also taken into account when there was no data to assess BR compliance (see levels 3 and 4 in Table 5).
5. Inclusion of examples for the assessment of level 1: Reference scales included examples of actions that organizations could have implemented to achieve level 1. Examples were given for at least one reference scale of each subcategory; except from "End-of-life responsibility," "Public commitment to sustainability issues," and "Promoting social responsibility," where no examples in the literature were found. These examples aimed at increasing this assessment's transparency by showcasing ways organizations could have achieved the best score.

It is worth noting that when indicators were combined in a reference scale, the presence of a policy was deemed sufficient for meeting the BR when there was no data regarding the action-oriented indicator (e.g., % of local workforce in LEMP1, Online Resource 1). Finally, following these steps in the establishment of reference scales ensured a consistent and transparent assessment of organizations' social performance.

- Data requirements: data sources and data collection strategy

The required data for the Site-Specific assessment and their sources are listed in Table 1. The main sources of data regarding social indicators were the organizations' employees. The WWTP operator facilitated a contact list of its first-tier suppliers. In view of the indicators selected, employees from the human resources and corporate social responsibility and similar departments and (area or country) managers had valuable insights and knowledge about the performance of their organizations and thus were considered suitable for participation. Thus, at least one employee per organization in one of these roles was invited to participate.

The main approach for data collection involved desk research and interviews/questionnaires with employees from each organization (see Fig. 2). The questionnaires prepared included open-ended questions and served as interview protocols (see Online Resource 1, Kokubo Roche 2022). Participants were given the choice to complete the questionnaire in an (online) interview or individually in an offline setting.

Table 6 Site-Specific activity variables calculated for each product system

Organization	Organization's share (%)
Reference System	
WWTP operator	11.72
Chemical Supplier A	0.01
Chemical Supplier B	2.14
Chemical Supplier C	64.34
Chemical Supplier D	3.15
Electricity Provider	18.64
Novel System	
WWTP operator	8.55
Chemical Supplier E (proxy)	75.75
Electricity Provider	15.70

Given all the different data sources considered (Table 1), data quality was assessed via a pedigree matrix (Online Resource 1, Table S30) in order to ensure the reliability and validity of the results (UNEP 2020).

- Activity variables calculation

The activity variables used in the Site-Specific analysis were calculated based on the total costs of treating 1 m^3 of wastewater. Given that these costs were calculated based on the material and energy inputs needed to deliver the functional unit (see Online Resource 1, Table S3 and Table S4), the WWTP operator's weight could not be determined. Thus, the cost of personnel normalized by functional unit was estimated (Eq. 2) and then added to the costs of the materials and energy inputs. The share of each organization in the Reference and Novel Systems is shown in Table 6.

$$\text{Personnel cost per FU} = \frac{\text{Annual average salary } (EUR) \times \text{ number ofemployees}}{\text{Annual treated wastewater } (\mathrm{m}^3)} \quad (2)$$

- Multifunctionality and allocation

The same multifunctionality solution employed in the Generic assessment was employed in the Site-Specific assessment.

Social life cycle impact assessment (S-LCIA)

- Site-specific S-LCIA: classification and evaluation steps

The classification of social indicators into impact subcategories and impact subcategories into stakeholder categories followed the same classification presented in the Guidelines and Methodological Sheets (Online Resource 1, Table S31). As indicated above, the evaluation of the social performances of organizations followed the same approach as Ramirez et al. (2014), where scores were granted based on the fulfillment of the BR and/or the context. Therefore, SAM facilitated moving directly from the inventory information to the IA step (Ramirez et al. 2014).

First, an organization's compliance with the BR was evaluated by considering the corresponding social indicators. If compliance was met, the organization achieved a score of 2 or 1, depending on the availability of information confirming that it is best in class or that it demonstrates proactive behavior. Failure to meet the compliance level resulted in a score of 3 if the organization operated in a negative context, or 4 if it operated in a positive one.

- Aggregation and weighting

These steps are common in the IA phase and can occur at various points (i.e., at indicator, reference scale, subcategory, and stakeholder category levels). Aggregation helps synthesize rich and complex information, facilitating decision-making and the communication of results. Furthermore, when aggregation is performed, weights are implicitly or explicitly applied to the inventory data, subcategories, or stakeholder categories.

In this study, aggregation first occurred at the reference scale level, as more than one reference scale existed for most subcategories. After an organization was assigned a score in each reference scale, the average of these scores formed the subcategory score for that organization.

Next, aggregation was performed at the subcategory level by combining each organization's subcategory score into a single subcategory score for the product system. This was achieved by employing the following:

a) Activity variables: These reflected the relative importance or contribution of each organization to the subcategory results and facilitated results per functional unit.
b) Equal weights: Each organization was given the same importance, considering that all organizations contributed equally to the subcategory results.

Finally, subcategory scores (based on activity variables or equal weights) were aggregated into stakeholder categories, which were then aggregated into final single scores for each product system.

3 Results

The results of the Generic and Site-Specific assessments are presented below. The social risks along the value chains of the Reference and Novel Systems are discussed in Section 3.1. The social performance results per organization and product system are discussed in Sections 3.2.1 and 3.2.2, respectively.

3.1 S-LCIA: generic results

3.1.1 Comparison between the Reference and Novel Systems

The social risks along the entire value chains of the Reference and Novel Systems totaled 2.6 and 1.4 mrh, respectively. As indicated in these results, the Reference System presented more social risks than the Novel System by 46%. The indicator results from PSILCA were aggregated per impact subcategory and stakeholder category (Fig. 3). Additionally, results per social indicator for both systems can be found in Online Resource 1 (Figure S1) and Online Resource 2. These results correspond to the treatment of 1 m^3 wastewater in each product system.

In both product systems, the subcategories with the greatest contributions to the final results were "Access to material resources," "Fair salary," "Freedom of association and collective bargaining," "Contribution to economic development," and "Corruption." Together, these subcategories represented 71% and 69% of the total results for the Reference and Novel Systems, respectively.

The hotspot subcategories and the most contributing indicators are listed in Table 7. The indicator "Biomass consumption" made up most of the social risks for the subcategory "Access to material resources." Biomass consumption measures the total biomass extraction in tons per capita and tons per km^2. In the foreground processes representing the Reference and Novel Systems, the first was assessed as "very low risk" and the second as "very high risk." It is not straightforward to assess how local communities are affected by high extraction rates; on the one hand, they may be affected by environmental degradation, and on the other, resource extraction may be due to the construction of infrastructure that benefits those communities (i.e., roads, hospitals) (Maister et al. 2020).

