Social Life Cycle Assessment of microalgae-based systems for wastewater treatment and resource recovery: key challenges for transformations towards a circular bioeconomy

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Abstract

The aim of this study was to assess the social impacts of microalgae-based systems for wastewater treatment and bioproducts recovery by using the Social Life Cycle Assessment (S-LCA) tool. In particular, two systems were analysed: 1) a system treating urban wastewater, and 2) another system treating wastewater from the food industry. Moreover, these alternatives were compared to 3) a system for bioproducts production from microalgae grown in a standard growth medium. The recovered bioproducts in all the systems considered were: natural pigments, biogas and digestate, which can be reused as biofertilizer. Results showed that the scenario using standard growth medium was the one showing the best results in all impacts and stakeholder categories (up to 24-fold lower impacts depending on the impact category). This was mainly due to: i) the simplicity of the system, which consequently improves health and safety for workers; ii) the absence of contaminants which consequently improves health and safety, acceptability and olfactory impact for both consumers and the local community; iii) the presence of well-established legislation, regulatory frameworks, and full-scale deployment, which benefit value chain actors and society. Overall, this study also identified several social factors hindering a transition towards a circular bioeconomy in the microalgae-based systems for the wastewater treatment and resource recovery sector.

Keywords: circular economy; bioproducts; natural pigments; bioenergy; biofertilizer; sustainability.

1. Introduction

The global need for moving towards sustainable development has increased the attention to potential changes in how societies and their economies work. One particular concept that has become central in the realm of sustainability is the circular economy (Rodriguez-Anton et al., 2019; Valverde and Avilés-Palacios 2021; Belmonte-Ureña et al., 2021).

In particular, the concept of bioeconomy is generating considerable interest within the idea of circular economy (Hadley Kershaw et al., 2021). According to the European Commission (2012), circular bioeconomy refers to the production of biological and renewable resources, as well as the valorisation of these products and their waste products through the production of goods such as food, feed or bio-based energy. In brief, it aims at converging the circular economy and the bioeconomy agendas with a particular emphasis on biotechnology (Hetemäki et al., 2017).

One of the biotechnology sectors that has received considerable interest in academia is the one related to using microalgae. In the last decades, microalgal technologies have been extensively studied because of their numerous applications in fields like biology, biomedicine, environment or industry. The potential benefits that using microalgae has can be key for the production of sustainable products like food, feed, fertilizers, fuels, fodder, cosmetics and other bioproducts. In this context, the use of wastewater, instead of chemical fertiliser to provide nutrients for microalgae growth, has been frequently studied in the literature due to the economic and environmental cost reduction that it implies. Additionally, microalgae can be used to treat wastewater, corresponding to the secondary or tertiary treatment of wastewater.

Conventional cultivation of microalgae are processes where algae are cultivated in reactors that require large surfaces, as well as clean water and chemicals. They can be cultivated in open (e.g. High Rate Algal Ponds, HRAPs) or in closed reactors (i.e. photobioreactors, PBRs). HRAPs are economic alternatives that can be utilized in locations where weather conditions are favourable for microalgae growth (i.e. warm climate). On the other hand, PBRs are designed to overcome the problems associated with open pond cultivation systems. As a drawback, these systems require high surface area, and high amounts of chemicals and clean water for microalgae growth.

Compared to the conventional cultivation of microalgae, using wastewater instead of clean water, chemical fertilisers or standard growth media has a great number of advantages that can ease the full-scale deployment of microalgal technologies. In fact, wastewater can provide nutrients (N, P) necessary for microalgae growth, reducing the large amounts of chemical fertilisers or culture media and clean water, thus improving the environmental footprint and the cost-effectiveness of these systems (Arashiro et al., 2022; Martins et al., 2018; Li et al., 2019).

On the other hand, several authors have advocated for the recovery of resources from treating wastewater using microalgae-based technologies. Chai et al. (2021) reviewed the several roles that microalgal technologies can have in the processes of wastewater treatment. In fact, the use of microalgae to remove nutrients in wastewater treatment can benefit the process through the recycling of nutrients and mitigating environmental impacts (by reducing chemicals and energy consumption) (Fernández-Acero et al., 2019; Li et al., 2019; Díez-Montero et al., 2020; Li et al., 2021; García-Galán et al., 2021) in comparison to conventional treatment methods (e.g. activated sludge systems) (Arashiro et al., 2018; Garfí et al., 2017; Renuka et al., 2021; Serrà et al. 2020; Vassalle et al., 2020).

In addition to the environmental and cost-wise impacts, the social implications that recovering resources from microalgae grown in wastewater should be taken into account as well. In fact, several social issues are connected to this kind of system. For instance, Dickin et al. 2016 describe the health risks arising from exposure to wastewater due to the large range of contaminants from municipal, agricultural, and industrial sources. Besides health, another relevant question regarding the use of wastewater for resource recovery is societal acceptance.

In fact, perception could be key for a more rapid introduction of this kind of system in societies (Villarín and Merel, 2020).

To the best of the authors' knowledge, despite the importance of considering social aspects in environmental technologies, no studies have been carried out to analyse the social impacts of resource recovery from microalgae wastewater treatment systems. Analysing all the social impacts over all the stages of the process lifecycle could be key to better understanding what the bottlenecks are at present (Padilla-Rivera et al., 2016, 2019).

In light of the above, the objectives of this study are twofold. On the one hand, it aims at developing a Social Life Cycle Assessment (S-LCA) framework to evaluate the social impacts associated with the life cycle stages of resource recovery from microalgae grown in wastewater; on the other hand, it identifies opportunities and challenges for large-scale implementation. These objectives are met by developing a comparative S-LCA of two microalgae-based systems for wastewater treatment and bioproducts recovery (i.e. natural pigments, biogas and the digestate which can be reused as biofertilizer): 1) one system treating urban wastewater, and 2) another system treating wastewater from the food industry (plant-based products). Moreover, for the sake of comparison, these alternatives were compared to 3) a system for bioproducts (e.g. natural pigments, biogas and digestate which can be reused as biofertilizer) production from microalgae grown in a standard growth medium. The novelty and originality of this study lie in the fact that, until the present, such an approach has never been taken to analyse the social impacts of wastewater treatment and resource recovery technologies.

The following section describes the methodological framework developed and followed to carry out the S-LCA. Then, the results obtained are discussed in Section 4, which also include a discussion on the key challenges and opportunities, the future directions and the limitations detected. Section 4 concludes.

2. Material and methods

This section describes the methodology used in the study, including the S-LCA background, the definition of the goal and scope of the analysis, the stakeholders and impact categories evaluated, and the approach followed for the normalisation of the results.

2.1. Social Life cycle assessment

Life cycle assessment (LCA) is widely acknowledged as an effective technique to assess the impacts of products and services. Following the three dimensions of sustainability, there exist different guidelines for developing social, environmental, and economic LCAs. Among these, the S-LCA has the purpose of evaluating social impacts in relation to certain stakeholders such as workers or local communities during the life cycle of the good or process under analysis (UNEP/SETAC, 2009, 2020).

The last years have witnessed a huge growth in studies using environmental LCA (E-LCA). However, previous work using S-LCA has been limited. Even though both methods are based on the same principles, there exist several important differences between them. One relevant divergent characteristic between S-LCA and E-LCA is that indicators to measure social impacts are seldom quantitative. An important consequence of this is that it is not always possible to determine the social impacts per functional unit. In addition, S-LCA also differs from E-LCA in the fact that impact subcategories may be divided by stakeholder groups. In the context of S-LCA, stakeholder groups are groups of individuals or organizations who may be affected by the processes or products being analysed, such as workers, local communities or value chain actors. Some authors have also discussed the uncertainty that is associated with S-LCA due to the nature of the data used (Macombe and Loeillet, 2014) and with bioeconomy resources due to the modelling and metrics employed (Brandão et al., 2022).

In this study, the S-LCA was conducted following the ISO 14040 framework, as well as the guidelines by UNEP/SETAC (2020), in which a methodology is presented to develop life cycle inventories. The framework consists of four phases. In the first one (i.e. Goal and Scope), the process or product under study is described by defining the purpose of the study, the functional unit, and the system boundaries. Then, the Life Cycle Inventory consists of collecting and organising the data for its analysis. In the Impact Assessment stage, this data is classified, aggregated and characterised according to performance reference points. Finally, in the phase of Life Cycle Interpretation, all relevant parts of the study are interpreted; namely, significant issues are identified, and recommendations and conclusions are drawn.

2.2. Goal and scope definition

Given that this study evaluated the social impacts associated with a system that has not yet been deployed at full-scale, the approach utilised was the Impact Pathway Approach (UNEP/SETAC, 2020). This approach is commonly used when the aim of the study is to predict the consequences of the product system, hence performing an ex-ante analysis.

In particular, the studied systems were the hypothetical wastewater treatment plants located in Barcelona (Spain) and described in Arashiro et al. (2022). As these authors outline, these systems were designed to treat a flow rate of 1.500 m^3/d. The systems were two microalgae-based systems for wastewater treatment and resources recovery (i.e. natural pigments, biogas and the digestate which can be reused as biofertilizer): 1) one system treating urban wastewater (Scenario UWW), and 2) another system treating industrial wastewater from the food industry producing plant-based products (Scenario IWW). Moreover, for the sake of comparison, these alternatives were compared to 3) a system for bioproducts (e.g. natural pigments, biogas and digestate which can be reused as biofertilizer) production from microalgae grown in a standard growth medium (Scenario SGM). The functional unit (FU) for the comparison of these alternatives was established as 1 m^3 of water.

The system boundaries are shown in **Figure 1**, **Figure 2**, and **Figure 3**. As can be seen, they range from the collection of wastewater to the obtention of the different outputs. The processes involved in the production of the infrastructure and equipment of the plant were not considered, as it was considered that the impact would be marginal compared to the overall impact.

