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Sustainability assessment of microalgae production for alternative feedstuff: An explorative study to advance insights

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A R T I C L E I N F O

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A B S T R A C T

Innovations in agricultural technology promise to tackle today's sustainability challenges. However, the development of such innovations typically lacks comprehensive evaluation of their sustainability. Thus, the technologies are potentially not aligned with current sustainability goals. Microalgae are an example of such an innovation, particularly their use as feedstuff. Drawing on data of two laboratory-scale photobioreactors (glass and polymethylmetacrylate), we evaluated the sustainability of microalgae production as alternative feedstuff in Switzerland. Methodological improvements were identified, and participation of stakeholders helped to enhance the comprehensiveness and evaluate the usefulness of such assessments. The ratio of the environmental impacts between both photobioreactors were between 4% and 35% except for water scarcity where the difference reached 65%. The social and economic indicators were comparable between both reactors. In both cases, the electricity input contributed most to the environmental impacts. Community engagement was an important social indicator. Neither of the photobioreactors were economically sustainable, which can be due to the laboratory scale, suggesting that future economic assessments need to be more refined and upscaled. A final stakeholder workshop confirmed the need for such assessments and highlighted limitations to be addressed in future studies: (1) the development of better methods for prospective sustainability assessments, (2) comprehensive stakeholder inclusion and corresponding resources planning, and (3) the careful evaluation of the sustainability of reference systems.

1. Introduction

Ensuring healthy, affordable and sufficient food for a rising World population that is sustainable in the economic, social and environmental dimensions, is a major challenge of the agricultural sector. Innovations in agricultural technology are increasingly called for to tackle the sustainability issues of the agri-food sector. Algae can be regarded as one of these technological innovations. The potential of microalgae for human nutrition (Jouannais and Pizzol, 2022; Maghimaa et al., 2025; Schade et al., 2020), as fertilizer (Fertahi et al., 2024) or animal feed (Ijaola et al., 2024) is increasingly being studied, but the sustainability of these uses is often only assumed. Inappropriate quantification of their sustainability or ignoring one of the sustainability dimensions can however lead to the development of unsuccessful or ineffective technology that lacks alignment with sustainability goals. An innovative use of microalgae in the agricultural sector therefore needs to both improve and balance economic, social and environmental outcomes to ensure its sustainability.

Besides accounting for all three sustainability dimensions, sustainability assessment methods should also follow a life-cycle perspective to avoid any burden shifting between life cycle assessment stages. Guinee et al. (2011) defined Life Cycle Sustainability Assessment (LCSA) as "a transdisciplinary integration framework of models, rather than a model itself". They further argued that the main challenge in LCSA is to structure, select and make the plethora of models practically available in relation to different life cycle sustainability questions. This challenge is illustrated in the recent review of Costa et al. (2019), where several studies used other methods for the sustainability evaluation of products, while a majority of LCSA studies combined LCA, S-LCA and LCC. Similarly, Visentin et al. (2020) found a large consensus in the use of LCA to

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evaluate the environmental sustainability of products but not for the social and economic dimensions. In an attempt to streamline the application of LCSA, Valdivia et al. (2021) proposed principles guiding its increased application. Among which completeness is a key principle. It means applying LCA, S-LCA and LCC to all product life cycle stages within the chosen boundaries. Another important principle is the transparency in the methodological choices and data sources. They also stress the need for an explicit communication of trade-offs within LCSA studies, but do not explicitly recommend the use of any multi-criteria decision analysis (MCDA) method. While Costa et al. (2019) found numerous LCSA studies relying on MCDA, they reported an equal number that are not using this method to aggregate LCSA results. The latter aligns with the initial recommendation of Kloepffer (2008) to perform separate assessments of each sustainability dimension.

Considering emerging technologies, the integrated life cycle sustainability assessment proposed by Keller et al. (2015), for example, combines life cycle assessment (LCA), life cycle costing (LCC) and a simplified social LCA method (S-LCA) with additional methods for the ex-ante evaluation of technologies. Further, Van Schoubroeck et al. (2021) focus their techno-sustainability assessment framework on guidance for indicators selection and multi-criteria analysis. Similarly, the sustainability assessment framework for energy technologies of Buchmayr et al. (2021) was focused on identifying suitable indicators rather than on following specific methods for each sustainability dimension. These frameworks have never been applied to microalgae as alternative feedstuffs and all lack a structured approach for stakeholder inclusion to ensure a good understanding of the assessed technology as well as to track, respond to, or actively support its social desirability (Schade and Schlag, 2003; Wüstenhagen et al., 2007). Among the limited number of studies quantifying several sustainability dimensions of microalgae use, Perez-Lopez 2018 combined environmental LCA with a S-LCA and a Cost-Benefit Analysis. The latter two focused on the enterprises central to the analyzed microalgae production system. Portner et al. 2021 combined an environmental LCA with a S-LCA where data representing the microalgae production system was combined with data from databases to represent the upstream and downstream processes (Pérez-López et al., 2018; Portner et al., 2021). The sustainability of algae as alternative feed has not been explored in all dimensions, despite rising interest in their potential (Bature et al., 2022; Zhu et al., 2024). Most studies focus on the environmental dimension of sustainability for algae use as food or feed (Schade and Meier, 2019; Smetana et al., 2017). All studies refrain from using the term Life Cycle Sustainability Assessment. This reflects findings that strictly applying LCSA to emerging technologies is difficult because of the lack of data to represent the analyzed system as well as the upstream and downstream processes, challenges to account for potential scale-up effects and the uncertainty related to the technology's design in itself (Padilla-Rivera et al., 2023).

The aims of this paper are therefore twofold: (1) to evaluate, using case-study data of laboratory-scale photobioreactors (PBRs), what can currently be concluded about the sustainability of microalgae production for feedstuff and (2) to identify methodological improvements that could enhance the effectiveness of such assessments. We adapted existing sustainability assessment frameworks to the case of microalgae production as alternative feedstuff in Switzerland, with an emphasis on stakeholder inclusion and the consideration of their feedback.