It is unclear which indicator contributed the most to the subcategory "Fair salary" because the indicators were aggregated automatically by PSILCA. Nevertheless, the foreground process contributions to this subcategory were due to the (sub-)indicators "Living wage, lower bound" and "Living wage, per month." Whereas these indicators alone cannot determine whether workers are paid fair wages in a

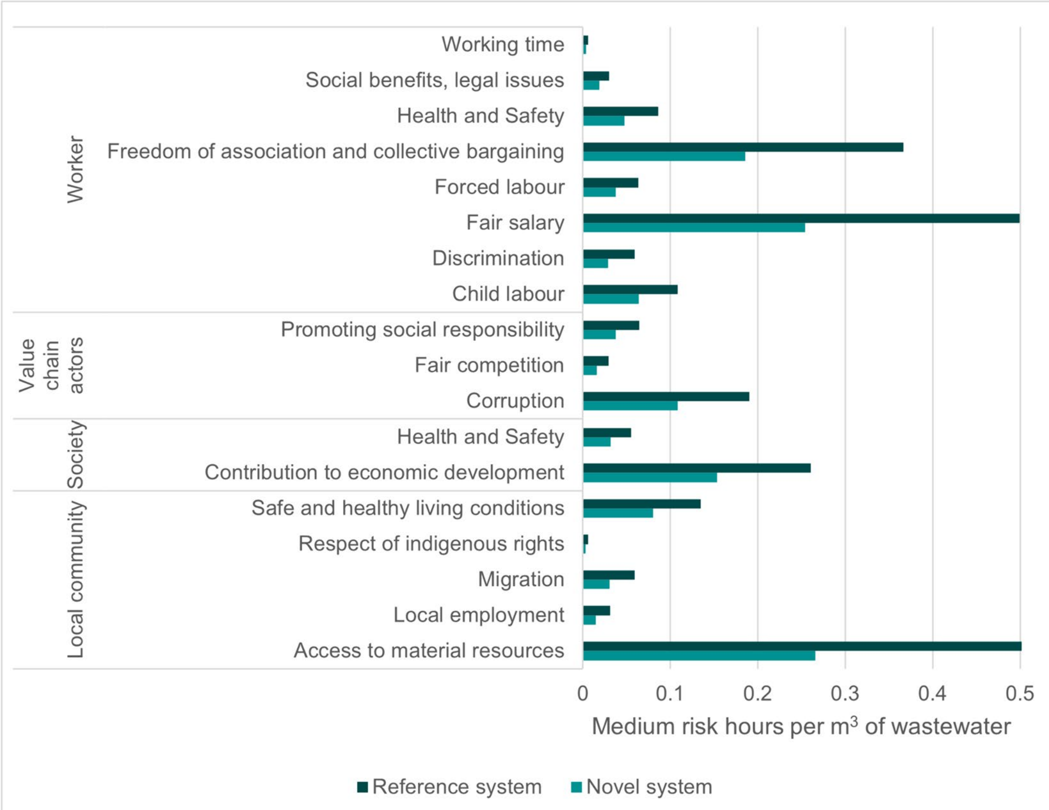

Fig. 3 Generic analysis results: social risks aggregated per impact subcategory and grouped by stakeholder category

Table 7 Generic analysis results: most contributing subcategories and indicators and social hotspots

Subcategory	Most contributing indicator			Foreground process contribution to indicator		Spain's contribution to indicator	
		Reference System (%)	Novel System (%)	Reference System (%)	Novel System (%)	Reference System (%)	Novel System (%)
Access to material resources	Biomass consumption	84	83	31	24	64	60
Fair salary	Fair salary	-	-	29[a]	23[a]	61[a]	58[a]
Freedom of association and collective bargaining	Trade union density	95	94	38	30	79	76
Contribution to economic development	Embodied value-added total	39	38	<1	<1	48	47
Corruption	Public sector corruption	75	75	9	6	19	16

[a]Contribution to subcategory "Fair salary"

given sector, they give a good indication as to whether sector average or minimum wages are fair.

Most social risks in the subcategory "Freedom of association and collective bargaining" can be attributed to "Trade union density." It is worth noting that this indicator only measures the level of unionization of workers, without considering the bargaining power of worker associations (Hayter and Stoevska 2011, p. 2). Therefore, even though the trade unionism level in Spain is low, collective bargaining plays a significant role in establishing the terms and conditions of work. Furthermore, the workers from most economic sectors in Spain are covered by collective bargaining agreements, and this right is protected by law (Ministerio de Trabajo y Economía Social, Ministerio de Inclusión, Seguridad Social y Migraciones 2021).

The subcategory "Contribution to economic development" included one indicator that represented opportunities for positive social impacts: "Contribution of the sector to economic development." As this indicator was "opportunity assessed" rather than risk assessed, the opportunity for positive social impacts (in mrh) was separated from this subcategory in Fig. 3.

The most contributing indicator to this subcategory was "Embodied value-added total." In contrast to the other indicators, the largest contributions to this indicator in both the Reference and Novel Systems did not come from the foreground processes. Instead, the "Chemicals, chemical products and man-made fibres" sector in France had the largest contribution, at 8%. Finally, the indicator "Public sector corruption" was responsible for most social risks in the subcategory "Corruption."

Overall, the most contributing indicators mentioned above were measured at the country level (except for "Embodied value-added total") and were assessed as "very high risk" or "high risk." This explains why the most contributing subcategories to the total results were the same for both systems. Moreover, the foreground processes representing the Reference and Novel Systems were the major individual contributors to most of these indicators (Table 7). Notably, most social risks in both systems originated from all the processes upstream in the value chains.

In addition, the contribution of the foreground process in the Novel System was smaller than that of the Reference System (Table 7). The main reason for this is that the worker hours of the Novel System were fewer than those of the Reference System's (Table 3), which is a direct result of the higher costs of treating 1 m^3 of wastewater in the former (Tables S3-4, and "unit labor costs" in Table 3). Even though the Novel System required more inputs than the Reference System, it presented fewer social risks due to allocation.

3.1.2 Relevant findings from the generic results

The results presented above regarding the most contributing indicators align with the study from Serreli et al. (2021), who also used PSILCA to assess a WWT system based in Italy. Their three WWT lines produced high social risks in "Public sector corruption" and "Trade union density." Furthermore, Andrade et al. (2022), who assessed the social impacts of agricultural activities in Spain, Belgium, and Germany using PSILCA, also found that the highest social risks of the agricultural practices in Spain were related to the indicators "Fair salary," "Biomass consumption," "Embodied value-added total," "Public sector corruption," and "Trade union density." Whereas Andrade et al. (2022)'s study was about agricultural activities, the results are comparable to the results of this work, given that most of those indicators are measured at the country level.

Finally, the social hotspot screening results that assisted in the selection of relevant impact subcategories to be evaluated in this study (Online Resource 1, Table S7) proved right in identifying two of the subcategories that resulted in actual hotspots in the Generic assessment ("Freedom of association and collective bargaining" and "Fair salary"). Thus, using databases to identify areas of concern and prioritize data collection is useful in S-LCA.

3.2 S-LCIA: site-specific RS results

3.2.1 Assessment scores of each organization

The scores of individual organizations in each reference scale can be found in Online Resource 1 (Table S32), while all the data collected and analyzed can be found in Online Resource 2. In addition, Fig. 4 and Fig. 5 show the social performance of all organizations in the Reference and Novel Systems, respectively.