Scenario UWW (**Figure 1**) is a combination of HRAPs for urban wastewater treatment and PBRs for cyanobacteria biomass cultivation, as described in Arashiro et al. (2022). First, there is a primary settler that is followed by four HRAPs, where a mixed culture of green microalgae is cultivated. Then, the flow goes through a secondary settler, where there is the harvesting of microalgal biomass and its separation from wastewater. Afterward, cyanobacteria-dominated biomass is cultivated in the PBRs and its effluent goes through a tertiary settler. Finally, the microalgae biomass is centrifuged and used for the recovery of bioproducts. Throughout the process, microalgae biomass and the residual biomass are used as a co-substrate for biogas production in an anaerobic digester.

In Scenario IWW (**Figure 2**), industrial wastewater from a food company is treated in an up-flow anaerobic sludge blanket (UASB) reactor followed by HRAPs cultivating *A. platensis* (Spirulina). First, wastewater goes through a sieve and then, through a UASB. The effluent from the UASB is then filtered and taken to HRAPs, where Spirulina biomass is cultivated. Finally, the microalgal biomass is harvested and separated from the treated water in a secondary settler and pigments are extracted after centrifugation.

Scenario SGM (**Figure 3**) is comprised of HRAPs cultivating *A. platensis* (Spirulina) with a standard growth medium (SGM). A SGM is a solution with basic elements such as water and nutrients, that are necessary for the growth of microalgae. Further details of the systems can be found in Arashiro et al., (2022).

The recovered products considered for the analysis were natural pigments, biogas and digestate which can be reused as biofertilizer. Regarding the recovery of natural pigments, it was considered that these pigments could be used for food or non-food products, and that they would substitute conventional pigments. It also needs to be noted that biogas was not considered a commercialised product because it is reused in the same systems. Indeed, in all the scenarios the biogas produced is converted into electricity and heat through a combined heat and power (CHP) unit which are then reused in the same systems. While this has effects on the E-LCA because this system allows avoiding the burdens of using heat and electricity, instead of heat from natural gas and electricity supplied through the grid, the effects in terms of the S-LCA are negligible. Finally, the digestate produced in the anaerobic digesters was considered a substitute for chemical fertilisers in all the scenarios.

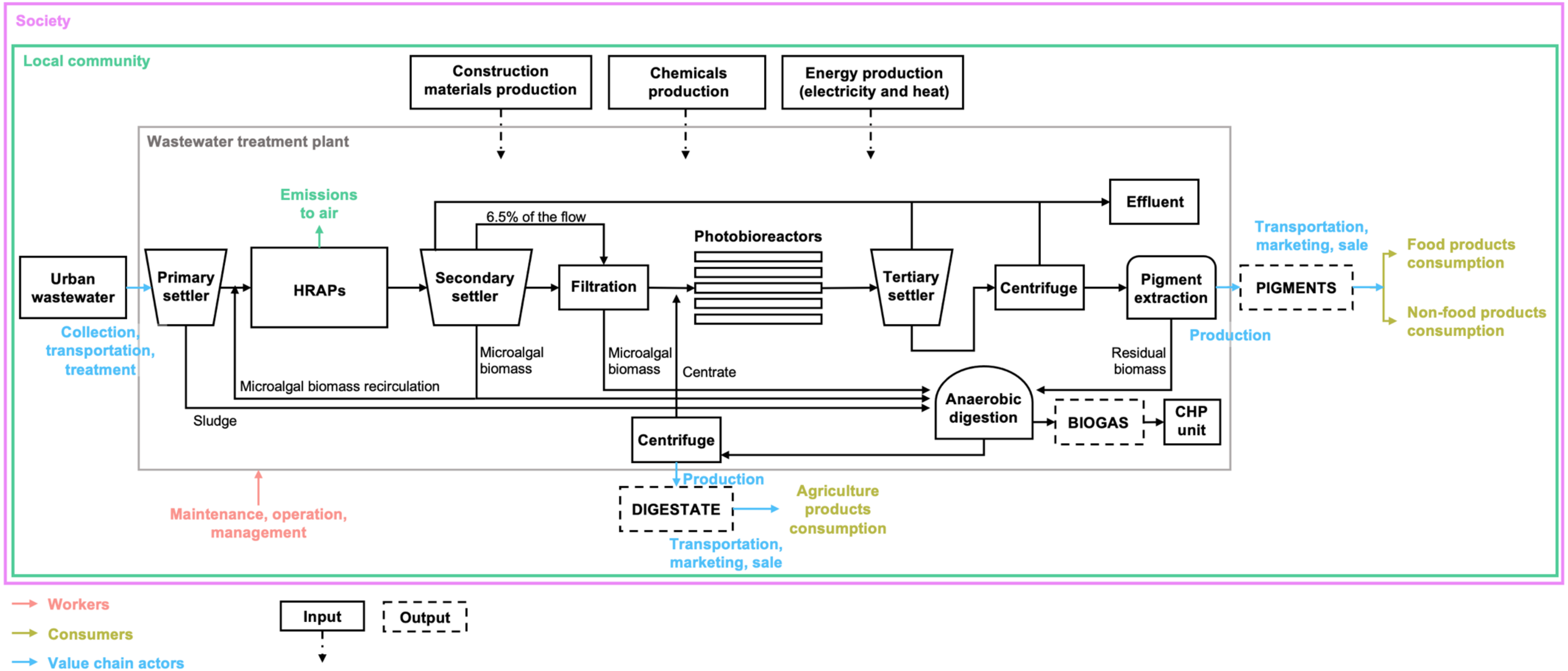

Figure 1 Flow diagram and system boundaries of Scenario UWW: urban wastewater treatment in high rate algal ponds (HRAPs) followed by photobioreactors (PBRs) cultivating cyanobacteria-dominated biomass.

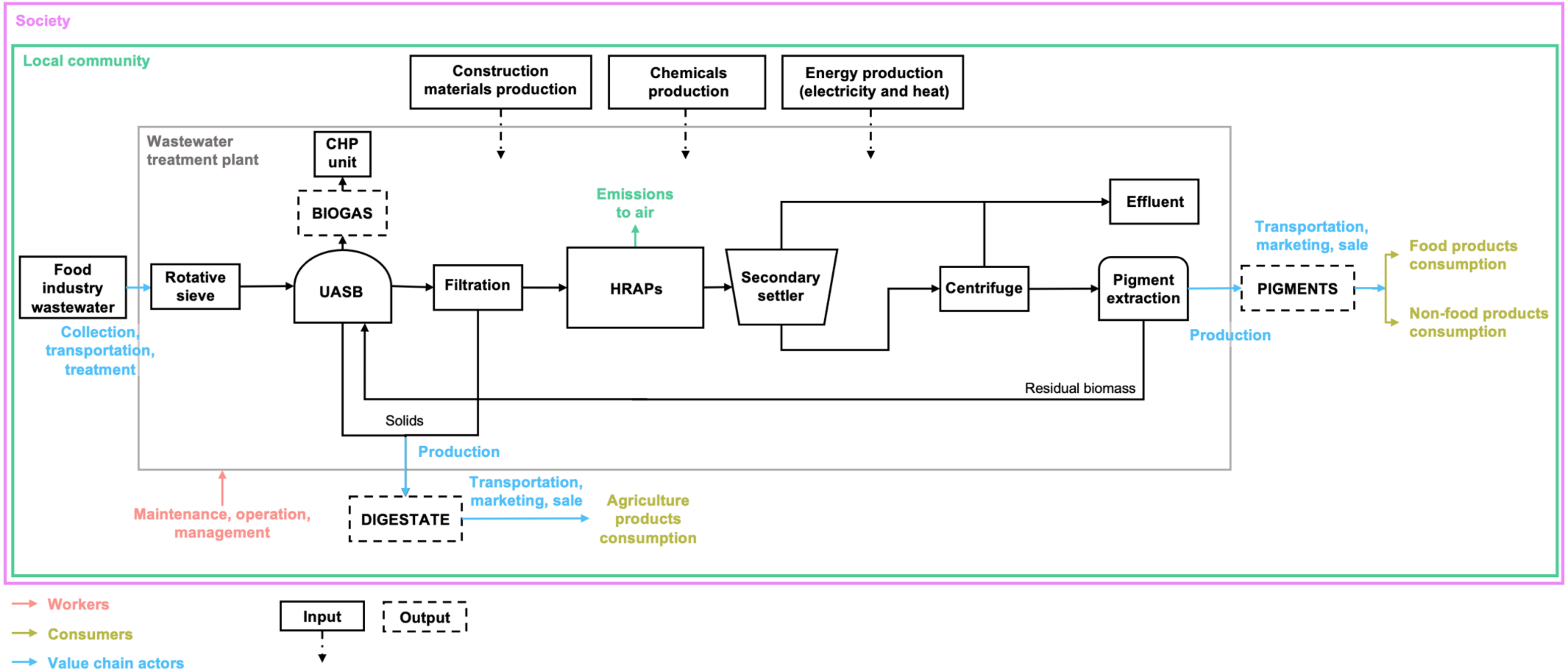

Figure 2 Flow diagram and system boundaries of Scenario IWW: industrial wastewater from a food company treated in an up-flow anaerobic sludge blanket (UASB) reactor followed by high rate algal ponds (HRAPs) cultivating *A. platensis* (Spirulina).

