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Sustainability indicator identification and selection for an innovative conceptual system: Phosphorus recovery from dairy wastewater

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ABSTRACT

In Europe, a decrease in the availability of phosphate rock resources has led to the development of emerging technologies for phosphorus recovery, with the purpose of generating products that can be used as fertilisers. An innovative conceptual system dedicated to the phosphorus recovery from dairy wastewater is considered in the paper. New technologies need to be assessed using relevant sustainability indicators. In this study, we developed an approach for identifying and selecting indicators. Based on searches of literature and expert interviews, three different tools were developed: an indicator screening framework, a questionnaire for finding actor priorities, and a list of indicator selection criteria. The new approach was successfully used to narrow down an initial set of 382 indicators identified in the literature to 26 that were considered representative and practicable for the assessment of the considered system.

1. Introduction

European food production has become highly dependent on the use of phosphorus (P) fertilisers (Schröder et al., 2010). The rock deposits from which most European P fertilisers originate are foreign, finite and non-renewable (Schröder et al., 2010). Awareness of the scarcity and growing demand for this finite resource for fertiliser production led the European Commission to declare phosphate rock as a critical raw material in 2014 and P as a critical element in 2017 (European Commission, 2020).

Considering the limited availability of phosphate rock, an alternative for P fertiliser production is needed. The European Union (EU) Circular Economy Package and the Critical Raw Materials Act prioritize the recovery and safe reuse of P from food and municipal waste flows (European Commission, 2016, 2023). Interest in technical development for recovery of nutrients from organic waste streams has therefore increased in recent years. Dairy wastewater (DWW) is interesting in this context – it is produced in large volumes by the dairy sector (Ashekuzzaman et al., 2019), it already requires treatment, and it is a potential source of P (Shilpi et al., 2018).

Innovations in nutrient recovery are not necessarily sustainable if they have considerable resource demand, generate large amounts of pollutant emissions or have other sustainability concerns related to e.g. social or economic dimensions. To date, however, relevant sustainability assessments of using DWW flows as a source for nutrients are few and they do not capture the required breadth of sustainability concerns. Only two studies report information from sustainability assessment of resource recovery from DWW, both dedicated to only environmental aspects; Elginoz et al. (2020) employed life cycle assessment (LCA) for the assessment of volatile fatty acid recovery from DWW, and Behjat et al. (2022) used a meta-analysis to compare results from earlier LCA studies of DWW treatment to results from LCA studies of P recovery technologies made for other contexts. There are studies describing the use of the LCA method for the environmental assessment of DWW treatment plants without resource recovery (Finnegan et al., 2018; Kopperi and Mohan, 2022) and of general cases of industry wastewater treatment (Beavis and Lundie, 2003). Larrey-Lassalle et al. (2017) combined the use of LCA with environmental impact assessment (EIA) for the assessment of wastewater treatment plants. Pugliese et al. (2022) performed energy and economic analysis for three different technologies for whey management.

Any sustainability assessment requires the selection of relevant indicators to assess. Indicators can be important sources of information for decision making at different stages of product or process development (Frederiksen and Kristensen, 2008; UN, 1993). Although an increasing number of suggested sustainability indicators can be found in literature,

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selections often need to be made on a case-by-case basis, since long and generic lists are impractical in terms of resource-limited assessments and for providing actionable information.

Therefore, guidance on the selection of indicators is required. According to Revi (1998), the characteristics of ideal indicators are easy to define but it is not easy to find practical indicators that actually embody these characteristics. Several authors have described processes for sustainability indicator identification and selection before. Mascarenhas et al. (2015) selected, through a participatory approach, sustainability indicators, where decision makers and planning practitioners were asked to score the importance of a base set of indicators. Gava et al. (2018) selected indicators by combining literature review with a Venn diagram for visualizing indicators and their relative importance for each pillar and pillar combinations. Hashemi et al. (2021) used a multi-criteria weighting and ranking approach to select sustainability indicators.

There is, however, a notable absence of studies specifically dedicated to the prioritization and selection of sustainability indicators that comprehensively cover all three core areas of sustainability performance (environment, economy, and society) for nutrient recovery from DWW. Zijp et al. (2017) reviewed sustainability assessment tools for the recovery of resources from different wastewaters. The study focused on providing guidance on selecting assessment tools and mapping the coverage of so-called themes, similar to what we here call indicators. Still, a method to screen a large set of indicators is missing.