In the Reference System, the WWTP operator, Chemical Suppliers B and C, and the Electricity Provider met or went beyond the BR for most subcategories. On the other hand, Chemical Suppliers A and D did not meet the BRs of six[2] impact subcategories. As for the Novel System, the WWTP operator and the Electricity Provider met the BR in most subcategories. However, none of the three organizations met the BRs of the subcategory "Safe and healthy living conditions." Furthermore, the social performance of Chemical Supplier E was deficient as it did not meet the BRs of six subcategories.

Relevant findings regarding the social performance of organizations in specific subcategories are hereafter described. In "Equal opportunities/discrimination," some organizations had a good performance because in addition to having management systems that promote equal opportunities and non-discrimination, they had a higher ratio of basic salary of women to men than the sector. However, it is worth highlighting that this indicator must be taken with caution, especially in these sectors. The chemical and energy sectors are both characterized by a strong male presence, particularly in management and technical positions. This means that the average salary of men might have been calculated from a dataset with many data points. In contrast, the average salary of women might have been calculated only on a few entries, which depending on their job positions, may make the average higher or lower. Furthermore, Chemical Supplier C's data for this indicator included only white-collar

[2] Note that in Fig. 4, the score of Chemical Supplier D in the subcategory "Safe and healthy living conditions" represents one reference scale instead of two. Also, note that the WWTP operator and the Electricity Provider were not assessed in "End-of-life responsibility"; thus, they were excluded from Figs. 4 and 5.

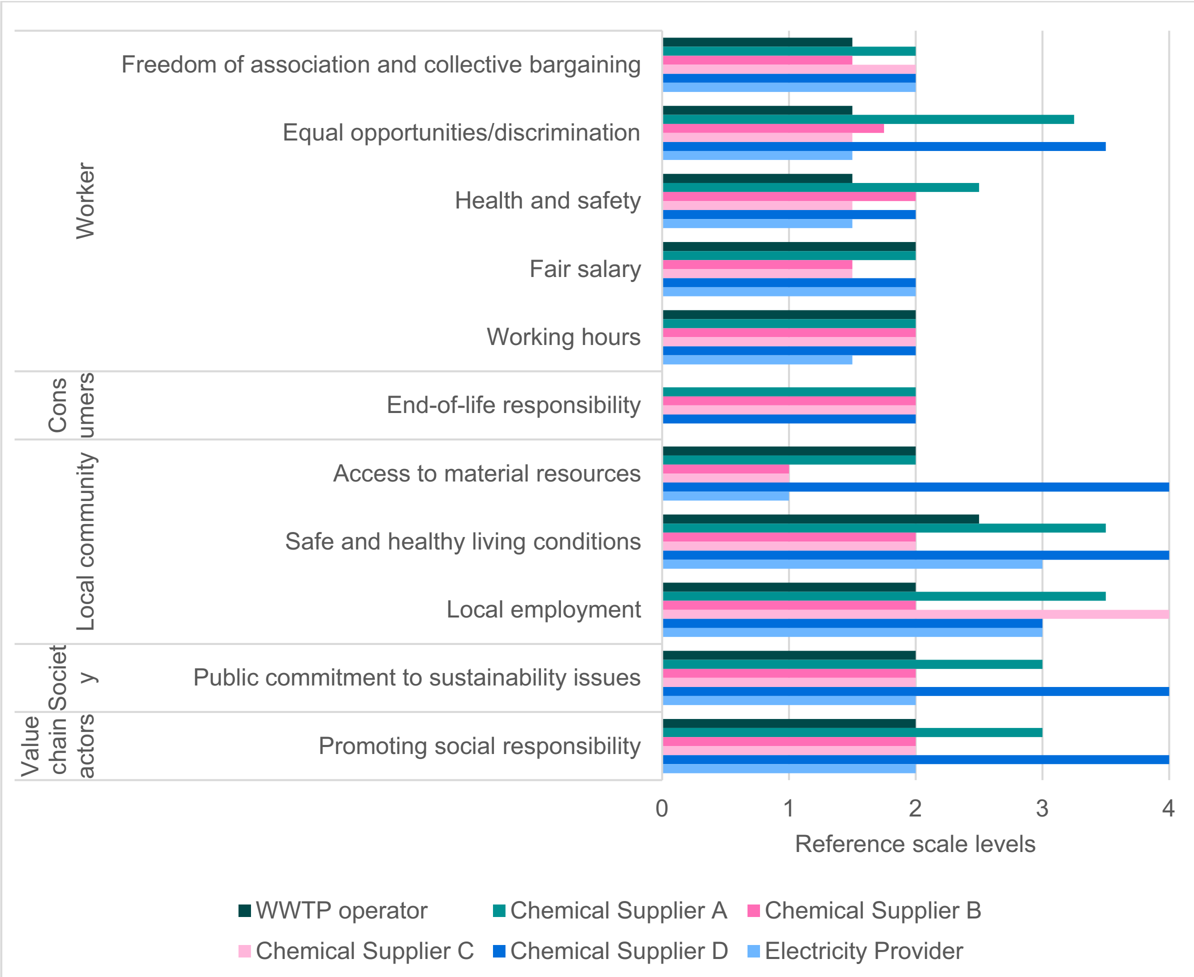

Fig. 4 Site-Specific results for the Reference System, per organization and subcategory

workers, which might give an erroneous impression of a narrow gender wage gap.

The subcategory "End-of-life responsibility" required special attention since the WWTP operator and the Electricity Provider could not be assessed due to the nature of their business operations. Given that the business activities of the WWTP operator can be described as construction work, infrastructure maintenance work, or utility operation, there is little that they can do to inform the end-user about the end-of-life options of their products or services. Likewise, the Electricity Provider supplies electricity, and while they provide information to their customers about the energy source and its environmental impacts, there is no additional information that they can provide on the end-of-life options.

In "Safe and healthy living conditions," specifically regarding the reduction of hazardous substances (SHLC2), some organizations did not meet the BR and/or there was no data. It can be noted that most organizations (including peers) only addressed hazardous wastes by (sometimes) establishing reduction goals, reporting the amounts generated and their end-of-life treatment. Very few organizations had policies and action plans to reduce the use of hazardous substances. Additionally, similar to the WWTP operator and the Electricity Provider in the assessment of "End-of-life responsibility," Chemical Suppliers D (chemical distributor) and E (distributor and storage of chemicals) were not assessed on this reference scale.