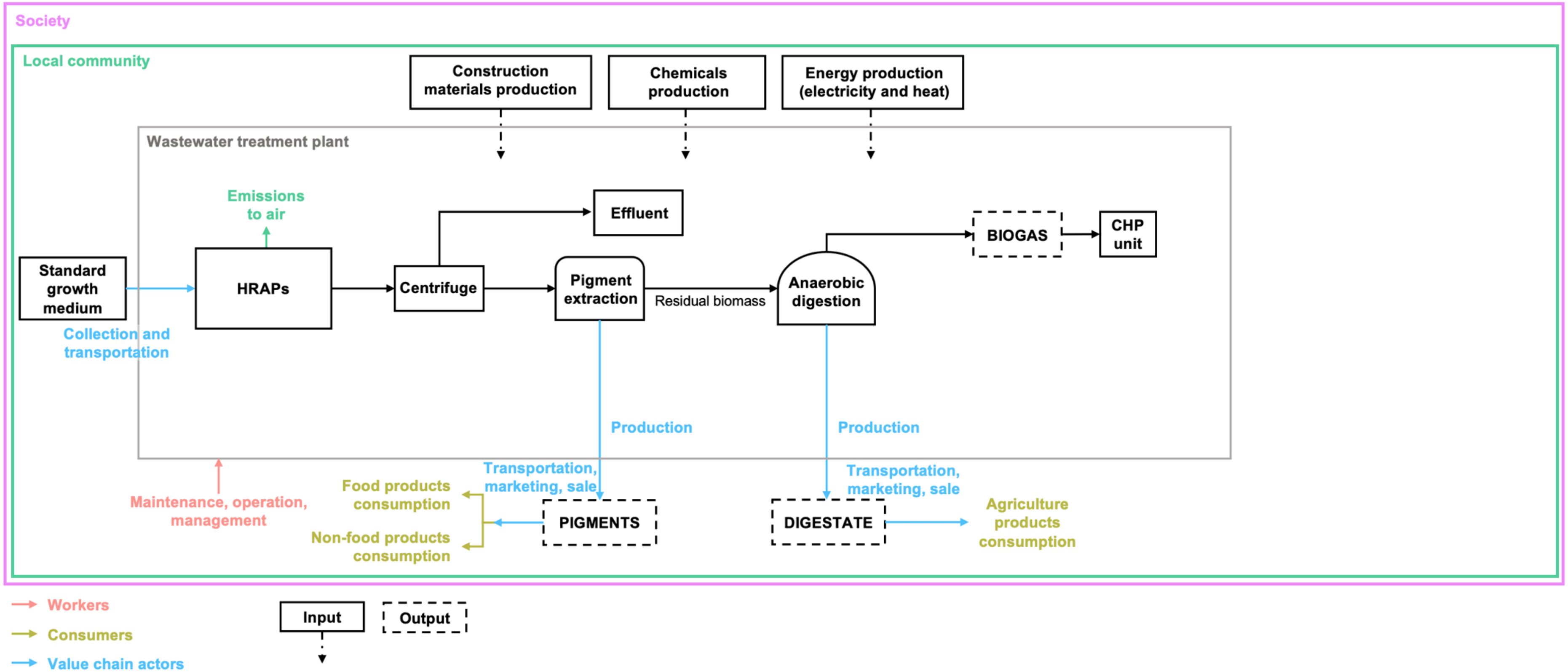

Figure 3 Flow diagram and system boundaries of Scenario SGM: high rate algal ponds (HRAPs) cultivating *A. platensis* (Spirulina) with a standard growth medium (SGM).

2.3. Stakeholders and impact categories

The stakeholders in this study for which the impacts were examined were the ones presented below. These stakeholders were selected following the guidelines by UNEP/SETAC Life Cycle Initiative (2009), which are currently commonly accepted.

1. Workers: technicians that maintain and operate the infrastructure of the studied systems.
2. Consumers: consumers of material/immaterial outputs considered (i.e. natural pigments for food and non-food products, and digestate as biofertiliser).
3. Local community: community living nearby the microalgae-based systems for wastewater treatment and resource recovery.
4. Value chain actors: actors directly involved in value chain activities (e.g. water agencies, farmers, wholesalers).
5. Society: society in general terms.

In the following subsections, the different stakeholders and their respective impact categories are described in more detail. Besides, the method used for the impact assessment is also presented. A summary of all this information can be found in **Table 1**.

Table 1 Summary of the stakeholders and respective considered impact categories and indicators

Stakeholders	**Description**	**Stakeholder subcategory**	**Impact category**	**Impact subcategory**	**Indicator**		**Reference for scale values assignment**
Workers	Technicians who maintain and operate the infrastructure, heads and administration		Health and safety	–	Maintenance and operation tasks risks	Hazard (Scale 1 to 5) x Severity (Scale 1 to 4) ^{QL,N}	Expert seminars
			Working conditions	Fair salary	Proportion with respect to decent wage level	Scale (1 to 3) ^{QL,N}	BOE (2019), (IECA, 2020)
				Working hours	Likeliness of working overtime	Scale (1 to 3) ^{QL,N}	Expert seminars
Consumers	Consumers of material/immaterial outputs (i.e. natural pigments for food and non-food products, and digestate as biofertilizer)	Pigments consumers	Health and safety	Food products	Probability of pathogens transmission	Scale (1 to 5) ^{QL,N}	AESAN (2019), EFSA (2019)
				Non-food products	Probability of pathogens transmission	Scale (1 to 5) ^{QL,N}	AESAN (2019), EFSA (2019)
			Quality and performance	Food products	Expressive and instrumental performance	Performance scale (1 to 5) ^{QL,N}	Literature review
				Non-food products	Expressive and instrumental performance	Performance scale (1 to 5) ^{QL,N}	Literature review
			Acceptability	Food products	Acceptance	Acceptance scale (1 to 7) ^{QL,N}	Expert seminars
				Non-food products	Acceptance	Acceptance scale (1 to 7) ^{QL,N}	Expert seminars
		Digestate consumers	Health and safety	–	Probability of pathogens transmission	Scale (1 to 5) ^{QL,N}	AESAN (2019), EFSA (2019), Nag et al., (2020)
			Quality and performance	–	Crop quality and growth	Performance scale (1 to 5) ^{QL,N}	Literature review
			Acceptability	–	Acceptance	Acceptance scale (1 to 7) ^{QL,N}	Expert seminars

Local community	Community living nearby the plant	Liveability	–	Olfactory impact	Proportion with respect to odour detection threshold ^{QT,N}	Arashiro et al., (2022); Gebicki et al. (2016)
		Socio-economic repercussions	–	Employment generation	Number of jobs generated ^{QT,P}	Expert seminars
Value chain actors	Actors directly involved in value chain activities (e.g. water agencies, engineers, promoters).	Promotion of social responsibility	Collection of the wastewater	Regulation implementation level	Scale (1 to 7) ^{QL,N}	Spanish legislation
			Treatment of the wastewater and production of the natural pigments, and digestate	Regulation implementation level	Scale (1 to 7) ^{QL,N}	Spanish legislation
			Transportation of wastewater and transportation and marketing of natural pigments, and digestate	Regulation implementation level	Scale (1 to 7) ^{QL,N}	Spanish legislation
Society	Society in general terms	Public commitment to sustainability issues	Wastewater treatment	Presence of documents on sustainability issues	Scale (1 to 3) ^{QL,N}	PWC (2018), EC (2020)
			Pigments production and use	Presence of documents on sustainability issues	Scale (1 to 3) ^{QL,N}	PWC (2018), EC (2020)
			Digestate production and use	Presence of documents on sustainability issues	Scale (1 to 3) ^{QL,N}	PWC (2018), EC (2020)
		Technological development	Wastewater treatment	Technology readiness level	Scale (1 to 9) ^{QL,N}	Literature review
			Pigments production and use	Technology readiness level	Scale (1 to 9) ^{QL,N}	Literature review
			Digestate production and use	Technology readiness level	Scale (1 to 9) ^{QL,N}	Literature review

Note: QL: qualitative indicator. QT: quantitative indicator. P: the higher, the more positive. N: the higher, the more negative.

2.3.1. Workers

In this study, workers represented the staff members that are responsible for the operation and maintenance of the microalgae-based systems for wastewater treatment and resource recovery. The main types of workers that may be found are (**Table 2**): i) heads, whose tasks are generally to coordinate operators, supply material and work equipment, or evaluate the plant functioning at different levels (CESPT, 2007); (iii) administration personnel, who are responsible for tasks related to informatics or day-to-day task administration, and iii) head operator, operators and technicians, who are responsible for verifying the correct functioning and manipulation of the electromechanical equipment (e.g. valves, bombes, centrifuges, settlers) of the plants, cleaning of the installations, or taking samples for its analysis.

Spanish regulations define employment categories as well as their minimum salaries (BOE 2019). Data on salaries included in **Table 2** were obtained from these regulations. The allocation of worker numbers for every scenario was done based on data from similar full-scale plants (Otero and Berlingeri, 2011; Gómez, 2017).

Two main impact categories were considered in this study for workers: 1) health and safety, and 2) working conditions (**Table 1**).

Table 2. Working categories and respective staff considered for each scenario and corresponding salary

Working category	**Salary** (€/year)	**Scenario UWW**	**Scenario IWW**	**Scenario SGM**
Head	18830	1	1	1
Administration personnel	17200	2	1	1
Head operator	17450	1	1	1

Technicians	16310	6	4	3
Operators – cleaning, janitors	15720	3	2	2*

*Note: Scenario UWW: microalgae-based system for urban wastewater treatment and resources recovery (i.e. natural pigments, biogas and the digestate which can be reused as biofertilizer); Scenario IWW: microalgae-based system for industrial wastewater treatment and resources recovery (i.e. natural pigments, biogas and the digestate which can be reused as biofertilizer); Scenario SGM: system for bioproducts (e.g. natural pigments, biogas and digestate which can be reused as biofertilizer) production from microalgae grown in a standard growth medium. *Includes one person full-time and one person part-time.*

2.3.1.1.Health and safety

First of all, the impact category health and safety was comprised of impacts derived from the maintenance and operation of the equipment. For the measurement of this category, two different indicators were used: hazard and severity (**Table 1**) (Campbell and Smith, 2007; Karakhan and Gambatese, 2018). The risk was obtained by multiplying these two indicators.