All of the relevant sustainability assessment methods discussed above are, however, for existing technologies, and not specifically for further development of early-stage technologies, which is the novelty of the current study. The recovery of P products from DWW and their use as fertiliser in farm activities do not yet occur at large scale. The technology readiness level (TRL) of the considered technologies for P recovery from DWW was deemed to be three (TRL=3). The technologies are at the beginning of early development since the considered technologies have been validated only through lab-scale studies within the REFLOW European Training Network (ETN), which focuses on P recovery from DWW in Europe (REFLOW ETN, 2019). This specific case study was part of a sustainability assessment work package that aimed at guiding the technology development at these early stages, and for this purpose, representative sustainability indicators needed to be identified. Given the lack of useful lists of indicators, an approach for identification and selection had to be developed.

The objective of this study is to guide the exploration of sustainability challenges and opportunities associated with innovative technologies for the DWW treatment with P recovery while they are at an early stage of development. The study aimed to identify a broad range of indicators for sustainability assessment and develop and use a method for selecting the most appropriate ones for the specific context. Specifically, the following two main questions were formulated to guide the research on indicator identification and selection: (1) What would be a useful approach for identifying and selecting sustainability indicators for the assessment of the innovative conceptual system of phosphorus recovery for fertilizer from dairy wastewater? (2) What is the outcome of using such an approach, i.e., which indicators would be selected for sustainability assessment of the specific system? This paper describes and explains the process of identification and selection of indicators. The answer to the first guiding question will in this paper be presented as the method employed although significant development work was undertaken to develop the method and its elements. The presented results are the indicator lists generated by using the developed method, i.e., the answer to the second guiding question.

2. Materials and methods

The sustainability indicators considered in this study were environmental, techno-economic, and social in order to cover the breadth of potential sustainability concerns. Environmental indicators provide information related to the release of substances, use of resources, and use of land (EEA, 2000). The anthropogenic pressures on the natural environment is evident through alternations and changes in environmental conditions (EEA, 2000). The techno-economic indicators, in our case, are used to assess the technological and economic aspects of an industrial process, product, or service, in order to estimate the performance and costs of the industrial system before it is built (Liu et al., 2018). Social indicators facilitate judgments regarding the condition of specific social aspects with respect to a set of values and goals (UNEP, 2009) by providing data-driven insights into various aspects of social life. They can be used to measure progress towards policy objectives but can also describe the present situation and main challenges, such as poverty and social exclusion (EEA, 2004).

The method applied here consists of 1) reviewing different scientific and policy documents to identify sustainability indicators and 2) selecting indicators by using three screening tools. Input comes primarily from literature and from two different groups of experts that were interviewed: researchers working on the technical development of the new technologies, and scientists at the Joint Research Centre (JRC), which is the EU's central scientific research institute.

Parts of product life cycles that were of specific interest primarily cover three sectors: DWW treatment (including sludge treatment), P recovery, and use of P products in agricultural activities. This system and the specific technologies considered are further described in the supplementary material (SM; SM1, section 1).

2.1. Identification of sustainability indicators

As already mentioned above, there are few academic studies specifically dedicated to relevant sustainability indicators. Żyłka et al. (2021) and Yapıcıoğlu and Yeşilnacar (2020) introduce energy consumption indicators related to DWW and to the removed pollutants load, but only for DWW treatment. Wang et al. (2020) used water quality indicators for the assessment of wastewater treatments based on an online monitoring system. For the assessment of urban water management, the city blueprint indicator (CBP) has been used (Feingold et al., 2018; Madonsela et al., 2019). The CBP is an indicator-based assessment aimed at holistic understanding of water management (Oliver-Tomas et al., 2019), for enhancing the transition towards water-wise cities by city-to-city learning (Koop and van Leeuwen, 2015). However, the mentioned indicator sets are not covering all three sustainability dimensions and are mostly different types of indicators than what is needed; the energy consumption and water quality indicators are at data inventory level rather than for impacts further down the cause-effect chain. The CBP is not pertinent to DWW treatment, since it is used to assess the sustainability of water management in a municipality, and to understand how advanced the municipality is in sustainable water management compared to other cities (Koop and van Leeuwen, 2015).