As for "Local employment," only the WWTP operator and Chemical Supplier B met the BRs of the corresponding reference scales. The rest of the organizations performed poorly due to data unavailability and/or not meeting the BRs. This result is in line with the findings of Tsalidis et al. (2020), wherein organizations in their Site-Specific analysis preferred to hire locally; however, only one organization implemented specific policies on this matter. Indeed, hiring locally might be a common practice of organizations, especially for roles involving shift work, even in the absence of specific policies on this aspect. One employee from the

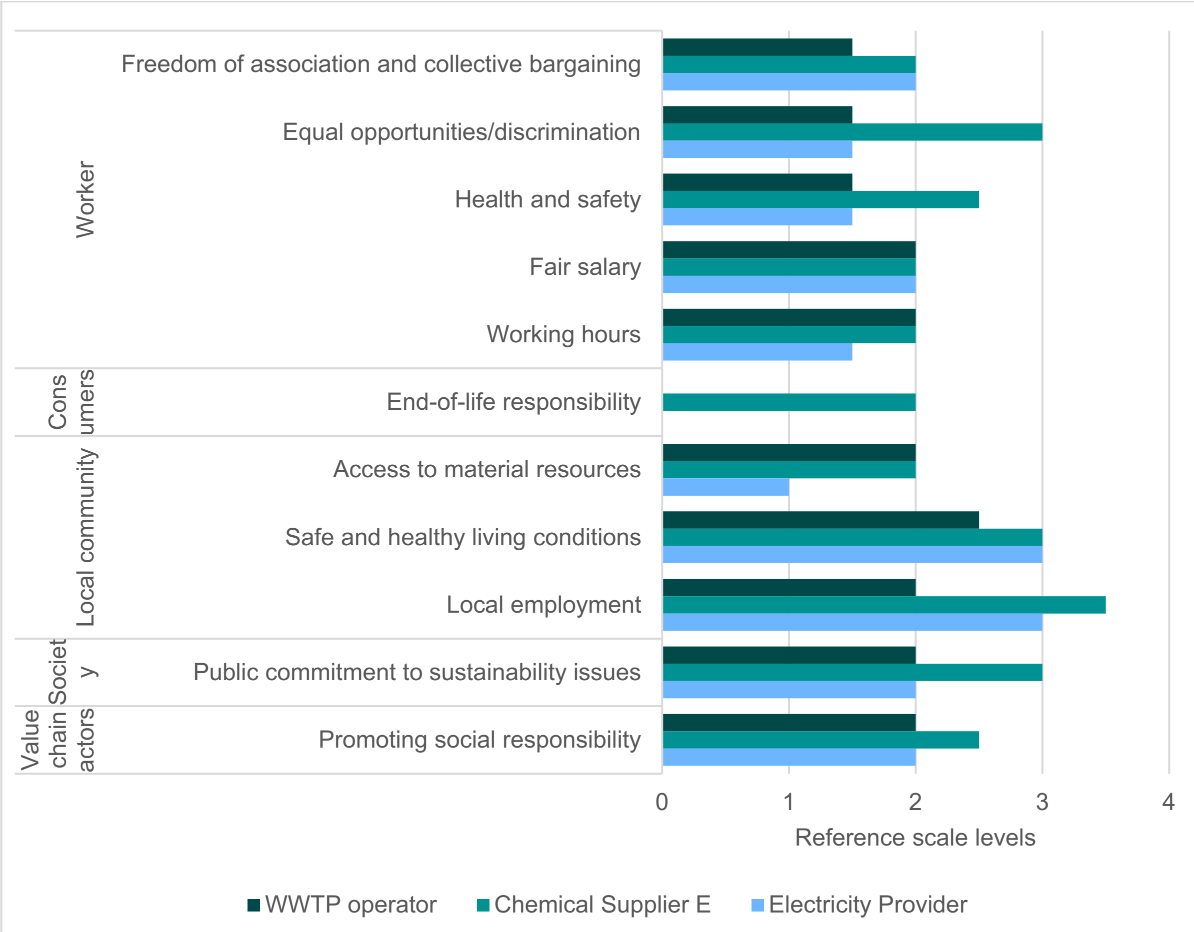

Fig. 5 Site-Specific results for the Novel System, per organization and subcategory

WWTP operator pointed this out: "There is no explicit policy on hiring locally, but this is normally used as a criterion for operative personnel" (participant from the WWTP operator, personal communication, April 5, 2022).

3.2.2 Comparison between the Reference and Novel Systems by subcategory

The social performance of the Reference and Novel Systems per impact subcategory are shown in Fig. 6. In general terms, the social performance of the Novel System was better than the Reference System's. Concretely, global social performance scores were calculated by aggregating the performance of organizations per impact subcategory. The calculation was carried out by considering each organization as having the same weight, and by considering their different shares in the treatment of 1 m^3 of wastewater. In the latter, a link was established between the conduct of each organization and the corresponding product system. Consequently, multifunctionality was solved by considering the allocation factor (in addition to organizations' weights) in calculating results. Therefore, the activity variable-based results correspond to the social performance of a system treating 1 m^3 of wastewater.

Although the BRs of most impact subcategories were met, the Reference and Novel Systems must still improve their social performance in certain subcategories (Online Resource 1, Table S33). The global social performance score of the Reference System was 2.20 when all organizations had the same weight. Larger scores were obtained in the subcategories "Equal opportunities/discrimination," "Safe and healthy living conditions," "Local employment," "Public commitment to sustainability issues," and "Promoting social responsibilities," mainly due to the poor performance of Chemical Suppliers A and D. In the activity variable-based results, the performance of the system (global social performance score: 1.92) was primarily determined by the performance of the organization with the largest share, i.e., Chemical Supplier C, whose contribution to the results ranged between 53 and 92%. Although the system's performance improved, scores in the subcategories "Safe and healthy living conditions," "Local employment," "Public