Seven different machines that are necessary for the three microalgae-based systems studied were considered as potential sources of hazard: centrifuge, settlers, HRAPs, PBRs, CHP unit, UASB reactor and sieve. For each machine, seven different events were considered when analysing their health and safety risks: oxygen deficiency, physical injuries, toxic gases and vapours, infections, fire, explosion and electrocution. These events are indicated by Spellman (2020) as the major types of hazards that exist at wastewater treatment plants.

Each machine was assigned a value for hazard and severity for each event. Then, the hazard and severity values were, as mentioned above, multiplied in order to obtain the risk. To obtain the total value of this impact category for each scenario, the risk of each machine and each event were added, by considering all the machines needed in each scenario.

The scales employed for hazard and severity are presented in **Table 3** and **Table 4**, respectively.

Table 3. Scale employed for the measurement of risk hazard

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

Table 4. Scale employed for the measurement of risk severity

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

Data for hazard and severity indicators was obtained from expert seminars carried out with experts in the field of wastewater treatment and resources recovery processes and technicians of wastewater treatment plants.

2.3.1.2.Working conditions

The social impact for the working conditions category was measured through two different subcategories: fair salary and working hours (Padilla-Rivera and Güereca, 2019).

The fair salary was measured by using the scale shown in **Table 5**, which compares the actual salaries (**Table 2**) with a decent wage level. This decent wage level was defined by examining data sources of socio-economic conditions in the area studied (IECA, 2020).

Table 5. Scale employed for the measurement of a fair salary for workers

Scale	**Description**
5	Salary more than 75% below decent wage level
4	Salary between 25 to 75% below to decent wage level
3	Salary around 25% of the decent wage
2	Salary between 25 to 75% above to decent wage level
1	Salary more than 75% above decent wage level

For every working category (**Table 2**), a value from the scale was assigned. Then, for each scenario, an average value was calculated also considering the number of workers per each working category (**Table 2**).

Regarding the working hours impact category, the likeliness of having to work overtime was evaluated using the three-factor scale shown in **Table 6** and quantified based on Anxo and Karlsson (2019). Data for this impact category was obtained from interviews with technicians and heads in similar plants.

Table 6. Scale employed for the measurement of working hours for workers

Scale	**Description**
3	High likelihood of having to work overtime

2	Medium likelihood of having to work overtime
1	Low likelihood of having to work overtime

The methodology used to obtain the final values for these impacts was similar to the previous impact category. For every working category (**Table 2**), a value from the scale was assigned. Then, for each scenario, an average value was calculated also considering the number of workers per each working category (**Table 2**).

2.3.2. Consumers

In this study, consumers were considered to be those stakeholders that would use or consume the different recovered bioproducts from the studied processes. As mentioned above, the recovered resources for consumers were two: the natural pigments for food and non-food products, and the digestate used as biofertiliser.

Three main impact categories were defined for this stakeholder group: health and safety, quality and performance, and acceptability. End-of-life responsibility, which refers to the presence, within an organization, of systems that provide information on end-of-life options for product consumers (Adami Mattioda et al., 2017), was not included as a potential category since the same results would be obtained for the three scenarios.

2.3.2.1.Health and safety

For this impact category, the guidelines by Harder et al., (2014), Heimersson et al. (2014) and Nag et al., (2020) were taken into account. The evaluation was done using a scale ranging from 1 (lowest risk for health) to 5 (highest risk). Potential pathogens in wastewater were searched in European and Spanish databases (AESAN, 2019; EFSA, 2019), and values were assigned based on the information given by this data.

In particular, three aspects were evaluated: the presence of health risks in natural pigments used for food, in natural pigments used for non-food products, and in digestate (**Table 1**). For the digestate, the different transmission pathways outlined by Nag et al., (2020) were also considered. In the end, the value for this impact category was obtained by adding the scale values separately for natural pigments (for food and non-food products) and digestate for each scenario.

2.3.2.2.Quality and performance

For the quality and performance impact category, an adaptation of the scale defined by Kince et al. 2011 was used, which is presented in **Table 7**. As it can be seen, it consists of five elements similar to a Likert scale, where the lowest value represents the best quality one to allow for consistency with other indicators.

Table 7. Scale used to evaluate quality and performance (adapted from Kince et al. 2011)

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

For natural pigments, the two characteristics that were measured were expressive performance (e.g. colour) and instrumental performance (e.g. usage simplicity or production process) as suggested by Haghighat et al. (2017). For the digestate, the two factors that were assessed were crop growth and crop quality. Scale values were assigned according to the literature (Arashiro et al., 2022; Barzee et al., 2019; Haghighat, 2017; Moldovan et al., 2017; Owamah et al., 2014; Panuccio et al., 2018). The final value for this impact category was obtained by adding the scale values separately for natural pigments (for food and non-food products) and digestate in each scenario.

2.3.2.3.Acceptability

Regarding the impact category acceptability, an adaptation of van der Laan's acceptance scale was employed (van der Laan et al., 1997). Specifically, the indicator acceptance was measured with a scale ranging from 1 (most positive) to 7 (most negative). This was done both for natural pigments (for food and non-food products) and digestate as biofertiliser. Scale values were assigned considering experts' opinions. As it was done in previous categories, the final result for this category was obtained by adding together the scale values assigned for every recovered resource separately for each scenario.

2.3.3. Local community

This group of stakeholders refers to the groups living nearby the treatment plant and any other location of the activities directly related to the processes involved in the resource recovery. Two impact categories were considered particularly relevant for this stakeholder, namely liveability and socioeconomic repercussions.

2.3.3.1.Liveability

Regarding liveability, in the context of the scenarios considered in this study, it was determined that the main attribute to be incorporated was air quality. Hence, in the present study, the olfactory impact of the treatment processes was considered the determining impact subcategory (Sochacka et al. 2021).

The olfactory impact has been studied in the literature by several authors (Snitz et al., 2013; Gebicki et al., 2015; Kowalewski and Ray, 2020), who have developed odour scales that are usually related to the products that are released into the air. For this study, inventory data obtained from the E-LCA (Arashiro et al., 2022) were used to examine what substances are released and which of them are prone to have an olfactory impact. In particular, for each scenario, the quantities of ammonia volatilised from the reactors (HRAPs) and due to the application of the digestate to soil were considered. These amounts were divided by the corresponding odour detection threshold (Kowalewski and Ray, 2020) to obtain the final value for each scenario.

2.3.3.2.Socioeconomic repercussions

The impact subcategory of the socio-economic repercussions for the local community was determined to be employment generation (Padilla-Rivera and Güereca, 2019). The measurement of this subcategory was done by calculating the number of workers needed times their corresponding total number of working hours. The job positions considered for this were the same as for the workers category (**Table 2**). The final value was obtained by adding the values for each job position and for each scenario.

2.3.4. Value chain actors

The impact categories analysed for value chain actors was the promotion of social responsibility, as is described below.

2.3.4.1.Promotion of social responsibility

This stakeholder category integrates all those actors that are involved in value chain activities. In this study, the impact category that was considered to be important was the promotion of social responsibility. For the processes involved in the different stages of wastewater treatment and resource recovery (i.e. wastewater collection and treatment, natural pigments and digestate production), it was considered that three subcategories had to be included, namely:

1. Collection of the wastewater, which includes the following value chain actors: the local government and water agencies.
2. Treatment of the wastewater and production of the natural pigments (for food and non-food products), and digestate, which include the following value chain actors: contractors and engineers.
3. Transportation of wastewater and transportation and marketing of natural pigments, and digestate, which include the following value chain actors: transporters and promoters.

The impacts were measured considering the implementation level of the regulation or legislation that regulates the actions of the considered value chain actors. For this, a scale from 1 to 7 was used, considering the aspects shown in **Table 8**. The final impact category value for each scenario was obtained by adding together the scale values assigned to each value chain actor group. Data for the assignment of scale values was obtained from Spanish regulations, including the Ley 22/2011, Real Decreto 833/1988, Real Decreto 952/1997, Orden

MAM/304/2002, and Orden AAA/699/2016 for waste; Orden AAA/1072/2013 and Real Decreto 1310/1990 for sludge; and Real Decreto 553/2020 for waste transportation.

Table 8. Scales used for the evaluation of promotion of social responsibility for value chain actors

Scale	Description
1	(New) regulations
2	Existing authority
3	Policy
4	Industry standards
5	Guidance
6	Information
7	Knowledge

2.3.5. Society

The last stakeholder category was analysed using two different impact categories: public commitment to sustainability issues, and technological development. These categories are described in more detail below.

2.3.5.1.Public commitment to sustainability issues

As for the former, the analysis was done based on a 1 to 3 scale where values were assigned depending on the existence of documents supporting the commitment to social sustainability issues that regulate the processes considered. Based on the suggestions by Stover (2000), the following were the plans, policies or documents that were searched: a supportive national policy, a strategic plan, a national plan that is highly placed within the government structure, a comprehensive program that addresses all key aspects of prevention, care, and mitigation, a comprehensive research program, adequate funding, and sustained monitoring and evaluation (US Agency for International Development, 2000).

The scale values were assigned for each main step where public commitment was considered relevant. In this case, they were: wastewater treatment process, the production and use of natural pigments for food and non-food products, as well as digestate production and use. Data for this impact category was gathered by examining existing policies at the Spanish level in terms of sustainability issues for the processes considered in this study (PWC, 2018; EC, 2020). After evaluating each of the aforementioned steps, the values allocated were then added together to obtain the final value of the impact category.