2. Methods

2.1. Sustainability assessment framework

The sustainability assessment framework used draws on Guinee et al. (2011) who suggested a transdisciplinary integration of different methods. Further, as recommended for sustainability assessment studies (Valdivia et al., 2021), the framework followed the four stages of the Life Cycle Assessment (LCA) as a general structure, namely (1) the goal and scope definition, (2) the inventory definition, (3) the impact assessment, and (4) the interpretation (Valdivia et al., 2021). LCA is a widely used, ISO-normed method for the evaluation of the environmental sustainability of systems or products (International Standard Organisation (ISO), 2006a, 2006b). It focuses on the environmental sustainability evaluation of a system or product. In this context, we revised each stage of an LCA to consider (1) all three sustainability dimensions, (2) a reference system the microalgae are supposed to replace, and (3) the inclusion of stakeholders (Fig. 1). While LCA was chosen for the environmental sustainability evaluation, the method to use for each sustainability dimension was left open for the social and economic dimension. This is in line with the open definition of sustainability assessment by Guinee et al. (2011) but it does not match the requirements of LCSA (Valdivia et al., 2021). It was justified here, because of the low degree of development of the analyzed technology. The choice of the method for economic and social evaluation depends on the goal and scope of the conducted study. Single indicators focused on specific stakeholder categories can for example be useful to identify sustainability improvement measures for manufacturers in particular. Comprehensive methodologies, like social LCA, are, on the other hand, more suited to provide a holistic picture of the sustainability of the life cycle of a technology. In addition to the goal and scope, other criteria such as the required comprehensiveness, the desired level of participation and the possible time constraints also influence the choice of the method. Stakeholder involvement requires first to identify relevant stakeholders. Their identification can be a two-step process as proposed by Leventon et al. (2016). In the goal and scope definition, one can choose to work with a "core team" of stakeholders that will be extended based on the decisions made. A core team of stakeholders is normally known but may not be comprehensive and the actual representation and expertise of stakeholders be unbalanced. Because members of the core team of stakeholders normally know other relevant stakeholders, snowballing methods can be used to identify and recruit further stakeholders. This can be facilitated with questionnaire surveys (Leventon et al., 2016). Network analysis can also facilitate the identification of stakeholders and help specifying relations between them (LINK consult, 2024). Mapping of identified stakeholders according to criteria of relevance to the assessment is useful to support representativeness and to match stakeholders with specific tasks or steps of the sustainability assessment (Raum, 2018; Reed and Curzon, 2015; Skarlatidou et al., 2019). Different criteria can be used in the evaluation of stakeholder involvement, like selectivity (Callegari and Mikhailova, 2021), early engagement (Ketzer et al., 2019) or consideration of stakeholders' feedback (Hoedl, 2022). A more comprehensive list of stakeholder identification and involvement methods is provided in the Supplementary Information (SI), S1. Our aim was not to provide fixed guidelines on how stakeholders should be involved in sustainability evaluations, but rather outline ways of involving them as depicted in the SI, S1.

In the following we detail each of the four stages of the sustainability assessment framework.

2.2. Goal and scope definition

The aim of this first stage is the definition of the goal and scope of the assessment. In addition, different methodological assumptions related to the functional unit, meaning the unit of the assessment or the choice of the sustainability evaluation methods and the impact categories are made.

The scope of this case study is the production of microalgae in Switzerland as input to livestock feed satisfying their nutritional requirements. Two aspects are relevant: first ensuring a sustainable production system and second guaranteeing the microalgae's suitability for a livestock feed ration. Given the early stage of this application, we focused on the first aspect using data from a laboratory-scale installation. This case study thus identifies which aspects of two laboratory-scale photobioreactors (PBRs) influence their sustainability most in anticipation of a potential technology scale-up and to obtain a first

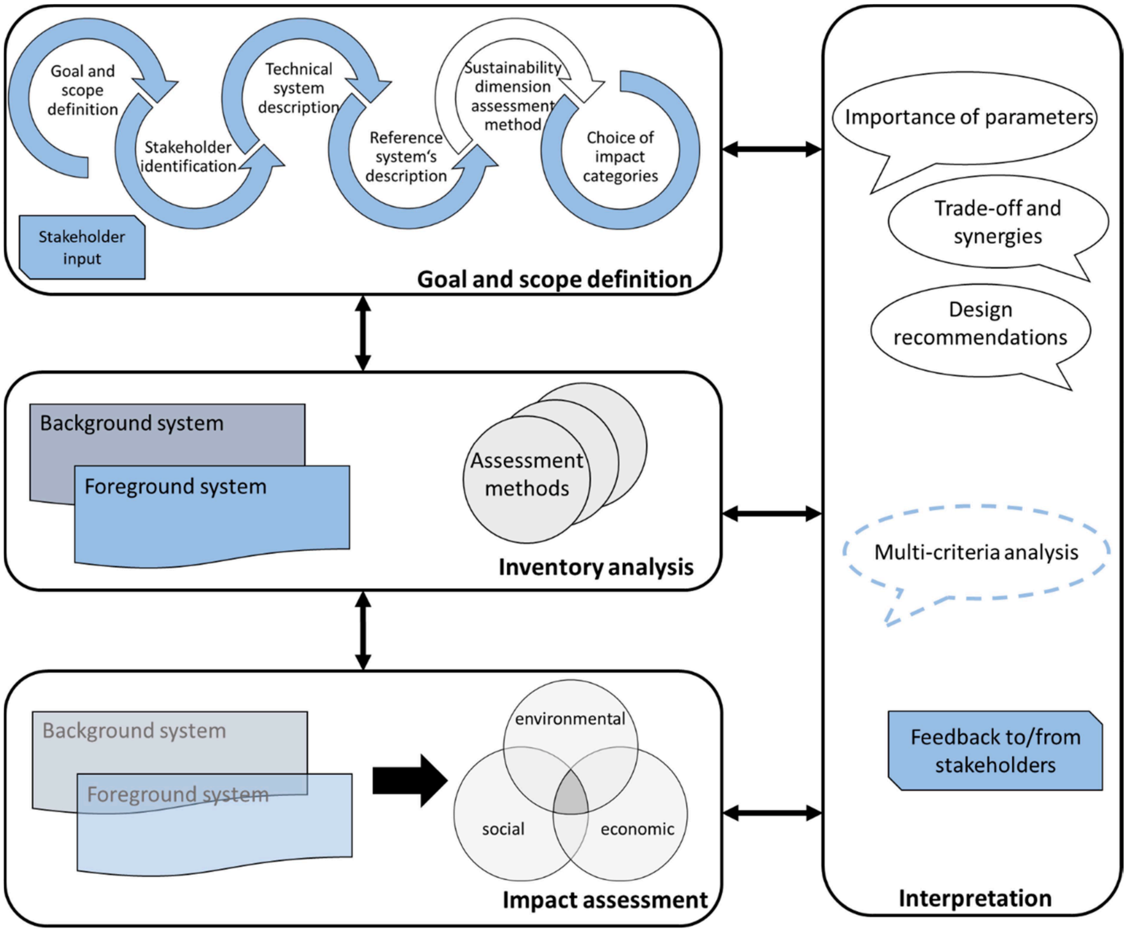

Fig. 1. Sustainability assessment framework. The elements in blue greatly benefit from stakeholder involvement.