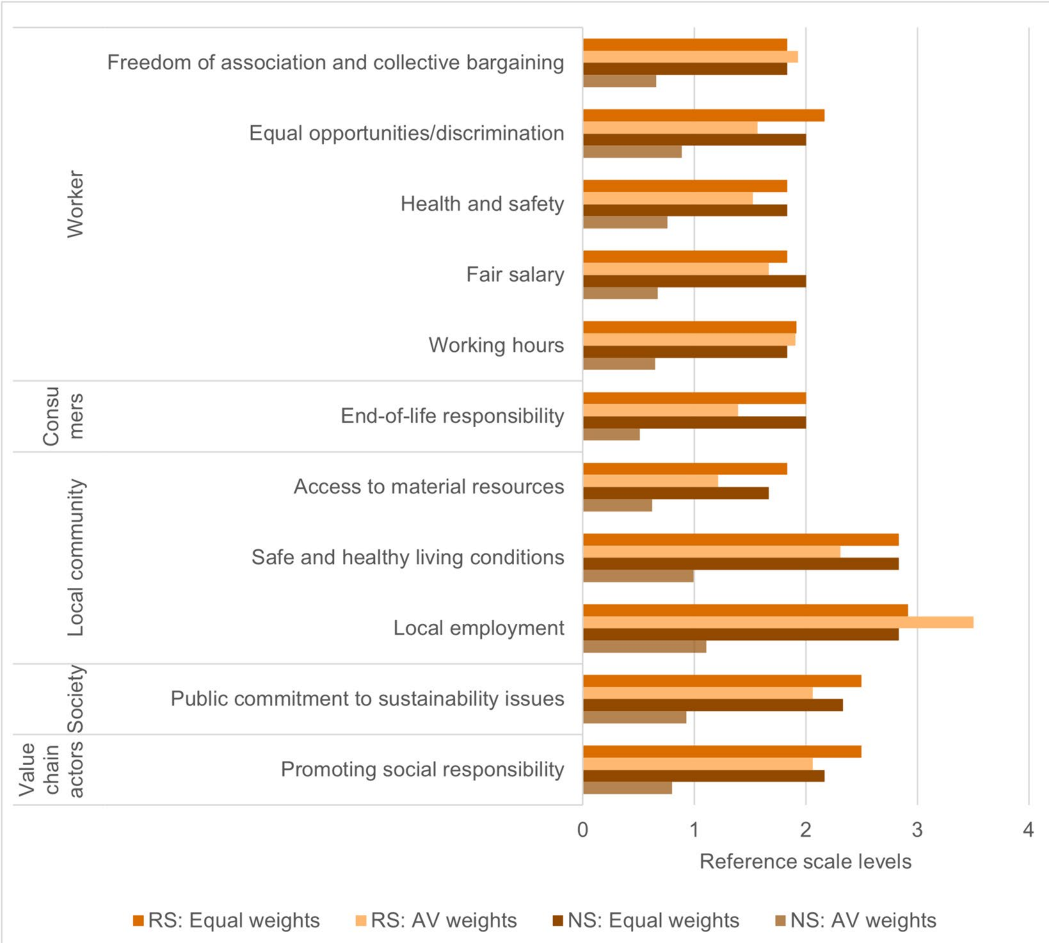

Fig. 6 Reference and Novel Systems' scores per impact subcategory, calculated based on equal weights and activity variable-based weights (allocated). RS and NS stand for Reference System and Novel System, respectively. AV stands for activity variable

commitment to sustainability issues," and "Promoting social responsibility" were beyond the BR level.

The global social performance of the Novel System equaled 2.12 when organizations were given the same weight, and the subcategories with negative performance were "Safe and healthy living conditions," "Local employment," "Public commitment to sustainability issues," and "Promoting social responsibilities." After the activity variables and allocation factors were considered, the global social performance score improved to 0.78. The allocated results of the Novel System can be mainly attributed to Chemical Supplier E's performance, whose contribution to the results ranged between 76 and 86%. Despite Chemical Supplier E's performance being (relatively) the poorest in the Novel System, allocation to the wastewater functional flow considerably favored the system's score.

Clearly, the global scores of both product systems improved when organizations' shares and allocation factors were taken into account; thus, level 2 was achieved in most (Reference System) and all subcategories (Novel System). However, these results must be interpreted with extreme caution as the calculation of global scores involved aggregations of reference scales, organizations, subcategories, and stakeholder categories, which introduced uncertainty.

3.3 Interpretation

3.3.1 Materiality assessment, completeness, and consistency checks

Social indicators contributing to the significant subcategories in the Generic analysis were identified in Section 3.1.1. In the Site-Specific analysis, significant subcategories affecting the global social performance of each product system were identified in Sections 3.2.1 and 3.2.2.

Regarding completeness, all the relevant technical processes (represented by organizations) and affected stakeholders were identified via the double-layer approach of the product system and system boundaries. The cut-offs of the

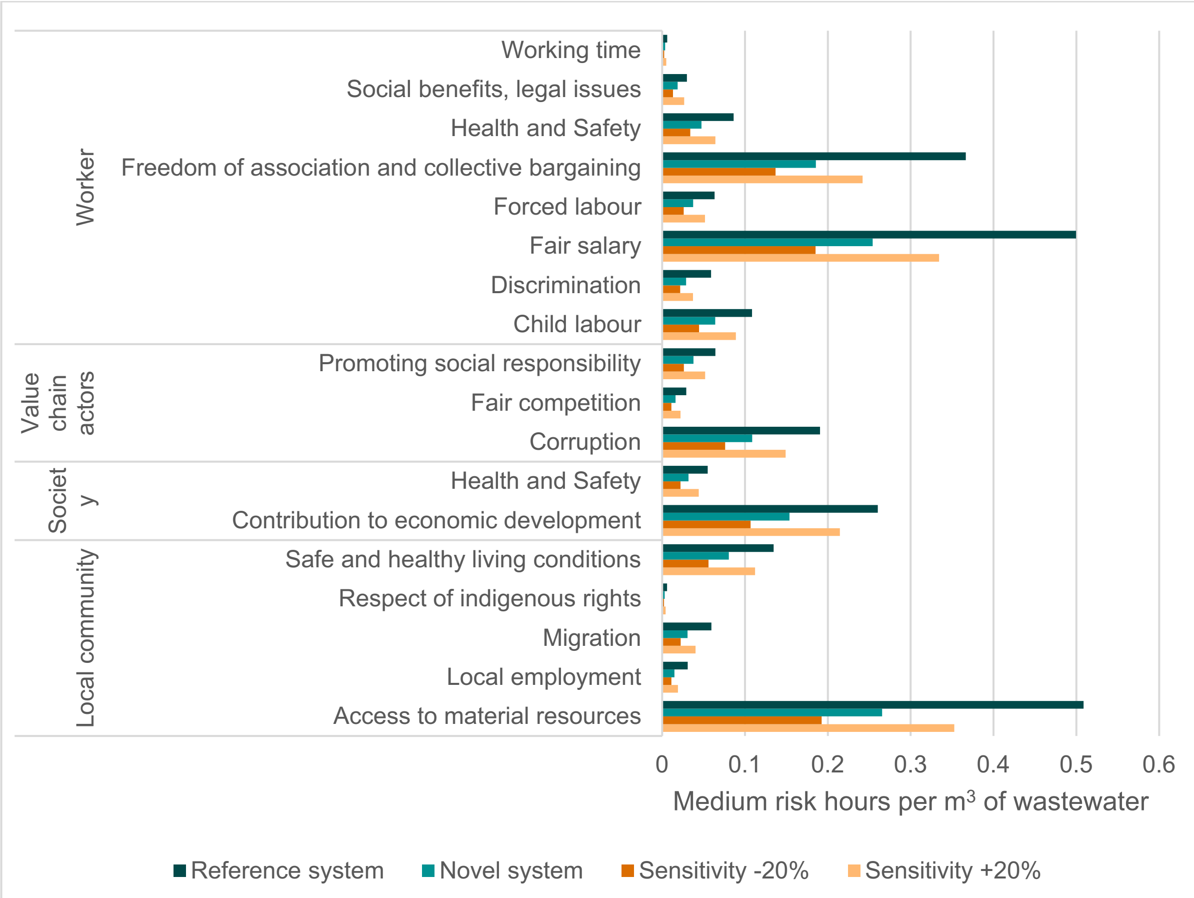

Fig. 7 Generic assessment results per subcategory and stakeholder category for the Reference System, Novel System, and sensitivity analysis, representing a 20% increase and decrease in inputs

product systems were justified mainly based on resource constraints (Section 2.2.2).