2.3.5.2.Technological development

Regarding technological development, Technology Readiness Levels (TRL) (Dovichi Filho et al., 2021) were employed to evaluate three different steps of the system under analysis: technology for wastewater treatment, natural pigments production and use, and digestate production and use. The scale used in this study is described in **Table 9**. For each scenario, a scale value was assigned to each step under analysis. The final value was obtained by adding the values of the three steps considered for each scenario. Data were obtained from the literature (Valchev and Ribarova, 2022).

Table 9 Scales used for the evaluation of technological development for society

Scale	Description

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

2.4. Impact assessment

Normalisation of the results was carried out using the MIN/MAX normalisation procedure. In this technique, the minimum value of the indicator is transformed into a 0, while the maximum value is converted into 1. The other values are transformed into a number between 0 and 1. This is reflected in Equation 1.

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

For this study, all indicators were normalised using the above equation except for socio-economic repercussions, whose scale was reversed (i.e. the higher the indicator, the better). In this case, the maximum value was transformed into 0, and the minimum one into 1.

3. Results and discussion

This section includes the results and discussion of the S-LCA, a consideration of key challenges and future research directions stemming from the results, and an evaluation of the limitations of the study.

3.1. Social LCA results and discussion

In this subsection, the results are presented for each of the stakeholder groups and impact categories described above. The final part of this subsection presents the results of the normalisation.

3.1.1 Workers

Figure 4 shows the potential social impacts for workers associated with the three scenarios analysed: 1) the microalgae-based system for wastewater treatment and resources recovery treating urban wastewater (Scenario UWW); 2) the microalgae-based system for wastewater treatment and resources recovery using industrial wastewater (Scenario IWW); 3) and the system for bioproducts production from microalgae grown in a standard growth medium (Scenario SGM). The impact categories shown in the diagram are health and safety on the one hand, and working conditions on the other hand.

Regarding the health and safety of the workers, it can be observed that the scenario with the worst performance was the scenario treating urban wastewater (Scenario UWW), which had impacts 2.5-fold and 1.2-fold higher than the scenario using standard growth medium (Scenarios SGM) and the scenario treating industrial wastewater (Scenario IWW), respectively (**Figure 4a**). The operation of the microalgae-based system treating urban wastewater requires a higher number of equipment and technologies (e.g. centrifuge, settlers, closed photobioreactors), which increases the probability of hazard events, including oxygen deficiencies, physical injuries, toxic gases and vapours, infections, fire, explosion, and electrocution. These results are supported by other authors, who have emphasised the health risks to which wastewater treatment plant workers are exposed (Kesari et al., 2021; Zielinski et al., 2021).

Regarding the working conditions impact category, all the scenarios showed similar social impacts. As mentioned in the previous section, working conditions were evaluated based on working hours and salary. For the fair salary sub-category, the scenario treating urban wastewater (Scenario UWW) had a slightly higher social impact, even though the differences among scenarios were relatively small (<2%). For the working hours sub-category, the scenario using standard growth medium (Scenario SGM) had impacts of up to 7% higher than the scenarios treating urban and industrial wastewater (Scenarios UWW and IWW). Such difference is explained by a higher number of workers (especially operators) necessary for the scenario treating urban wastewater (Scenario UWW), given the higher complexity of the plant.

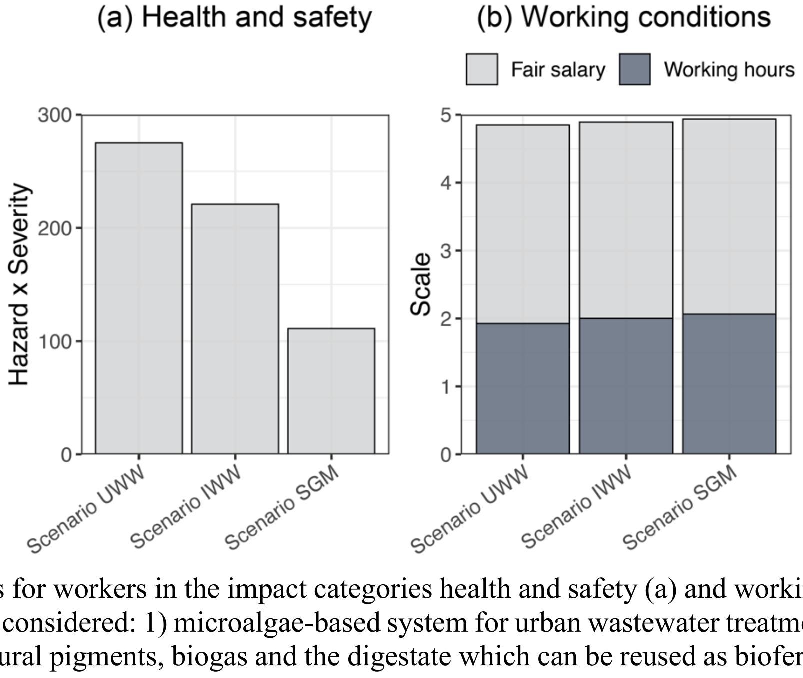

Figure 4. Results for workers in the impact categories health and safety (a) and working conditions (b) for the Scenarios considered: 1) microalgae-based system for urban wastewater treatment and resources recovery (i.e. natural pigments, biogas and the digestate which can be reused as biofertilizer) (Scenario UWW); 2) microalgae-based system for industrial wastewater treatment and resources recovery (i.e. natural pigments, biogas and the digestate which can be reused as biofertilizer) (Scenario IWW); 3) system for bioproducts (e.g. natural pigments, biogas and digestate which can be reused as biofertilizer) production from microalgae grown in a standard growth medium (Scenario SGM).

3.1.2 Consumers

Concerning consumers, the results are shown in **Figure 5**. First of all, as for health and safety for natural pigments consumers, the scenario using standard growth medium (Scenario SGM) had the lowest potential impacts, representing a reduction of 50% and 33% with respect to the scenarios treating urban (Scenarios UWW) and industrial wastewater (Scenario IWW), respectively. This was due to the fact that resources obtained from treated wastewater can carry more risks deriving from bacteria, viruses, parasites or any other type of pathogen (Verbyla et al., 2015; Romeiko et al., 2020). This applies both to food and non-food products, but the potential threat is higher for the former. Moreover, in food-industry wastewater, there is usually no presence of pathogens and heavy metals. Similarly, for digestate consumers, the best scenario in terms of health and safety was that one using standard growth medium (Scenario SGM), while the worst was the scenario treating urban wastewater (Scenario UWW), due to the higher probability of pathogens transmission in the latter.

Regarding the quality and performance of natural pigments, the scenario using standard growth medium (Scenario SGM), in which pigments are produced under more controlled conditions and the desired algae species are grown, achieved the best results both for food and non-food alternatives (impact 50% lower with respect to the other scenarios). Regarding the digestate, the impact on the quality of crops and their growth was found to be similar for the three scenarios.

Regarding acceptability, the worst scenario was that one using urban wastewater (Scenario UWW), both in the case of the natural pigments and the digestate. Urban wastewater contains used water from houses and apartments, while wastewater from the food industry is used water from manufacturing or chemical processes which is under high levels of control given food regulations. Accordingly, the perceptions that citizens have with regard to the health impacts that these wastewater types have is more likely to be more negative in the case of urban wastewater. Again, the best scenario in this sub-category was the scenario using standard growth medium (Scenario SGM) (impact by up to 30% lower than other scenarios). Indeed, in this scenario, the production of the bioproducts is free from pathogens, heavy metals or other contaminants which can decrease the level of citizens' acceptability.