estimate of the sustainability of such a system compared to a currently established protein source. Studies published on the sustainability assessment of algae production report functional units based on kg dry mass (Schade and Meier, 2020), kg of certain ingredients (Pérez-López et al., 2014) or the corresponding energy content of algae whenever algae are planned to be used as alternative fuel (Morales et al., 2019). In our case study, microalgae are produced as alternative protein source for livestock feed rations in Switzerland and 1 kg of protein was taken as a functional unit. The definition of the goal and scope resulted from an iterative process organized around online meetings between two research groups (a sustainability assessment research group and a microalgae biotechnology group) at Agroscope to set an achievable goal that can still provide useful insights for the emerging technology of algae production. These two research groups can be seen as the core team of stakeholders. The defined goal and functional unit influenced the choice of the reference system. Soy was chosen as reference because it is currently the most common protein source in animal feed. It was decided to use available literature and database entries to describe the social, economic and environmental sustainability of the reference system.

2.2.1. Stakeholder identification

We explored the network of stakeholders surrounding the algae case in Switzerland with eight persons among which three were familiar with the innovation under investigation and the rest was not, thus extending the core team defined for the goal and scope definition. The result of this analysis is presented in the SI, S2.

2.2.2. Technical system description

The system boundaries include the construction of the laboratory PBR for producing the microalgae, its operation and maintenance, the treatment of the biomass and the end of life of the PBR. Biomass treatment for harvesting required only microfiltration since the algae feed is meant to be consumed in liquid form (Costa et al., 2022). A detailed flowchart of all included processes is provided in the SI, S3. We assumed that all algae produced were used as feedstock only, so that no allocation of the sustainability impact over different co-products was necessary. To inform decisions for future scaling-up based on existing infrastructure, this work focused on two operating laboratory-scale PBRs, one made from glass and the other from polymethylmethacrylate (PMMA) which are available at the Biotechnology group of Agroscope (Bern, Switzerland) and on the production of two algae species: *Parachlorella kessleri* and *Scenedesmus obliquus*.

The following scenarios were tested, to provide more decision support and evaluate the influence of some methodological choices on the results based on observations from the literature:

- S_elec: Operating the PBR with the Swiss electricity grid mix or with solar, wind, hydro or gas power since previous studies have shown the influence of electricity on the environmental impacts of microalgae production
- S_land: To evaluate the influence of the land use type on the environmental impact results, placing the PBR on an artificial area was compared to placing it on grassland
- S_alu: Increasing the share of recycled aluminum in the PBR composition from 20 % to 100 % given the environmental impact of aluminum

Table 1
Definition of the social indicators used in the case study on microalgae as alternative feedstuff.

Stakeholder group	Impact subcategory	Indicator	Level B (=basic requirement)	Level A	Level C	Level D
Workers	Working hours	Working hours per week	average over employees < 48h/week		average number of hours worked per week is >20 % lower than the average number of hours worked per week in the sector/country	average number of hours worked per week > 8 h/d and >48 h/week (International Labour Organization, 1919, 1930)
	Fair salary	Lowest salary is fair	Lowest salary ≥ minimum wage in sector/country	lowest salary > minimum wage in the sector/ country	-	lowest salary < minimum wage in the sector/ country
	Education	Contribution to professional development	At least one person shifts to a higher competence level/ education level over the time	50 % of the employees shift to a higher competence level/ education level over the time	-	no change
	Equal opportunities	Ratio male/female employees	Ratio = 1	-	Ratio ≥ 1.2 or Ratio ≤ 0.8	Ratio ≥ 2 or Ratio ≤ 0.5
		Ratio of basic salary of men to women by employee category	Ratio = 1	-	Ratio ≥ 1.2 or Ratio ≤ 0.8	Ratio ≥ 2 or Ratio ≤ 0.5
Local community	Local employment	Percentage of workforce hired locally	50 % hired in the country where company is	>50 % of total employees of the organization hired locally	-	<50 % of total employees hired locally (because employment rate in Switzerland is around 80 %, so above the 50 % ratio set by Ramirez et al. (2014) this level is level D)
		Evidence that local hiring preferences	Company has put in place local hiring preferences	-	-	Company has no local hiring preferences put in place
	Community engagement	Number and quality of meetings with community stakeholders	One meeting with community stakeholders	Evidence of reaction/response to the inputs of the community stakeholder meeting	-	No meeting with community stakeholders
		Diversity of community stakeholder groups that engage with the organization	Two community stakeholders	more than two community stakeholders	-	only one community stakeholder

- S_CO2: Modelling of the CO_2 input as liquid CO_2 or as avoided burden, meaning without considering any electricity input to improve the comparability with existing studies (Pérez-López et al., 2018; Schade and Meier, 2020)

The default scenario for each PBR assumes the Swiss electricity grid mix, placing the PBR on non-agricultural land modelled as artificial area, 20 % recycled aluminum in the PBR's composition and modelling CO_2 as liquid CO_2.