To generate a long gross list of indicators, relevant publications from any point in the past were sought. Below, the approach employed for each sustainability dimension is further elaborated.

2.1.1. Environmental

The approach used for identifying environmental indicators focused on the scope of assessing dairy industries, wastewater treatment plants, and fertiliser use in agricultural activities. Since some of the authors had earlier engaged in reviewing LCAs for relevant technologies and compiled indicators suggested or used in those contexts, this was a natural starting point for environmental indicators. Behjat (2022) reviewed LCA studies that assessed either DWW treatment or P-recovery technologies. Skowrońska and Filipek (2014) analysed LCA studies that assessed the production and use of fertilisers and also provided a set of indicators. Further documents were then recommended by experts from the JRC during interviews, primarily European guidelines.

2.1.2. Techno-economic

No techno-economic assessment of this type of system has yet been published so the search had to be done differently than for environmental indicators. Literature focusing on the techno-economic assessment of innovative technologies was sought, and two particularly useful articles were identified based on keywords. Labib et al. (2013) presented an example of a techno-economic assessment of technologies under development, specifically for producing biodiesel from alternative fuel sources. Ögmundarson et al. (2020) combined indicators from LCA and techno-economic assessment to derive a decision support tool for the early stages of technology development. Considering that the system assessed in our study was under development and focused on the production of P fertiliser products from an alternative source, these papers were considered representative. Based on the references provided in these articles, it was possible to discover a larger set of indicators listed in other reports, which focused mainly on European economic indicators and indicators of a circular economy.

2.1.3. Social

Regarding social indicators, a report that proposed a practical and harmonized method for organizations to assess the social impacts of products was consulted, building on existing standards at the global level: the UNEP SETAC Guidelines for Social Life Cycle Assessment (S-LCA) of Products (UNEP, 2021). From this source, it was also possible to track a UNEP report on Methodological Sheets for subcategories in social LCA. The social indicators suggested in the UNEP guidelines are from political standards and documents published by international organizations, implying that these indicators are based on political consensus (Arvidsson et al., 2015). The search for social indicators in our study, unlike that for the environmental and techno-economic indicators, was generic; indicators that could be used for the assessment of any system, whether existing or not, and in all sectors worldwide, were looked for.

2.1.4. Compilation

Table 1 lists the sources finally considered; these include previous indicator compilations in journal papers, technical reports, and European guidelines.

The information collected from the review was compiled and assembled to generate a large initial set of indicators. Because the same kind of indicator was sometimes considered in more than one source, before proceeding with the first screening, the initial compiled list was narrowed down by removing duplicates, namely those with the same name and units.

2.2. Selection of indicators

Fig. 1 shows the overall approach adopted to select a practical subset of the identified indicators. It employed three screening tools as well as a final refinement and polishing step.

2.2.1. First screening: selection based on a screening framework

The first screening consisted of selecting indicators using an indicator screening framework, which intended to clarify relationships between explored elements that make up the system, and various environmental, techno-economic, and social aspects (Ögmundarson et al., 2020). The framework was developed in the specific context of our study based on the technical activities that were assumed to be needed to make-up a full value-chain for the production and use of fertilisers from P recovered from DWW. The elements of the framework were identified through a series of interviews with experts (see section 2 in the SM1 for more details) and placed in relation to the different processes of the conceptual technical system (see section 1 of the SM1) to generate the framework that would guide the first screening (see Fig. 2). The framework focuses on three different sectors and for each of them, three different elements were considered: material flows, actors, and EU policies.

The material flows help to inform about resource consumption, waste generation, and pollution, which is information that is crucial for understanding the potential environmental impacts of the industrial processes. Actors are those who can affect the new system, and who can be provided actionable information in relation to single processes of the system based on the indicators (Freeman, 2010; Lyon et al., 2020). The list of actors in the framework helps to highlight their varying responsibilities and abilities to influence decision-making. EU policies that cover issues such as agricultural policy, food safety, and environmental standards may influence the development of the system by directly impacting EU decision-making in every member state. The list of EU policies in the framework ensures alignment of the process involved in the three sectors with the legal requirements and sustainability goals.