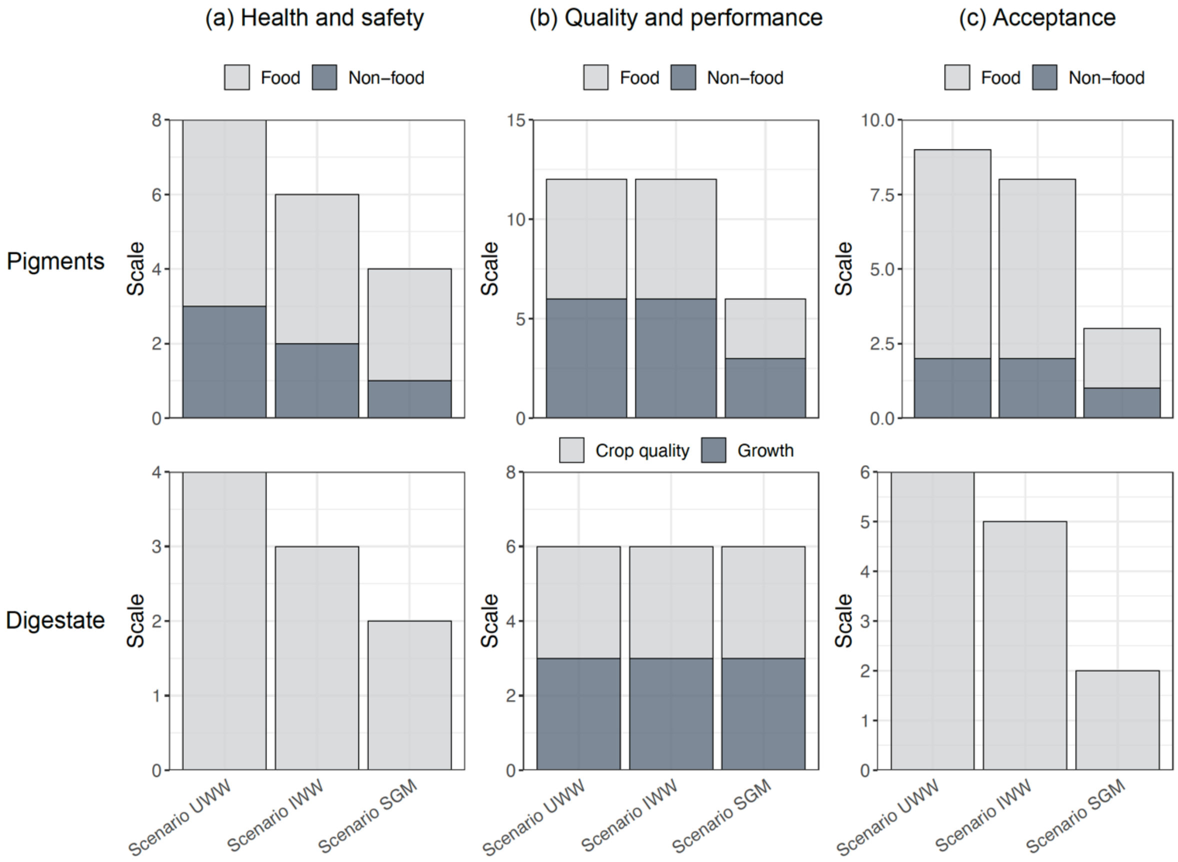

Figure 5. Results for consumers in the impact categories health and safety (a), quality and performance (b), and acceptability (c) for the Scenarios considered: 1) microalgae-based system for urban wastewater treatment and resources recovery (i.e. natural pigments, biogas and the digestate which can be reused as biofertilizer) (Scenario UWW); 2) microalgae-based system for industrial wastewater treatment and resources recovery (i.e. natural pigments, biogas and the digestate which can be reused as biofertilizer) (Scenario IWW); 3) system for bioproducts (e.g. natural pigments, biogas and digestate which can be reused as biofertilizer) production from microalgae grown in a standard growth medium (Scenario SGM).

3.1.3 Local community

Concerning the local community, results are shown in **Figure 6**. On the one hand, results showed that the scenario treating urban wastewater (Scenario UWW) was the most harmful one when examining liveability. Among the different outputs of the three systems, this scenario was found to release the highest amount of ammonia, whose olfactory impact has a highly negative perception among individuals. According to Gebicki et al. (2016), ammonia has a sharp pungent smell and low concentrations of this substance cause high impacts as the odour detection threshold is at 1E-6 g/m^3 (Gebicki et al., 2016).

From a comparative perspective, the impact produced by the scenario using wastewater (Scenario UWW) was 24-fold higher than the scenario using standard growth medium (Scenario SGM), while only 2.6-fold higher than the impact produced by the scenario using industrial wastewater (Scenario IWW) (Figure 6a). This was mainly due to the fact that in the scenario using standard growth medium (Scenario SGM) ammonia emissions to air were way lower than in other scenarios, since almost all the nitrogen is assimilated by microalgae. Moreover, urban wastewater contains higher concentrations of nitrogen than food-industrial wastewater, which leads to more frequent processes of ammonia volatilisation (Arashiro et al., 2022).

Odour is a social problem for local communities, not only due to the nuisances that it causes but also because of health issues that arise from high concentrations of odorous compounds (Conti et al., 2020). In line with the results of this study, wastewater is one of the major contributors to ammonia, odour and particulate matter emissions (Ni et al., 2012; Conti et al., 2020).

On the other hand, the scenario using urban wastewater (Scenario UWW) was the scenario with the highest employment generation opportunities (impact up to 1.7-fold lower than other scenarios). Therefore, the socio-economic repercussions were most positive in this case (Figure 6b). At the other extreme, the scenario using standard growth medium (Scenario SGM) had the lowest number of jobs created, which led this scenario to be the most negative one in this impact category. As described by Padilla-Rivera et al. (2016), the generation of employment is key for economic development.

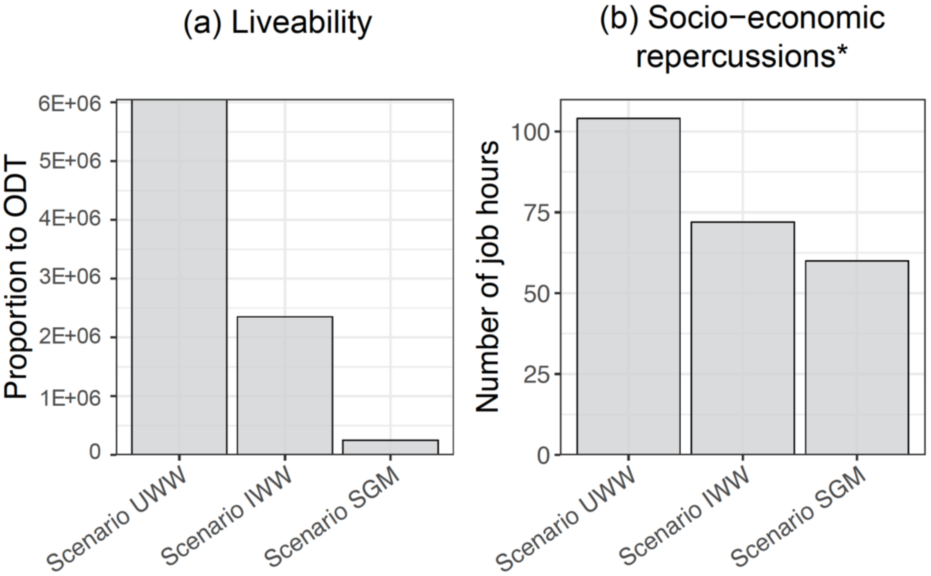

Figure 6. Results for the local community in the impact categories liveability (a) and socio-economic repercussions (b) for the Scenarios considered: 1) microalgae-based system for urban wastewater treatment and resources recovery (i.e. natural pigments, biogas and the digestate which can be reused as biofertilizer) (Scenario UWW); 2) microalgae-based system for industrial wastewater treatment and resources recovery (i.e. natural pigments, biogas and the digestate which can be reused as biofertilizer) (Scenario IWW); 3) system for bioproducts (e.g. natural pigments, biogas and digestate which can be reused as biofertilizer) production from microalgae grown in a standard growth medium (Scenario SGM). * The higher the value the better; ODT: odour detection threshold

3.1.4 Value chain actors

As for the stakeholders' group of value chain actors, results are shown in **Figure 7** for the impact category of promotion of social responsibility in the stages of (a) wastewater collection, (b) wastewater treatment and natural pigments and digestate production, and (c) transportation of wastewater and transportation and marketing of natural pigments and digestate (Table 1).

The scenario treating industrial wastewater (Scenario IWW) had the highest impact in the three sub-categories (up to 3-fold higher than the other scenarios), while the scenario using standard growth medium (Scenario SGM) had the lowest impact in all three sub-categories. The lack of full-scale deployment of the microalgae-based systems for wastewater treatment and resource recovery (Scenarios UWW and IWW) could be the reason why there is still a low number of regulations for these systems, while several standards and legislative frameworks already exist for conventional systems (Scenario SGM) (UNE-EN ISO 11133:2014). Additionally, between the scenario treating urban and industrial wastewater (Scenarios UWW and IWW, respectively), there are slightly more standards and new regulations for the former (Directive 91/271/EEC).

Finally, while from a social perspective scenarios using wastewater (Scenarios UWW and IWW) have the most negative impacts, other authors have emphasised that wastewater treatment schemes may have positive economic impacts not only for the local community as described in the previous section but also for value chain actors (Maaß and Grundmann, 2016).

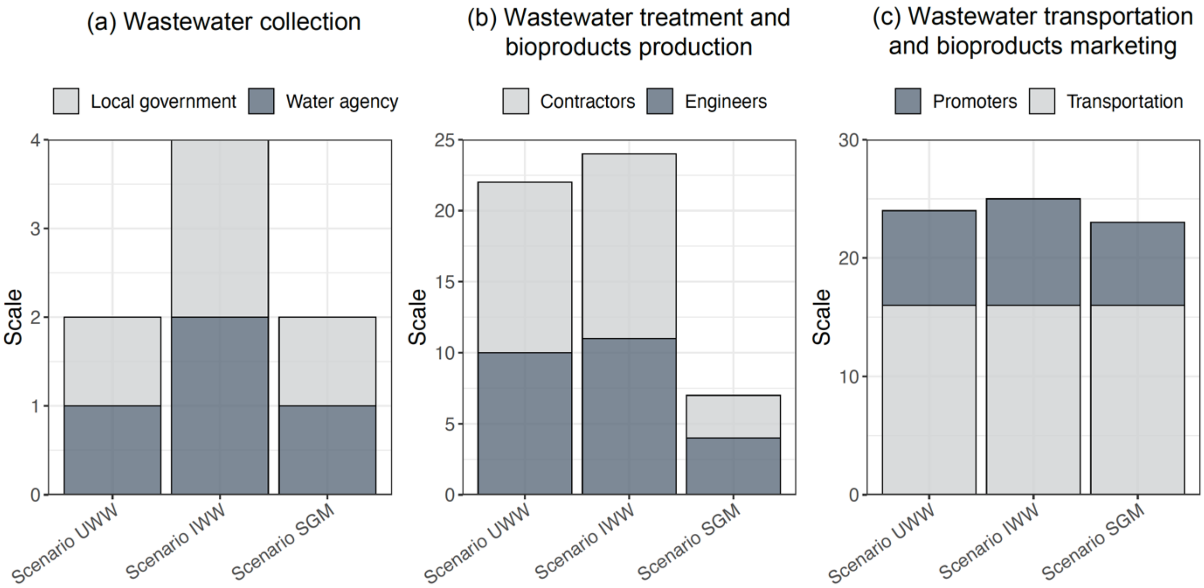

Figure 7. Results for value chain actors in the impact category of promotion of social responsibility and for different value chain actors for the Scenarios considered: 1) microalgae-based system for urban wastewater treatment and resources recovery (i.e. natural pigments, biogas and the digestate which can be reused as biofertilizer) (Scenario UWW); 2) microalgae-based system for industrial wastewater treatment and resources recovery (i.e. natural pigments, biogas and the digestate which can be reused as biofertilizer) (Scenario IWW); 3) system for bioproducts (e.g. natural pigments, biogas and digestate which can be reused as biofertilizer) production from microalgae grown in a standard growth medium (Scenario SGM).