Allocation rules and system boundaries were applied consistently in both product systems and in both assessment levels. In the generic analysis, the monetary flow of inputs was consistently handled to maintain uniformity with the exchange rate in PSILCA. Furthermore, input quantities and worker hours were carefully calculated in alignment with 1 USD of process input.

3.3.2 Data quality check and sensitivity analysis

A data quality pedigree matrix was employed to assess data quality. Data was assessed on four criteria, and a score from 1 to 5 was assigned to each criterion.

The data quality results are presented in Online Resource 1 (Table S32) and Online Resource 2. The best data quality corresponds to that of the WWTP operator since more primary data was collected, and more than one employee corroborated the information, increasing the source's reliability. Data regarding the performance of Chemical Suppliers A, D, and E had the poorest quality due to the limited availability of site-specific data. In fact, no employee from Chemical Suppliers A and E and the Electricity Provider participated in the study. This resulted in the use of generic information to assess the performances of the former two, which had implications on the source's reliability, and temporal and geographical conformance.

- Sensitivity analysis

Due to the Novel System's ongoing pilot-scale operation, adoption of relatively new technologies, and the use of upscaled data in the above calculations, the inputs might be over- or underestimated. Therefore, a sensitivity analysis was performed to evaluate the effects of altering input quantities by ±20% on the Generic assessment results (Fig. 7). This sensitivity analysis is also justified by potential process variations and improvements, and the volatility of prices, aiming to explore potential outcomes under varying conditions. Unaggregated results can be found in Online Resource 1 (Figure S2).

By modifying chemical and electricity inputs, the cost of treating 1 m^3 of wastewater shifted. This caused changes in the allocation factors and worker hour values (Online Resource 1, Table S34). Notably, despite altered input amounts, inputs per 1 USD of treated wastewater remained the same (Online Resource 2). This is explained by the fact that chemical and electricity inputs altogether determined the cost of treating 1 m^3 of wastewater. Thus, when input quantities were calculated per 1 USD of treated wastewater, the results represented their shares in the cost of treating 1 m^3 of wastewater.

The 20% input reduction and 20% input increase resulted in 0.99 and 1.86 mrh, respectively. The former corresponds to a 28% reduction in the social risks of the Novel System, while the latter corresponds to a 35% increase. In both cases, less social risks than the Reference System were achieved. Furthermore, these input adjustments yielded the same hotspot subcategories and indicators.

This sensitivity analysis emphasizes the effect of changes in input quantities on the results. The amount of chemicals and electricity used in a fully operational WWTP representing the Novel System could influence the conclusions drawn from the S-LCA. It is crucial to further investigate the effects of an alternative method for calculating the costs of treating 1 m^3 of wastewater.

4 Discussion

In this section, issues related to the use of a database in S-LCA, the selection of impact subcategories and indicators, organizational traits, activity variables use, and multifunctionality are addressed. The section concludes with a comparison between the Generic and Site-Specific assessments in Section 4.3.

4.1 Generic assessment

One limitation of using databases built on multi-regional input-output tables is that economic sectors are aggregated, including various types of activities. Thus, the social flows are not specific to a process but rather represent different processes within a sector. This lack of granularity has important implications for the calculation of social risks of the foreground processes. The social flows were replicated from the economic sector to which WWT belongs, i.e., “Market sewage and refuse disposal, sanitation and similar activities.” However, these social flows represent an average from sewage collection, distribution, wastewater treatment, and other activities. In a future study, this can be improved by collecting data on each indicator for the foreground process at hand instead of mainly relying on data from the database.

In the context of the product systems analyzed, there are two aspects that could contribute to improving their social risk results. Firstly, as discussed in Section 3.3.2, the data employed in the assessment was upscaled to better represent a full-scale operation of the Novel System; thus, it might be under- or overestimated. As better approximations of the full-scale operation become available, the inputs can be adjusted, leading to more accurate results. This reflects the nature of prospective LCA, where results are subject to change as technology advances and more data becomes available.

Secondly, for both the Reference and the Novel Systems, the results can change based on the quality and specificity of the data used. For instance, the risk level of social indicators can shift (e.g., from high risk to very high risk with risk factors of 10 and 100, respectively) as more reliable or sector-specific information becomes available. Therefore, by considering data updates both at the process and social indicator levels, the results will represent (at least) the foreground processes more accurately.

It is noteworthy that the quantity and price of inputs affect the results, as they determine the social risks from upstream processes. An increase in the quantity or price of inputs will correspondingly increase the social risks, and vice versa. However, while the amount of inputs used in a process can typically be considered fixed (excluding the Novel System, which is not yet operating at full scale), prices are subject to market conditions. Therefore, the social risks of a system are susceptible to changes in input prices. Additionally, in the Novel System, the assumed prices for recovered materials, which were considered high-quality marketable resources, influenced the allocation factors and consequently the results. In future studies, the effect of these coproduct prices on the allocated results should be examined. It should be noted, however, that higher prices do not necessarily equate to higher social risks.

As previously mentioned, indicators at the country level made major contributions to the subcategories where most social risks occurred. However, country-level indicators introduce an important uncertainty in the Generic assessment results because they serve as proxies for sector-specific indicators. Consequently, different economic sectors are highly prone to over- or underestimation of the actual risks they incur.

Using the activity variable “worker hours” to calculate social risks in subcategories or indicators that are not related to working conditions has limitations. Indeed, the number of hours of work necessary to produce 1 USD of output is not related to how stakeholders other than workers are affected. For instance, the drinking water coverage in a country (an indicator of the “Access to material resources” subcategory, stakeholder “Local community”) will not be determined by the hours worked to produce 1 USD of output in a sector.

Thus, the social risk results of those subcategories unrelated to the stakeholder category "Workers" are difficult to interpret (Serreli et al. 2021).

4.2 Site-specific assessment

4.2.1 Selection of social impact subcategories and indicators

The indicators used in this work were mainly drawn from the Methodological Sheets. Nonetheless, it is essential to recognize that the Methodological Sheets do not provide an exhaustive list of indicators and they do not necessarily address main issues of concern in a case study, sector or country. Consequently, it is strongly suggested to include indicators specific to the context of a study. Notably, more than half of the reviewed S-LCAs in the water sector included subcategories and indicators different from those proposed in the Guidelines. For example, Padilla-Rivera et al. (2016) included indicators such as the availability of wastewater management documentation, performance monitoring program, and effluent quality.