2.2.3. Sustainability assessment indicators and methods

The LCA impact assessment method SALCA (Swiss Agricultural Life Cycle Assessment) was used to evaluate the environmental sustainability of both PBRs and the different scenarios (Douziech et al., 2024). All impact categories available in SALCA were kept ensuring comprehensiveness. For the economic and social dimension, we reviewed literature to find appropriate methods that focus on a technology and its delivered product (SI, S4). Among available methods, we chose to evaluate the economic sustainability by calculating the net benefit (NB) per PBR as the sum of the benefits from protein production and selling and the sum of capital and operating costs, reflecting established practices (Pérez-López et al., 2018; Portner et al., 2021). An adapted social LCA focused on the foreground processes and based on the reference scale approach (Rafiaani et al., 2020; Ramirez et al., 2014) was developed for the social sustainability assessment. This choice was driven by a comparison of different sustainability evaluation studies of microalgae, where such a simplified application of social LCA is typical (Keller et al., 2017; Pérez-López et al., 2018; Portner et al., 2021; Rafiaani et al., 2020; Van Schoubroeck et al., 2021). A detailed comparison of the reviewed literature is provided in the SI, S5. The stakeholders' core team chose to focus on workers and local communities as they are the stakeholder groups typically considered in social sustainability studies of microalgae production. The impact subcategories and indicators retained per stakeholder group align with literature and were agreed upon during an online meeting with the stakeholders' core team and additional stakeholders from Agroscope (Table 1). No database was used to represent the background system, since the focus was put here on the foreground system. This aligns with simplified S-LCA studies conducted thus far and also with the UNEP S-LCA guidelines who do not foresee the mandatory use of a S-LCA database (UNEP, 2020).

2.3. Inventory analysis

In the inventory analysis the inputs and outputs associated with the analyzed technology and those necessary to evaluate the chosen indicators are compiled. These inputs and outputs are collected per unit process of components within the system boundaries as defined in the goal and scope phase (SI, S3). The list of input and outputs to a system is called a life cycle inventory. It is important to differentiate the foreground from the background system, and by extension the level of detail for the data gathering. The foreground entails the analyzed technology and the background system is more up- or downstream of the analyzed system as well as the reference system. For the background system, generic data from databases is often used. For the environmental assessment, ecoinvent or Agribalyse are examples of such background databases (*AGRIBALYSE*, 2020; ecoinvent Centre, 2018).

In this study, the technical and most of the economic data of the foreground for the environmental assessment were gathered from the research group operating the PBRs through questionnaires and online meetings. The questionnaires are available in the SI. Literature was needed to fill data gaps. A detailed table of all inventory flows and assumptions used to model both PBRs is given in the SI together with the data sources, while a summarized list of the inventory flows is provided in Table 2. A Python model based on Brightway (Mutel, 2017) and lca_algebraic (Jolivet et al., 2021), two Python packages, was developed and used to evaluate the environmental sustainability, relying for the

Table 2
Summarized list of inventory flows for the polymethylmetacrylate (PMMA) reactor and the glass reactor. DW stands for dry weight.

	Unit	PMMA reactor	Glass reactor
Reactor volume	L	174	235
Reactor mass (including valves, electronics, filters)	kg	83	195
Areal productivity rate	$g/m^2/d$	14.38	15.01
Annual microalgae production	kg DW/year	15.19	14.06
Lifetime	y	12	20
Protein content	%	40	40
Annual CO_2 input	kg/year	45.56	42.19
Annual electricity input	kWh/year	5′986	9′387

background inventory flows on ecoinvent v3.9.1.

The social data for the manufacturing and operating phase (foreground) was gathered from the PBR manufacturing companies and the PBR operators with help of questionnaires.

The reference values necessary to define the social indicators were taken from different literature sources (Bundesamt für Statistik, 2018; International Labour Organization, 1919, 1930; Statista, 2024).

For the reference system, as set in the goal and scope, indicator results from literature were used for rough estimates of the social and economic sustainability (Pashaei Kamali et al., 2017; Zortea et al., 2018). For the environmental sustainability, we used existing ecoinvent inventories on soybean production for the different regions in Brazil and for Switzerland combined with the soybean feed production inventory for Switzerland. We assumed transport via train and lorry to get the Swiss soybean to the facility for feed production and then to the farm and added transport via ship to import the Brazilian soybean to Switzerland. The distances were taken from existing market inventories. All these inventories describe non-irrigated soybean cultivation. We chose Brazil and Switzerland since 92 % of the soybeans in Switzerland come from Europe and the rest from Brazil (Pelosi, 2021). We used a protein content of 470 g/kg soybean according to (Banaszkiewicz, 2011).

2.4. Impact assessment

In the impact assessment, the life cycle inventory results are converted into impacts according to the indicators chosen in the goal and scope phase. The impacts were calculated for the default setting of the analyzed technology, for the scenarios defined in the goal and scope stage and for the reference system as decided in the goal and scope definition stage.

2.5. Interpretation

In the interpretation stage, the results of the sustainability assessment are discussed in relation to the goal and scope of the study. Here the differences between the systems analyzed or scenarios were of particular interest. Further, trade-offs and synergies between the different indicators under all scenarios evaluated were explored and reflected upon. This reflection can be quantitative or qualitative depending on the indicators. However, it should be related to the aim of the innovation. If possible, recommendations on the technology's design should be made. Considering the scale at which the sustainability assessment was carried out, the sustainability assessment results computed were not integrated to provide a single score of the sustainability evaluation. This ensured that conclusions could be drawn for each sustainability dimension individually, thus best accounting for the limitations specific to each dimension. Such an approach also promises transparency and nuanced interpretation on part of stakeholders. Although limited, the few available studies on the sustainability of microalgae photobioreactor allowed to reflect on some of the assumptions made. In addition, a workshop was carried out with eleven participants including three industry representatives (Pork industry and algae industry), three members of agricultural and environmental associations and five researchers specialized either in sustainability evaluation, pork feed, or algae cultivation. Apart from informing the invited stakeholders about the sustainability assessment results, this workshop aimed at gathering feedback on the usability of the framework, on possibilities to increase the relevance of the case study application and at discussing avenues for future research. First, the chosen goal and scope were discussed in view of a future study to identify what the current work was missing. Second, ways of improving data quality were discussed. Third, questions related to the sustainability assessment framework and its usability were discussed before formulating a more general outlook.

3. Results

3.1. Environmental sustainability of the photobioreactors

Fig. 2 compares seven environmental impacts of the glass and PMMA-PBR for the default configuration with Swiss electricity mix, agricultural soil occupation, the use of liquid CO_2, and a share of recycled aluminum of 20 %. The focus was put on these seven environmental impacts, because they are most popular in literature. Results for the remaining impact categories are given in the SI.