3.1.5 Society

Regarding society, results for impact categories of public commitment to sustainability issues and technological development are shown in **Figure 8**. As mentioned above, different steps of the processes were taken into account: the wastewater treatment process, the production and use of natural pigments (for food and non-food products), and the production and use of digestate.

As it can be observed, the scenario using standard growth medium (Scenario SGM) yielded a low result for both impact categories (impact up to 2.5-fold lower than other scenarios). This was because more regulatory frameworks regulate the processes for these conventional systems (UNE-EN ISO 11133:2014) and their technological development is in the latest phases of the TRLs. In both impact categories, the highest impact was obtained for the scenario treating industrial wastewater (Scenario IWW), since less regulation on sustainability issues and full-scale experiences have been developed compared to urban wastewater (Scenario UWW) (see, for instance, Incover, 2019; Algae Parc, n.d.; All-gas, 2020; Algae for Future, 2022).

Specifically, regarding the public commitment to sustainability issues category, there are slightly more policies and strategic plans dealing with the reuse of urban wastewater (PWC, 2018; EC, 2020; Directive 91/271/EEC). On the contrary, for industrial wastewater, there are not yet as many regulatory frameworks or documents on sustainability issues (MITECO, 2020). Moreover, there exists at present a national control program highly placed within the government structure in Spain called the National Plan for Purification, Sanitation, Efficiency, Savings and Reuse (known as Plan DSEAR from its Spanish name) (Ministerio para la Transición Ecológica y el Reto Demográfico, 2021). This plan deals, among other aspects, with the treatment and reuse of urban and industrial wastewater. While it encourages microalgae-based wastewater treatment systems, they are still in the development stages.

Regarding the use of natural pigments recovered in the scenarios treating urban and industrial wastewater (Scenarios UWW and IWW, respectively) for food products, Spanish legislation currently forbids this kind of use (Real Decreto 1620/2007). Concerning the production of non-food goods with these pigments, the law does not specifically consider this case, even though it does warn about those cases in which products for humans are to be in contact with regenerated water. Finally, the use of recovered resources (i.e.biofertilizer) from wastewater for agricultural uses is admitted (Regulation EU 2019/1009), and at present, the restrictions are the same for industrial and urban wastewater.

Regarding technological development, as mentioned above, while conventional systems using standard growth media are well established, the microalgae-based systems for wastewater treatment and resource recovery are still in the development stage, especially the downstream activities for bioproducts recovery. Moreover, bioproducts obtained from wastewater treatment processes are already being used for agricultural purposes (e.g. as biofertilizer), even though full-scale or pilot-scale experiences mainly used urban instead of industrial wastewater (see, for instance, Incover, 2019; Algae Parc, n.d.; All-gas, 2020; Algae for Future, 2022).

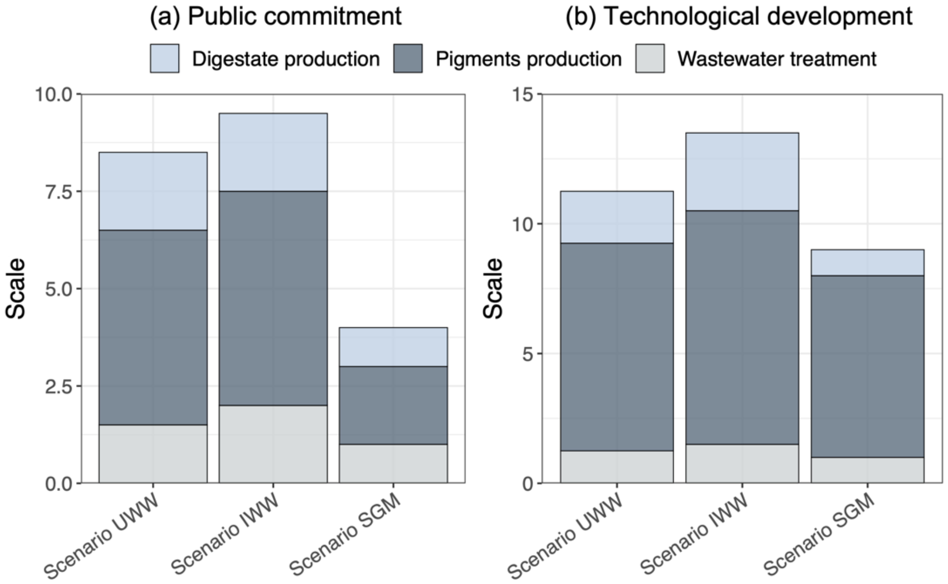

Figure 8. Results for society in the impact categories public commitment (a) and technological development (b) for the Scenarios considered: 1) microalgae-based system for urban wastewater treatment and resources recovery (i.e. natural pigments, biogas and the digestate which can be reused as biofertilizer) (Scenario UWW); 2) microalgae-based system for industrial wastewater treatment and resources recovery (i.e. natural pigments, biogas and the digestate which can be reused as biofertilizer) (Scenario IWW); 3) system for bioproducts (e.g. natural pigments, biogas and digestate which can be reused as biofertilizer) production from microalgae grown in a standard growth medium (Scenario SGM).

3.1.6 Normalisation

Figure 9 shows the normalised data of the S-LCA for all the results discussed in the previous subsections. It can be seen that the lowest impacts were given for the scenario using standard growth medium (Scenario SGM), where only stakeholder groups Workers, Consumers and Local community influenced the normalised results. Thus, this scenario was the one showing the best results in all impacts and stakeholder categories. This was mainly due to: i) the simplicity of the system, which consequently improves health and safety for workers; ii) the absence of contaminants (e.g. pathogens, gases emissions) which consequently improve health and safety, acceptability and olfactory impact for both consumers and local community; iii) the presence of well-established legislation, regulatory frameworks and full-scale deployment, which benefit value chain actors and society.

Comparing the scenarios treating wastewater (Scenarios UWW and IWW) the scenario treating food-industry wastewater (Scenario IWW) had slightly higher social impacts (1.05-fold higher) than the scenario treating urban wastewater (Scenario UWW). In particular, the former (Scenario IWW) had the most negative impacts on Value Chain Actors and Society. This was mainly due to the fact that the absence of legislation, regulatory frameworks and technological development is currently worse in the case of microalgae-based products recovery from industrial than urban wastewater.

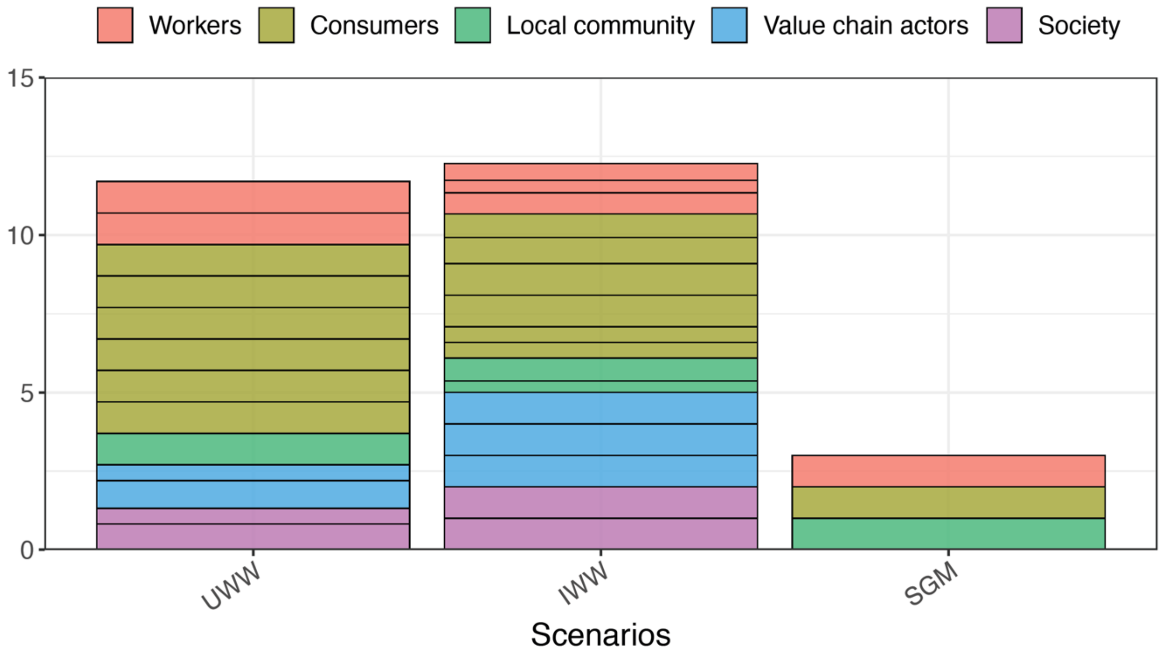

Figure 9. Normalised results grouped by scenario for the Scenarios considered: 1) microalgae-based system for urban wastewater treatment and resources recovery (i.e. natural pigments, biogas and the digestate which can be reused as biofertilizer) (Scenario UWW); 2) microalgae-based system for industrial wastewater treatment and resources recovery (i.e. natural pigments, biogas and the digestate which can be reused as biofertilizer) (Scenario IWW); 3) system for bioproducts (e.g. natural pigments, biogas and digestate which can be reused as biofertilizer) production from microalgae grown in a standard growth medium (Scenario SGM).