Additionally, certain indicators proposed in Methodological Sheets might prove impractical or redundant for some organizations, sectors, or countries. For example, evaluating the performance of the WWTP operator and the Electricity Provider in the "End-of-life responsibility" subcategory was infeasible due to the nature of their operations (infrastructure work and electricity supply, respectively). Similarly, since Chemical Suppliers D and E distribute chemicals, they were excluded from the assessment in SHLC2 (reduction of hazardous substances use). Moreover, subcategories such as "Freedom of association and collective bargaining," "Fair salary," and "Working hours" involve indicators that are well-regulated in the countries where the evaluated organizations operate. Therefore, although the Guidelines and Methodological Sheets aim to bring methodological uniformity to S-LCA, it should be emphasized that the provided list of subcategories and indicators serves as guidance rather than strict rules. The introduction of new European sustainability reporting standards might, to some degree, facilitate harmonization of social indicators for different sectors in this region.

When a product system is composed of organizations from different sectors or locations, different social aspects become more or less relevant to each one of them. Particularly, the hotspots identified in this study might not be issues of relevance for all the organizations assessed. For example, contributing to better health and safety conditions in a community might not be directly linked to Chemical Supplier D's activities; hence, it may not be a material issue for them. Similarly, contributing to local employment by purchasing from local suppliers might not be relevant to Chemical Supplier C if it needs large quantities or specific raw materials that local suppliers cannot provide. Indeed, choosing social indicators especially relevant to wastewater treatment facilities is only helpful for assessing the wastewater treatment stage. This is why it is crucial to define in the goal definition how and by whom the results of an S-LCA will be used.

In this work, including social indicators related to wastewater treatment may not be considerably beneficial since the same organization is responsible for operating both the Reference and the Novel Systems. Thus, the social performance will remain the same. An exception would be the inclusion of WWT-related indicators that are particular to each product system, e.g., more training might be needed with newer technologies in the Novel System or workers might be more or less exposed to entrapment risks. Similar to the inclusion of household expenses in Opher et al. (2018)'s study, other aspects that could also be considered are the effect on user's expenses and the public acceptance of treated wastewater reuse in the Novel System.

4.2.2 Influence of organizational traits on data collection and calculation of results

Considering the social indicators, the size of the small organizations studied, and the nature of their businesses, the question about whether it is fair to assess them with the same "rule" used to assess larger organizations arises. In fact, smaller organizations may face constraints in terms of resources (time, capital, and human), which might limit their activities exclusively to the economic realm. The BRs of subcategories, such as "Access to material resources" and "Safe and healthy living conditions," might be particularly challenging for smaller organizations to achieve. The reason is that these organizations (such as Chemical Supplier D) may have activities that are not significantly harmful to the environment and for whom active interactions with local communities are not a material issue.

Similarly, committing to sustainability issues is seemingly not a priority for the smaller organizations assessed. Hence, if addressed, this is rather superficial in their codes of conduct, and they do not report on sustainability matters (PCSI1) nor control their suppliers' sustainability performances (PSRE2). However, this may change in Europe as the Corporate Sustainability Reporting Directive (CSRD) has entered into force and listed Small and Medium-Sized Enterprises (SMEs) also need to abide by the Directive (Directive 2022/2464) (European Commission (n.d.); European Parliament 2022).

Notably, the lack of sustainability-related or annual reports posed a considerable challenge in accessing data of small organizations. Furthermore, reluctance to share social data information might be related to the relative lack of awareness about S-LCA and the fact that social indicators often regard data that might be sensitive for businesses to share.

In some instances, distinguishing a "no data" from a non-compliant situation presented challenges. For instance, it was difficult to determine whether organizations were non-compliant or simply lacking data in the evaluation of efforts to minimize the use of hazardous substances (SHLC2). This is because most organizations only focus on hazardous waste management, with little or no information on policies to minimize the use of hazardous substances. Likewise, some participants did not disclose information about certain indicators, which does not necessarily mean that their organizations do not meet the BR or that they lack the data. However, a "no data" and a non-compliant scenario result in different outcomes (score of 3 or 4).

4.2.3 Impact assessment method

RSs were established based on BRs that aligned with subcategory descriptions and social indicators from the Methodological Sheets. Ensuring the alignment of BRs with subcategories and indicators, and that the latter evaluated conformance with the BRs relied on researcher judgment. The method adopted in the construction of the RSs used BRs as intermediaries between subcategory descriptions and social indicators, establishing a clearer link. Other RSs directly used indicators and referenced them to international agreements thereby establishing them as BRs (Ramirez et al. 2014; Padilla-Rivera et al. 2016; Hannouf and Assefa 2018; García-Sánchez and Güereca 2019). This coupling with international agreements results in a more straightforward development of RSs and reduces subjectivity. However, not all indicators can be referenced to national legislation or international agreements, and this process results in nearly one RS per social indicator. Conversely, combining social indicators into one reference scale allows for fewer RSs, yet building RSs is more complex and time-consuming.

Another benefit of this RS-building approach is that subcategories are not defined by social indicators. Accordingly, gaps between the subcategory definition and social indicators can be clearly identified, and more social indicators can be added as needed. Since the availability of social indicators and subcategory-specific BRs are the base for establishing a RS, there is no shortcut or standard RS for all subcategories, i.e., each RS must be built separately.

Although valuable, considering the geographical context in the assessment is confined to levels 3 and 4. Not considering the context in levels 1 and 2 can be understood as a normalization step, mainly when the organizations in the product system operate in very different social contexts (e.g., different geographical locations with varying social risks). For an organization embedded in a negative context, meeting the BR or achieving proactive behavior might be more challenging compared to an organization in a positive context, as it might require implementing more policies and procedures. An improvement can be made by including context consideration in the assessment of levels 1 and 2.

4.2.4 Use of activity variables

As social impacts are mainly attributed to the behavior of organizations, linking the behavior of organizations to a specific waste treatment system is troublesome (Section 1.1.2). The approach used in this work to facilitate that link was the use of activity variables. Nevertheless, this carries some limitations. Firstly, the (relative) good or bad social performance of an organization whose share is the largest is given more importance and determines most parts of the results while the performance of other organizations is overshadowed. Secondly, multiplying the share of each organization by the social performance scores may introduce more uncertainty in the results as some indicators are qualitative and were converted to semi-quantitative values (UNEP 2020).

In most cases, the social inventory data regarding an organization's activities cannot be exclusively linked to one product because the performance of organizations does not have a quantitative link to their products. If an organization is involved in corruption and bribery, it will continue to perform such practices regardless of how many types or units of products they produce. In other cases, the link is direct, e.g., producing more of a particular product may imply more accidents or more hours of forced labor. Additionally, the fact that an organization has a supplier in a high-risk area of human rights violations and this supplier may be linked to such violations is of enormous importance. In comparison, which of the supplier's products is linked to forced labor or how many products are purchased from this supplier become irrelevant issues.