The environmental impacts of the glass PBR were between 8 % (non-food agricultural land occupation) and 41 % (renewable resource use) higher than the ones of the PMMA reactor. No trade-offs between the environmental impact results of both reactors were observed: the glass PBR had higher environmental results than the PMMA reactor across all categories. This is directly related to the electricity requirement for lighting of the glass PBR which was 3.6 times higher than the one of the PMMA reactor. The Swiss electricity mix is largely based on hydropower and the production of hydropower from alpine reservoirs negatively affects the remaining water available in the area due to evapotranspiration (Karimpour et al., 2021). Besides this, both reactors showed similar environmental impacts. The most influencing parameter for both PBRs was the electricity requirement during operation and maintenance, mostly for lighting and heating. The contribution of electricity requirements during operation and maintenance ranged from around 50 %, for human toxicity in terms of cancer cases to >90 % for the cumulative energy demand. Besides that, the additional electronic components in form of the sensors, modelled directly from the ecoinvent v3.9.1 process "Electronic component, active, unspecified", also contributed to the environmental impacts of the PBRs (around 10 to 20 % depending on the environmental impact). Finally, the aluminum contained in the frame of the PMMA-PBR and in the LED support structure of the glass-PBR negatively impacted the climate change, marine, freshwater and terrestrial eutrophication categories.

Overall, changing the type of electricity had the largest impact on the results for both PBRs (S_elec), while changing the land use type (S_land) only affected the land occupation impact categories, soil quality and the land use biodiversity impact as shown in the SI, S6. More specifically, for the PMMA PBR, changing the electricity source to only photovoltaic (PV) electricity, only hydropower or only wind power reduced the environmental impacts of non-renewable resources use, water scarcity and the total land occupation by approximately 80 %, 60 %, and 67 % respectively. However, it increased the use of renewable resources by around 20 %. Further switching the electricity source from the Swiss mix to pure hydropower or pure wind power reduced the climate change, freshwater eutrophication and terrestrial ecotoxicity impacts by on average 36 %, 47 % and 57 % respectively. Changing to full PV electricity had little influence on these three impact categories. Choosing gas-based electricity increased the climate change impact by over 700 % and the use of non-renewable resources by over 160 %. At the same time,

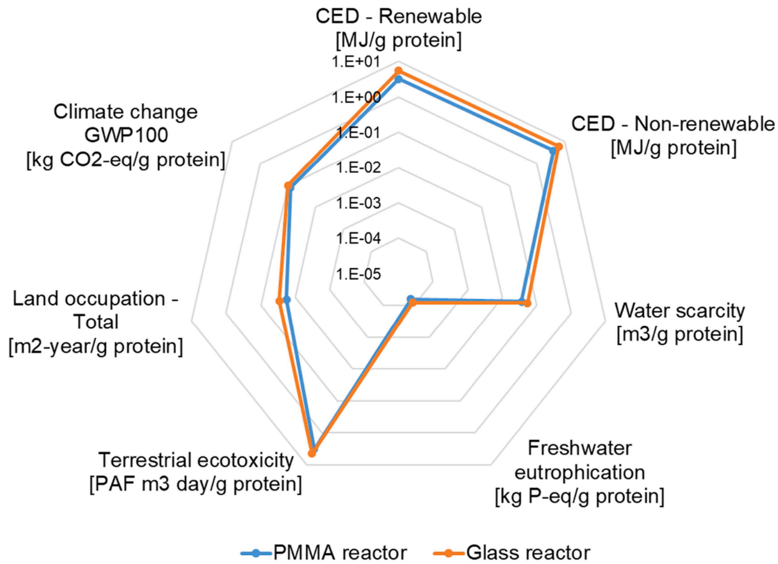

Fig. 2. Environmental impact assessment of the polymethylmetracrylate (PMMA) reactor and the glass reactor for a selection of environmental impacts for the default configuration with Swiss electricity mix, agricultural soil occupation, the use of liquid CO_2, and a share of recycled aluminum of 20 %.

the use of renewable resources decreased by 98 %, water scarcity by 47 %, freshwater eutrophication by 37 %, total land occupation by 73 % and terrestrial ecotoxicity by 14 %. These tendencies are also observed for the glass PBR with even higher percentage values given the higher electricity input to this PBR.

3.2. Social sustainability of the photobioreactors

The social impact assessment showed that not all companies had local hiring preferences but that all companies showed strong engagement with stakeholders, that could be more diversified. Also, despite having static indicators for equal opportunity, improvements in that area could be possible (Table 3). Unfortunately, data could not be collected for all indicators and companies. Hence several indicators could not be evaluated. This limitation could not have been prevented through the use of databases and is a major limitation of working with primary data in the social sustainability evaluation.

3.3. Economic sustainability of the photobioreactors

Finally, the economic assessment clearly showed lower benefits compared to the current costs (<0.01 %). This is mainly driven by the electricity costs, which represent 91 % to 99 % of the total costs. The capital costs represented <1 % of all costs. The costs for the CO_2 input and the culture media made up most of the remaining costs. The fact that the technologies did not appear beneficial is directly linked to the focus put on laboratory-scale PBRs, whose operational parameters have not been optimized economically and do not benefit from economies of scale. Because the quantitative results of the economic assessment would not add to the discussion and to ensure confidentiality of the reported economic values, we report only the outcome and not the single quantitative values.

3.4. Comparison with the reference system

Fig. 3 shows the comparison between the soybean feed products from Brazil and Switzerland and the protein produced by the PMMA and the glass reactor using the Swiss electricity mix and an electricity mix based on natural gas for seven environmental impact categories. The results for all SALCA impact categories are provided in the SI.

Fig. 3 depicts the importance of considering several impact categories and different system configurations. While for climate change the impacts of 1 *g* of protein produced by the PMMA and glass PBR were lower than the soybean feed when Swiss grid electricity is used, it becomes comparable when considering an electricity input based on natural gas. Electricity based on natural gas has larger climate change impacts than the Swiss grid electricity mix which relies heavily on hydropower. Further, for terrestrial ecotoxicity, the impacts of protein produced by a PBR were higher than from soybean feed (except for soybean produced in the Goiás state of Brazil) and it was the opposite for land occupation.