3.2 Key challenges and opportunities

The environmental benefits associated with recovering products from wastewater treatment processes have been widely recognised until the present (Arashiro et al., 2018, 2022). They are particularly important for a transition towards a circular economy. Nonetheless, the systems and processes presented in this paper have been shown to still face numerous challenges. Some of the most important ones are the commercial and social acceptance of products and services, the lack of standards at a Spanish and European level for compliance and quality criteria considering health conditions, the costs of facilities and infrastructures and their impact on the economic viability and management of the risks, as well as issues derived from spatial planning and management. All these factors are conditioning the full-scale deployment of these systems, and the most significant ones are described in more detail below.

In the first place, except for citizens working in areas strongly linked to water governance, there exists a general lack of knowledge regarding the potential for water reuse in society and the benefits that such reuse could have for the status of water bodies and water security (Al-Saidi, 2021; Faria and Naval, 2022). This is one reason why generating trust and improving the social perception and acceptance of this kind of recovered resources are essential. To begin with, resources could be recovered from industries where acceptance is already widespread, such as industries producing plant-based food.

The aspect of perception leads to the second challenge: the lack of a robust regulatory framework. At present, there exist some gaps in terms of standards and legislation dealing with the different stages of the recovery processes (Santos et al., 2022; Rebelo et al., 2020). Such a framework would be a supporting element for generating trust among users as it would provide legal certainty to consumers of those resources recovered from wastewater treatment processes. At the European level, there already exist some standards, and these could be used to guide and reinforce the national frameworks. Such regulations would be useful to control quality indicators and their parametric limits as well as to better understand those output substances associated with wastewater that may have an impact on human health and/or the environment. Additionally, the availability of these documents could allow transferring to society the benefits that are associated with this activity as well as strengthening confidence towards these products.

In terms of technology, the systems presented herein have not yet been deployed on full-scale (Arashiro et al. 2022). Therefore, even though small-scale and pilot-scale systems have been analysed, further challenges may arise when increasing the scale of the processes. A better understanding of the real challenges of full-scale systems is essential when it comes to bringing these processes into practice.

Linked to the above issue is the fact that, currently, there is a lack of knowledge of the real capacity as well as the interest of the economic sectors to acquire and/or use the recovered resources based on the process costs and other impacts (i.e. Samarasinghe and Wijayatunga, 2022). In fact, there are several different configurations through which the recovered bioproducts could be introduced into the market. **Figure 10** suggests a model to implement the circular bioeconomy for resource recovery and use from microalgae-based systems treating wastewater. One configuration potentially advantageous in terms of seeking an equilibrium across the three sustainability pillars would be that wastewater treatment plants produced algal biomass instead of the final products (i.e. pigments, digestate), which would be sold to companies specialised in producing them. This would allow avoiding the overcomplication of wastewater treatment plants, which traditionally have been simple infrastructures. Besides, there would be economic benefits, as no specialised staff would be necessary in the plant and the biomass could be sold to the market.

As emphasised above, there should be a regulatory framework covering several stages of the process, including algal culturing in the treatment plants, the sale of the biomass, the extraction of high-value products from this biomass, the retail sale and wholesale, the consumption and the final disposition of the products.

In addition to the above, the biomass should be sold to companies near the treatment plants to avoid transportation for long distances (and, therefore, environmental impacts). This would pose certain spatial and territorial restrictions on the system deployment, but some configurations would facilitate it, such as industrial symbiosis.

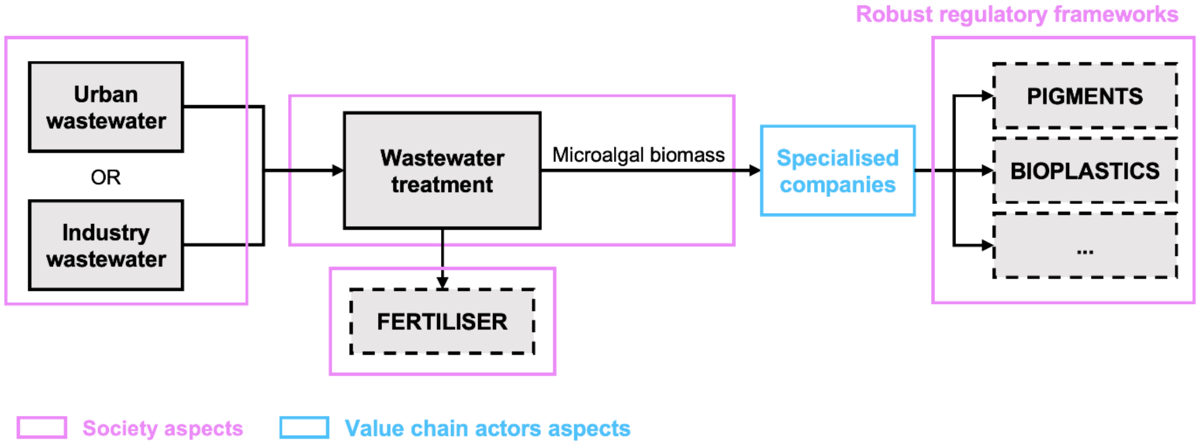

Figure 10. General framework for the configuration of a model to implement the circular bioeconomy with microalgal biomass obtained in wastewater treatment processes

3.3 Future directions

In the short term, there are three fundamental action areas that practitioners, government bodies and researchers ought to carry out in order to catalyse the progress toward a circular bioeconomy. In the first place, dissemination regarding the benefits of reusing wastewater should be implemented for citizens to develop more positive perceptions towards these systems. Secondly, eco-labels of products could include information on whether recovered products from wastewater have been used in order to encourage companies to recycle water, and citizens to purchase these eco-labelled products. Thirdly, future research should aim at integrating LCA approaches with other tools for assessing sustainability. For instance, exergy analysis can help obtain a more holistic picture of bioproducts recovery from microalgae-based systems (Aghbashlo 2019, 2021).

3.4 Limitations of the study

Having discussed the practical implications of this study, its limitations should be described. The work presented here has two main limitations. First, in comparison to E-LCA, S-LCA has more uncertainties due to the complexity inherent in measuring social impacts. In this study, this has been tackled by defining robust measurement scales and by conducting an uncertainty analysis that is included as Supplementary material. The uncertainty analysis showed that when variations in the data are introduced, the scenarios using wastewater (Scenario UWW and IWW) were still the ones with the highest impacts, followed by the scenario using standard growth medium (Scenario SGM). Therefore, if there were uncertainties in the data, while the absolute resolutions might be different for the three scenarios, the ranking among them would remain the same.

Another uncertainty linked to the study arises from the fact that it is based on hypothetical plants and, therefore, the data used are estimations instead of real metrics. Additionally, data was assigned using experts' opinions. One way of making the analysis more robust would be to deploy a survey to be answered by a larger sample.

Second, when measuring social impacts, the context is particularly important due to social processes being valued and perceived differently in different regions of the world. As such, while the work presented here can be useful for researchers and practitioners worldwide, they are representative of the European context. In other regions, the legislative frameworks for the systems analysed, as well as the perceptions held towards this kind of technology can differ.

4. Conclusions

This article developed and presented an ex-ante evaluation of the social impacts deriving from microalgae-based systems for wastewater treatment and bioproducts recovery (e.g. natural pigments, biogas and digestate which can be reused as biofertilizer) to boost the circular bioeconomy. The social life cycle methodology has been used. In particular, two scenarios were considered: one system treating urban wastewater and another system treating wastewater from the food industry. Moreover, for the sake of comparison, these alternatives were compared to a system for bioproducts (e.g. natural pigments, biogas and digestate which can be reused as biofertilizer) production from microalgae grown in a standard growth medium. The findings from this study allowed identifying the major challenges and opportunities for deploying these systems at industrial scales.

Results showed that the scenario using standard growth medium was the one showing the best results in all impacts and stakeholder categories considered. This was mainly due to: i) the simplicity of the system, which consequently improves health and safety for workers; ii) the absence of contaminants which consequently improves health and safety, acceptability and olfactory impact for both consumers and the local community; iii) the presence of well-established legislation, regulatory frameworks and full-scale deployment, which benefit value chain actors and society.

Comparing the scenarios treating wastewater, the scenario treating food-industry wastewater had a slightly higher social impact than the scenario treating urban wastewater. In particular, the former had the most negative impacts in the Value Chain Actors and Society impact categories. This was mainly due to the fact that the absence of legislation, regulatory frameworks and technological development is worse in the case of industrial than urban wastewater.

Three key aspects were identified when evaluating the most relevant challenges: i) social acceptance of consumers towards the use of products recovered from wastewater treatment processes; ii) the lack of robust regulatory frameworks, and ii) low technological development and lack of full-scale demonstration sites.

Finally, microalgae-based systems for wastewater treatment and resource recovery are promising alternatives to boost the circular bioeconomy in the water sector. More efforts should be made in order to overcome the negative social perception and generate trust and acceptance, to develop robust regulatory frameworks over the whole life cycle of the process (wastewater treatment, production, use and disposal of the bioproducts) and to implement and optimise full-scale systems to cover the technological development gap.

Abbreviations

Table 9 List of abbreviations used

Abbreviation	Definition
CHP	Combined heat and power
E-LCA	Environmental Life Cycle Assessment
HRAP	High Rate Algal Pond
IWW	Industrial wastewater
LCA	Life Cycle Assessment
ODT	Odour detection threshold
PBR	Photobioreactor
SGM	Standard growth medium
S-LCA	Social Life Cycle Assessment
TRL	Technology Readiness Level
UASB	Up-flow anaerobic sludge blanket
UWW	Urban wastewater

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