A useful tool for connecting material flows to specific environmental issues is the classification system in life cycle impact assessment (LCIA), as described by the International Organization for Standardization (2006). See Section 3 of SM1 for an overview of LCIA methodology, including the hierarchical structure of endpoint indicators with subcategories presented by midpoint indicators (endpoints were not considered here, but can be used when a sorting of that kind is meaningful). The material flows in the framework were matched, when possible, with the environmental indicators in the compiled initial list of indicators, guided by the LCIA method of ReCiPe 2016 (Huijbregts et al., 2016). SM2 sheet “Environmental (I)” provides more information on how environmental indicators and input/output materials were matched.

Actors and EU policies were used to select techno-economic and social indicators. These two categories of indicators were sorted into subcategories used in the reviewed literature, and this grouping of indicators was retained and used in our study, both for the initial screening and for guiding further detailed screening in subsequent steps. The social indicators under subcategories and stakeholders that were deemed irrelevant to the system and the context considered for this case study were removed (e.g., the stakeholders “children”). Techno-economic and social indicators that could provide meaningful support to the actors listed in the framework were then selected. The screening was guided by what could enable the actors in the framework to make decisions relating to the further development of elements in the system. i.e., information that related to possible consequences of activities in the system. More information on which actor that matches the techno-economic and social indicators is provided in SM2 sheets “Techno-economic (I)” and “Social (I)”. Finally, social indicators with a clear

Table 1
Documents reviewed for the identification of indicators for sustainability assessment of phosphorus recovery from dairy wastewater.

Indicators	Sources
Environmental	Life cycle assessment studies listed by Behjat et al. (2022), and Skowrońska and Filipek (2014)
	EU technical report on "Consumer footprint indicator" (Baldassarri et al., 2017)
Techno-economic	Combining Environmental and Economic Performance for Bioprocess Optimization (Ögmundarson et al., 2020)
	Techno-economic indicators for base catalysed transesterification of oil (Labib et al., 2013)
	EUROSTAT report on "Principal European Economic Indicators" (EUROSTAT, 2009)
	EASAC report on "Indicators for a circular economy" (EASAC, 2016)
Social	Handbook for Product social impact assessment 2018 (Goedkoop et al., 2018)
	UNEP report on “Methodological Sheets for subcategories in social life cycle assessment (S-LCA) 2021″ (UNEP, 2021)

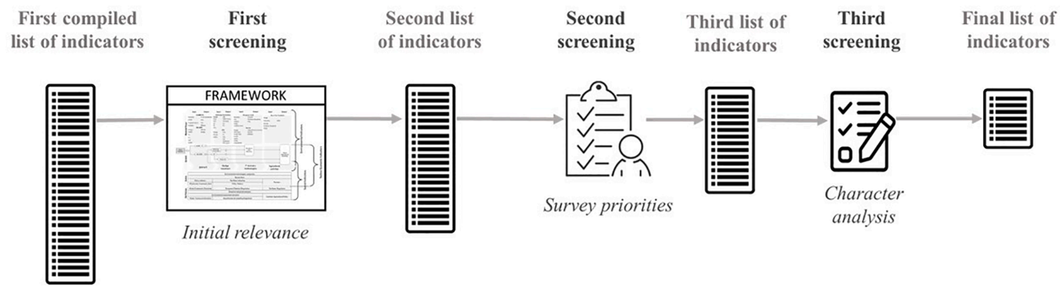

Fig. 1. Graphical representation of the approach to select sustainability indicators.