The comparison of the social sustainability of microalgae with the

Table 3
Social impact assessment results for the indicators defined per impact subcategory and stakeholder group for the glass and polymetylmetacrylate (PMMA) reactor manufacturing company and the operating company.

Stakeholder groups	Impact subcategory	Indicator	Glass Reactor Manufacturing company	PMMA Reactor Manufacturing company	Operating company
Workers	Working hours	Working hours per week	B	B	B
	Fair salary	Lowest salary	*n.a.*	A	A
	Education	Contribution to personal development	*n.a.*	*n.a.*	B
	Equal opportunity	Ratio male/female employees	*n.a.*	D	*n.a.*
		Ratio basic salary men/women	*n.a.*	B	*n.a.*
Local community	Local employment	Percentage of workforce hired locally	*n.a.*	A	D
		Evidence of local hiring preferences	B	D	B
	Community engagement	Number and quality of meetings with community stakeholders	B	A	B
		Diversity of community stakeholder groups that engage with the organization	*n.a.*	B	B

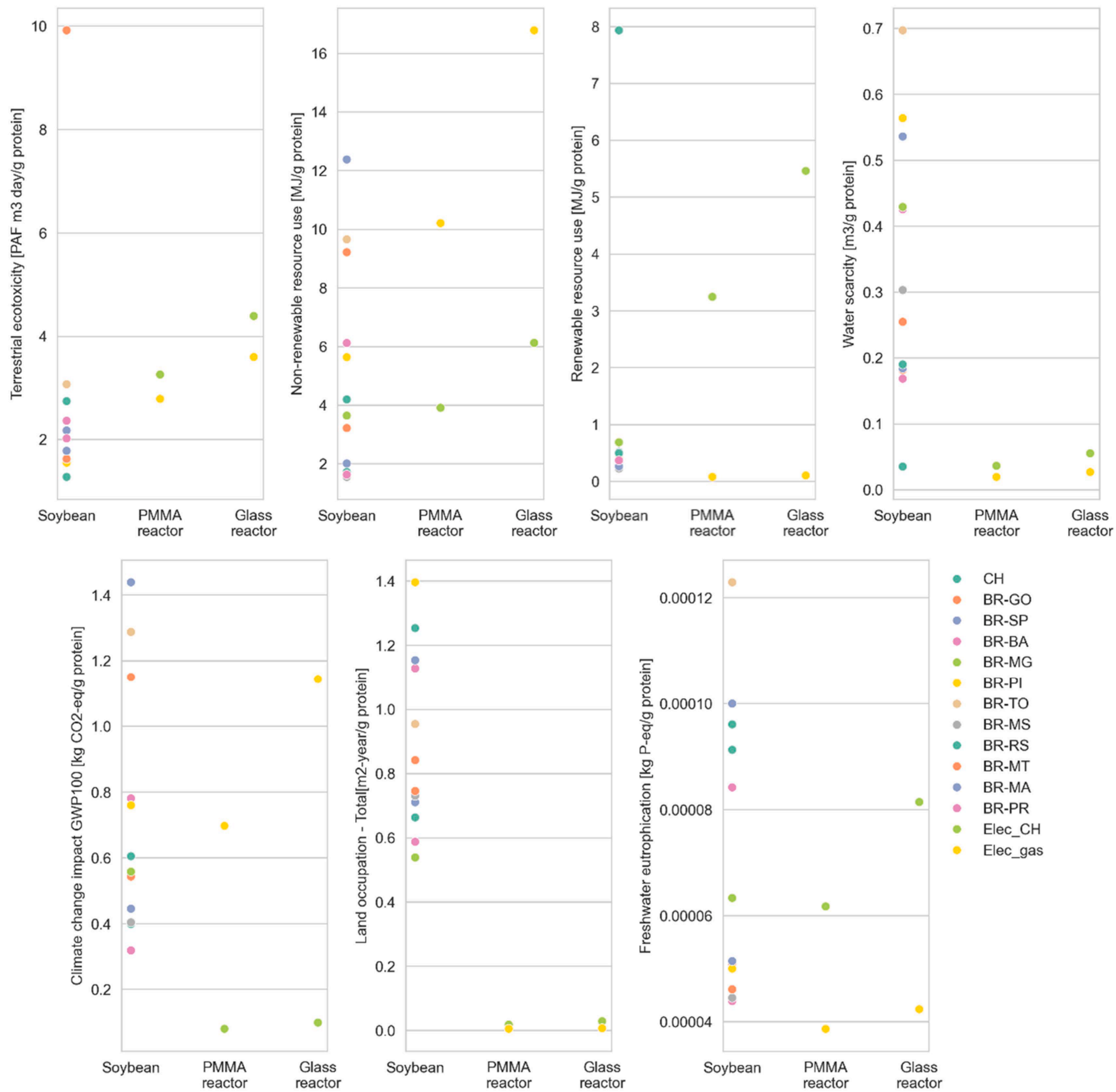

Fig. 3. Comparison of the environmental sustainability of the PMMA and glass photobioreactors with different electricity mixes as input (Swiss = CH and natural gas = gas) to soybean feed products from different regions in Brazil (BR-) and Switzerland (CH) per gram protein output. The abbreviations after BR- represent the different provinces of Brazil: Goiás GO, São Paulo SP, Bahia BA, Minas Gerais MG, Piauí PI, Tocantins TO, Mato Grosso do Sul MS, Rio Grnade do Sul RS, Mato Grosso MT, Maranhão MA, Paraíba PR.

reference system was also based on literature, but proved more difficult. Zortea et al. (2018) evaluated the sustainability of soy production in Southern Brazil. The social sustainability was assessed for workers, local community and value chain actors. Freedom of association (workers) and supplier relationships (value chain actors) presented the most positive results, while education and training (workers), local employment (local community) and education and training (value chain actors) were the most critical social impacts. Pashaei Kamali et al. (2017) also evaluated the social sustainability of different soy production techniques but focused solely on the number of working hours per hectare and day without evaluating them to a reference system. Since this indicator does not correspond to the one chosen in this study, a comparison is not possible. However, the findings of Zortea et al. (2018) about education and local employment contrast to the positive outcomes found in the context of the microalgae production.