Therefore, considering that inventory data cannot be linked to one specific product and that the social performance of an organization is not proportional to a product (its function), using activity variables to link the results to the product system is artificial and comes with limitations. Similar to choosing an allocation method in E-LCA, using activity variables introduces bias in S-LCA, which must be acknowledged. Essentially, allocation and activity variables serve methodological purposes. Yet in reality, environmental impacts cannot be split among coproducts as if they exist in isolation, and social impacts are not entirely specific to a defined product. Thus, what Guinée et al. (2004, p. 33) concluded on the multifunctionality problem can be applied to the S-LCA issues discussed here: wishing to link the social performances of organizations to a specific product system results in the use of artifacts such as activity variables. Since this problem can only be solved artificially, there may not be a "correct" way of doing it, and there is room for more advancements in this regard in the S-LCA field.

4.2.5 Multifunctionality and social impacts

In the site-specific analysis, activity variables were used to account only for the social impacts of treating wastewater. Specifically, as the link between organizations' social performance and the product system was established, not only could the results be calculated in terms of the functional unit, but also the multifunctionality problem in each product system could be solved. However, it is essential to note that how the activity variables are calculated directly affects the final results and adds another level of uncertainty to multifunctionality handling in S-LCA studies applying the RS approach. In reality, it does not matter how the allocation is performed because the social impacts are not entirely specific to a determined product. In fact, there might not even be a correct solution to multifunctionality (Guinée et al. 2004). Nonetheless, solving multifunctionality is particularly relevant in resource recovery systems or circular economy systems that produce coproducts. In turn, comparing the social impacts of a business-as-usual process with those of a more resource-efficient process will not yield very different results if the recovered resources (i.e., coproducts) are not considered.

Having acknowledged the limits of allocation and multifunctionality solutions in general, the question that still remains is the following: do circular economy systems (characterized by multifunctionality) produce more or less social impacts than conventional systems? Arguably, they might produce less negative impacts on stakeholders assuming that their products would replace those coming from socially deficient systems (e.g., replacement of magnesium imported from Russia, where the impacts on workers were mainly negative (Tsalidis et al. 2020)). However, resource recovery systems may also result in more social impacts. Following the previous example, the reduction of imports could translate into fewer hours of work, less access to training, fewer contributions to the economic development of that region, and stakeholders there might be negatively affected. Therefore, special attention must be paid to issues like the ones above, particularly when attempting to compare such systems.

4.3 Comparison between the Generic and Site-Specific assessments

The Generic and Site-Specific assessments served different purposes. The former was employed to determine the social risks throughout the entire value chain of the Reference and Novel Systems, while the latter assessed the social performance of these systems by evaluating the behavior of the organizations involved (i.e., the WWTP operator and its first-tier suppliers). Thus, the analyses differed in their scope (complete versus part of a value chain), the type of data used (national and sectoral indicators versus organizational indicators), the impact assessment approach (S-LCA database impact assessment method versus SAM), and the results (social risks in medium risk hours versus social performance score index). Additionally, based on how the IA step was performed in each type of assessment, changes in WWT inputs had little to no effect on the Site-Specific results compared to the Generic assessment results. This was particularly the case when equal weights were applied to the organizations involved and when no allocation was performed.

The Generic and Site-Specific assessments are complementary. A Generic assessment assists in prioritizing processes or subcategories that should be included and for which data should be collected in a Site-Specific assessment. Moreover, it provides an overview of where a value chain is vulnerable to social issues, enabling organizations (particularly the focal organization) to focus on areas and issues flagged. Nonetheless, it should be noted that some social issues identified in a given CSS might not occur in a particular system. That is why a Site-Specific assessment is relevant, as it is more focused on the particular organizations involved.

5 Conclusions

The limitations and challenges of the S-LCA method and S-LCAs applied in the water sector were addressed in this work. In contrast to the reviewed S-LCAs, all four phases of the S-LCA framework were addressed and reported on, and the construction of reference scales and how the scoring was performed were presented transparently. Other contributions include the use of an activity variable that was not specific to subcategories related to working conditions in the Site-Specific assessment, and the explicit handling of the multifunctionality of the Novel System. Moreover, the main challenges of SAM were addressed, facilitating a detailed and complete social performance evaluation in all impact subcategories.

The Generic analysis results indicated that the Novel System entailed fewer social risks than the Reference System per 1 m^3 of wastewater treatment. However, these results are rather sensitive to changes in input amounts or prices. It is important to note that this study evaluated a pilot system, which introduces uncertainties related to future optimizations and technological developments. The data used in this assessment is the most updated available at the time of the study. Nonetheless, it is expected that data will continue to evolve as the technology advances from pilot to full-scale implementation.

This evolving nature of data and technology is characteristic of prospective LCA studies. Therefore, while the current results provide valuable insights, they should be interpreted with the understanding that ongoing improvements and updates in data quality will likely refine these findings further.

On the other hand, the Site-Specific assessment showed that different results can be obtained by considering activity variables and solving multifunctionality vis-à-vis assigning the same importance to all organizations forming a system. Under the former approach, the results are specific to the functional unit, and the Novel System's performance was considerably better than the Reference System's as all organizations met the subcategories' compliance levels. It is worth noting that the use of allocation factors favored the Novel System in both the Generic and Site-Specific assessments. By contrast, the performance of organizations in the Reference and Novel Systems was below compliance in a few subcategories based on average performance results, indicating opportunities for further improvement.

These results can be helpful for the WWTP operator, as they point to areas in the supply chain of the studied WWT systems that can be prioritized for improvement. Therefore, it is recommended that the WWTP operator considers the relevance of social issues in their decision-making processes while selecting suppliers and redesigning value chains. Nevertheless, these results must be taken with caution, in light of all the assumptions and limitations discussed. Furthermore, both the Generic and Site-Specific assessment results reflect social conditions that are particular to a given point in time, indicating that S-LCA results are inherently subject to changes as the organizations involved and their performance, as well as the local social conditions, change.

Although S-LCAs can aid in the comparison of alternatives, when the RS approach is applied, S-LCA results do not represent product-specific information, and methodological challenges remain in the assessment of circular products (Tsalidis et al. 2023). In particular, solving multifunctionality through allocation in S-LCA is even more artificial than in E-LCA. Thus, careful deliberation is required to determine whether results should be calculated per functional unit, even when comparing alternatives. In any case, unaggregated results and transparency in aggregation methods are strongly encouraged in S-LCA studies. Despite addressing these limitations, further research and development of the S-LCA method are needed to evaluate the social effects of novel resource recovery systems, especially when comparing them with conventional systems.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-024-02370-2.

Acknowledgements The authors would like to sincerely thank the WWTP operator for their valuable support and contribution during the data collection and manuscript revision processes.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Akemi Kokubo Roche. The first draft of the manuscript was written by Akemi Kokubo Roche, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This work has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 869474. The opinions expressed in this document reflect only the author's view and reflect in no way the European Commission's opinions. The European Commission is not responsible for any use that may be made of the information it contains.

Data availability All data gathered and analyzed during this study are available in the Supplementary Information. Online Resource 2 will be made available upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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