Both studies also evaluate the economic sustainability of soybean production. Zortea et al. (2018) identify that feedstock costs drive most of the costs per kg soybean produced followed by infrastructure. Pashaei Kamali et al. (2017) report that all analyzed production systems were profitable. This comparison shows that the driving costs of soybean production are completely different to those of microalgae production, where electricity was a main driving factor.

3.5. Interpretation

3.5.1. Comparison with literature

The comparison of the environmental impacts of the PBRs with literature was based on impacts per kg biomass since it is the functional unit mostly available in literature. For the PMMA-PBR, the climate change impacts range from 32 kg CO_2-eq/kg biomass to 279 kg CO_2-eq/kg biomass for the Swiss electricity mix and electricity from natural gas respectively. For the glass PBR, the values range from 40–457 kg CO_2-

eq/kg biomass. For a vertical PBR operating outside in the Netherlands, Pérez-López et al. (2017) report a climate change impact ranging from 214 kg CO_2-eq/kg biomass to 2665 kg CO_2-eq/kg dry weight for Summer and Winter respectively. Jouannais and Pizzol (2022) report values of 15 and 98 kg CO_2-eq/kg dry weight for a vertical tubular PBR operating in Spain without thermoregulation and in Denmark with thermoregulation. Schade et al. (2020) calculated the lowest climate change impacts between 1.4 to 4.7 kg CO_2-eq/kg dry weight for a PBR without any thermoregulation. Finally, Taelman et al. (2013) found that climate change impacts reduced from 40.6 kg CO_2-eq/kg dry weight for a 240 m^2 pilot Proviron Advanced Photobioreactor Technology to 14.76 and 2.08 with increasing area (1320 m^2 and 2.5 ha respectively). The latter two values are based on hypothetical scale-ups. All studies report the importance of the electricity input for thermoregulation when the PBR is located outside or for mixing when thermoregulation is not necessary. Since the PBRs assessed in our case are located indoors, the lighting is one main contributor not often mentioned in other studies where sunlight provides the necessary energy.

3.5.2. *Outcomes of the workshop*

In the stakeholder workshop the discussion of goals and scope of future research centered around four main areas. First, upscaling the results to large scale production. Second, better identify areas of improvement for microalgae cultivation, possibly by accounting for extended range values for the different parameters. Third, define the product better by accounting for example for protein quality or the entire feed ration. Finally, the social and economic evaluations were criticized for their lack of depth and consultation with stakeholders.

The discussion concerning data highlighted the need for appropriate stakeholder inclusion also in the data gathering process and the use of Swiss soybean production as a reference system. Furthermore, the use of other industrial processes as models for technological upscaling was discussed, emphasizing that microalgae production, being a biological process, can only be upscaled after successful intensification. The feedback on the other two topics addressed in the workshop, namely the sustainability assessment framework and results in general, partly reflected comments on the goal and scope. This highlights the importance of upscaling the technology for a better use of the results, better stakeholder involvement to create “attachment” to the evaluation, and a broader definition of the product e.g., for inclusion in human nutrition. Related to that last point, the need for consumer acceptance studies was also raised. Additional comments were related to a better visualization of the results, comparing results to literature, a more thorough comparison with the reference system and the need for concrete recommendations for stakeholders from the analysis conducted. This last point was linked to the added value of presenting results by sustainability dimension, which helps structure and prioritize the recommendations.

In summary, while the need for such sustainability assessment studies was recognized and the efforts made in this study acknowledged and welcomed, the usefulness of the results for actual decision making remained open.

4. Discussion

We evaluated the sustainability of microalgae production as alternative feedstuff using case-study data of laboratory scale photobioreactors to state what can be concluded about the sustainability of this system and identify methodological improvements that could enhance the effectiveness of such assessments. The remainder of the discussion section is organized into two parts to investigate both aspects.

4.1. *Current insights on the sustainability of microalgae production as feedstuff*

The final stakeholder workshop showed that the findings need to be communicated more clearly for stakeholders to take actionable insights from the evaluation. This communication is slightly more difficult since both evaluated PBRs showed similar sustainability assessment results. Hence no system could clearly be preferred. Still, we showed that both systems benefited from a reduction in the amount of electricity used and from the choice of an electricity mix with little environmental impacts since it was the main contributor to all environmental impacts. Further, a reduction of the overall amount of aluminum in the design of the PBR and an increase in the amount of recycled aluminum used also reduced several environmental impacts such as climate change or terrestrial and freshwater ecotoxicity. We also found that the electronics, modelled directly from the ecoinvent v3.9.1 process “Electronic component, active, unspecified” contributed to several impact categories. Future studies on similar laboratory systems could investigate this part in more detail to look for improvement possibilities. For social sustainability, it appeared that not all companies had local hiring preferences. Further, despite being static, the indicators for equal opportunity showed potential for improvement. Finally, all companies engaged with stakeholders, but this engagement could be diversified. The results of the social sustainability evaluation could be improved by covering more actors along the life-cycle as this should increase generalizability of social sustainability outcomes. The results of the economic assessment were to be expected since we focused on laboratory scale PBRs, not optimized for economic sustainability. The limited representativeness of economic sustainability evaluations of emerging technologies acknowledged in this study aligns with conclusions from other studies (Padilla-Rivera et al., 2023). Comparison with literature was only possible for the environmental sustainability dimension using studies considering microalgae for use as biofuels or complements in human nutrition and confirmed the findings of this study.

4.2. *Avenues for improvement*

Overall, it is important to interpret the results of this analysis with caution since only laboratory scale PBR in a laboratory-scale setting are considered. Applying the framework to the end-scale installation, meaning scaling up the results, would be important to inform on the choice of the PBR supplier as well as to get insights into farmers’ and consumers’ perspectives on the proposed technology and application. This is particularly important for the economic sustainability evaluation, which showed lower benefits compared to the current costs. This limitation was recognized by the stakeholders invited to the workshop. Scaling up the technology to provide sustainability insights at a larger scale is likely to be the first next step when evaluating the sustainability of microalgae as alternative feedstuff. Carrying out this first step could help derive more tangible and actionable results, thus meeting stakeholder concerns.

Related to the need for scaling-up sustainability impacts, sustainability evaluations of novel technologies would greatly benefit from the use of more advanced LCSA databases—such as Soca (Ashrakat et al., 2025), PSILCA (Maister et al., 2020), and SHDB (Social Hotspot Database, 2022) for the social sustainability dimension. These databases offer broader indicator coverage, improved global supply chain analysis, and more nuanced risk and trade-off assessments than what was possible with the simplified S-LCA approach applied in this study, despite their partly patchy geographical coverage of certain processes. Additionally, applying novel methods like HILCSA (Holistic and Integrated Life Cycle Sustainability Assessment) could further refine our analysis by putting the sustainability evaluation in a broader context such as the Sustainable Development Goals (SDGs) and so ensure appropriate regulations are put in place (Zeug et al., 2021).

While prospective LCA is increasingly being used for the environmental impact assessment of technological innovations, equivalent methods for the social sustainability assessment are lacking. This is an essential avenue for future methodological developments for the sustainability assessment of upscaled technologies.

The literature reports attempts to evaluate the environmental impacts of scaling-up laboratory production to industrial applications that can be differentiated into bottom-up, top-down, or patent-based approaches (Schade and Meier, 2020; Spreafico, 2025). Bottom-up approaches would start with a lab- or industrial-scale reactor and end with an upscaled design using literature data (Smetana et al., 2017). Top-down approaches use location-specific data to infer on the environmental impacts of industrial facilities (Schade and Meier, 2020). Finally, patent-based approaches use patents to build foreground inventories of innovative technologies that can be used in a prospective context (Spreafico et al., 2023). In the context of microalgae production, bottom-up approaches are more common. Vazquez-Romero, Perales, Pereira, Barbosa and Ruiz (Vazquez-Romero et al., 2022), for example, suggest an upscaling from 1 ha to 10 ha using the scale factor rule and assuming the process in itself stays the same, while Novoveska, Nielsen, Eroldogan, Haznedaroglu, Rinkevich, Fazi, Robbens, Vasquez and Einarsson (Novoveska et al., 2023) more generally depict three potential pathways for large-scale cultivation of microalgae: ponds, photobioreactors and biofilms systems that all have advantages and disadvantages. Schade and Meier (Schade and Meier, 2020) evaluate the environmental impacts of microalgae production from a top-down approach by relying on equations using location-specific parameters that can easily be adapted. Patent-based approaches have, to the best of our knowledge, not yet been applied to identify possible scale-ups of microalgae production. Applying the framework suggested by Spreafico (Spreafico, 2025) would imply the following steps for the identification of sustainable future scale-ups of industrial microalgae production facilities: (1) identifying the environmental problems of the current product, (2) searching the eco-design solutions, and (3) selecting the eco-design solutions. The sustainability assessment of our study is a major input to (1) so that in step (2) one could focus on searching patented solutions reducing for example the electricity consumption in microalgae production and the weight of aluminum frames. After having identified the eco-design solutions, it would be possible to extract data for the foreground inventory as described in (Spreafico et al., 2023) to finally select a scaled microalgae production method meeting eco-design goals.

Besides upscaling, placing the technology in a broader context is also required to increase the usefulness of such sustainability assessments. This is likely to increase the relevancy of its comparison with the reference system. This is a further aspect of such sustainability analysis, to improve their ability to assess how the sustainability of the technology compares to current systems. This should be done for an upscaled system, as reflecting our finding comparison with laboratory-scale technologies was insufficiently insightful. Ideally, the comparison would rely on the same methodology, implying the application of the sustainability assessment framework to the reference system too.

Another aspect not considered sufficiently in our study and in the sustainability assessment of microalgae as alternative feedstuff in general, relates to consumer and farmers acceptance, and to stakeholder inclusion more broadly. We started off with a reduced stakeholder team. This reduced team likely does not cover all stakeholder views and might introduce bias, for example, in the definition of design scenarios. However, as we extensively mapped stakeholders later on this could be swiftly revised for future applications to better capture the potential diversity of perspectives and insights of stakeholders and ensure the “attachment” of the stakeholders to the study and its results. For example, stronger relationships with the food industry, farmers and consumers could be pursued to contribute to the relevance and acceptability of the technology. Stakeholders could also be involved earlier in the project cycle to enable more iterations of engagements with them to inform assessment and technology development steps (Ehlers et al., 2025). Moreover, our analysis could also be extended to estimate the potential use of the microalgae by farmers and consumer behavior. All such activities require careful and sufficient resource planning.

5. Conclusion

We used case-study data of laboratory-scale PBRs to evaluate the sustainability of microalgae production for feedstuff and identified methodological improvements that could enhance the effectiveness of such assessments. Both results rely on a framework for sustainability assessment adapted from literature to include stakeholder feedback. This stakeholder inclusion ensured an accurate representation of the evaluated technology, supported data gathering, supported reflection on the results and identified further areas of research. While we could derive recommendations to improve the environmental and social sustainability of laboratory-scale PBR, we clearly showed that research is needed for a complete sustainability evaluation of the use of microalgae in feedstuff. This research should be articulated around three lines: (1) the development of new methods for prospective sustainability assessments, (2) a comprehensive stakeholder inclusion and corresponding resources planning, and (3) careful evaluation of the sustainability of reference systems to allow meaningful comparisons.

This study underscores the importance of early-stage sustainability assessments for novel agricultural technologies like microalgae production. However, to fully realize the potential of such approaches, future work does not only need to address the methodological gaps mentioned above but would also greatly benefit from more comprehensive representation of the background system using LCSA databases. This would increase indicator coverage, expand the scope of the analysis to global supply chains and thus allowing for more systematic risk, trade-offs, and synergies evaluations. Aspects that are particularly relevant for novel technological, where the risk of unintended burden-shifting across sustainability dimensions is high.

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Data availability

All data supporting the findings of this study are available within the paper and its Supplementary Information, apart for the data for the economic and social sustainability evaluation.

CRediT authorship contribution statement

Mélanie Douziech: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Alexandra Baumeyer Brahier:** Writing – review & editing, Investigation. **Mariluz Bagnoud:** Writing – review & editing, Investigation. **Melf-Hinrich Ehlers:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.clcb.2026.100213.

Data availability

The majority of the data is available in the Supplementary Information files.

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