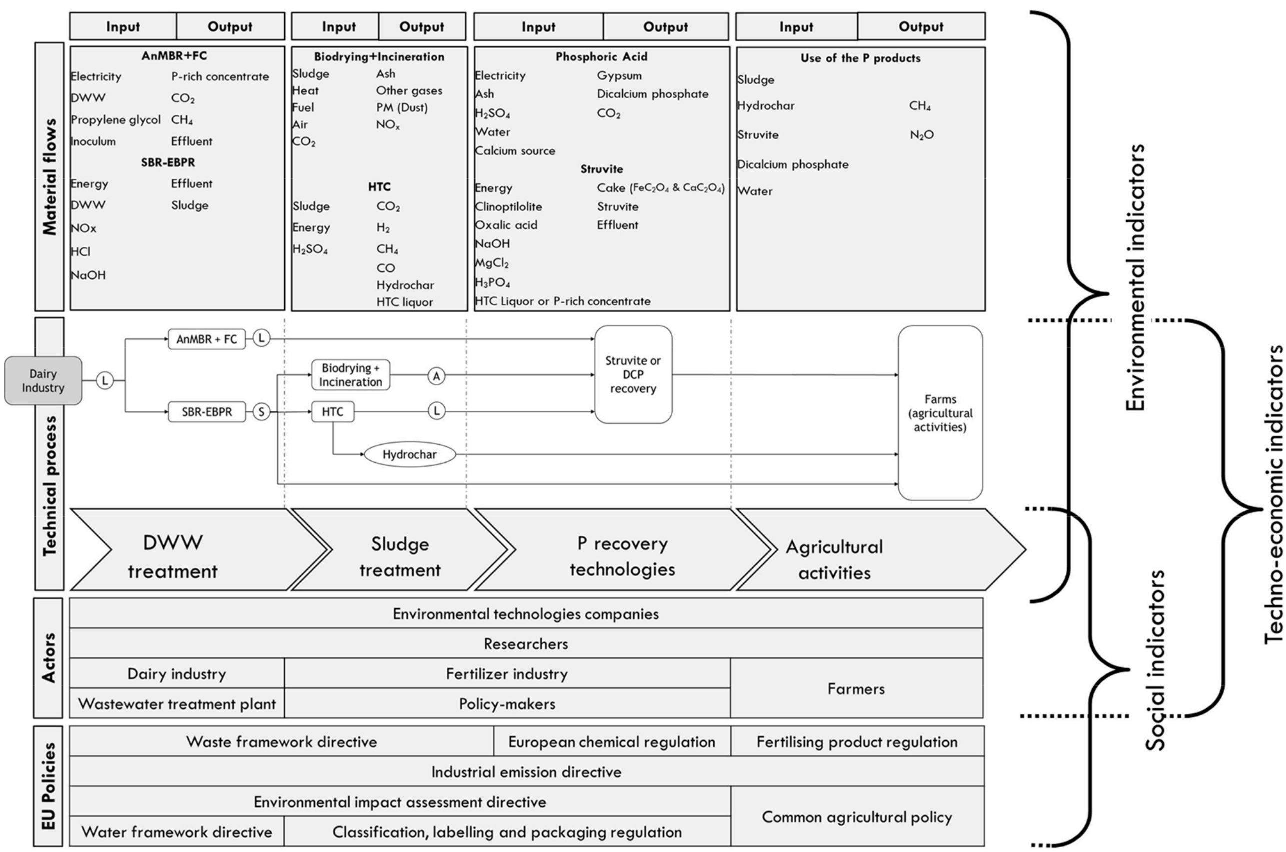

Fig. 2. Framework describing how material flows, actors, and EU policies are linked to the technical aspects of the considered system. The figure also illustrates which elements of the framework are used for guiding the selection of different types of sustainability indicators.

connection to the listed EU policies were selected, as they would allow for an understanding of whether the elements in the system and their further development are in accordance with relevant EU policies.

2.2.2. *Second screening: selection based on an actors' questionnaire*

For the indicators to be useful in decision-making, which indicators that actually cover the main concerns of more specific actors in the technology sectors needs to be known. Therefore, a questionnaire that would allow different actors to prioritise different types of concerns was developed (see section 4 in the SM1). To avoid overwhelming actors with a large number of indicators or too many details, broader areas of concern, rather than single indicators, were listed. For finding these broader areas of concern, the indicators obtained from the first screening (using the framework) were grouped and rephrased to create a limited and intelligible list for the questionnaire (see SM 1, section 4).

The actors evaluated each such area of concern (see detailed results in section 5 of the SM1). This provided an understanding of the areas that should be prioritised and was used in the second screening of indicators to select indicators within areas of high concern and remove others. Only areas of concern considered of higher importance by the actors were kept.

2.3. *Third screening: selection based on indicator criteria*

Finally, the list of indicators was screened using selection criteria, to narrow down and refine the remaining list. The selection of indicators has the potential to determine the outcome of optioneering processes and therefore, it is important to have transparent reasoning regarding the criteria for selecting indicators (Lebacq et al., 2013). To identify and choose selection criteria, studies proposing lists of indicator selection criteria were reviewed (see section 6 in the SM1). The selection criteria were assembled, merged, and rephrased to form a new synthesis list to be used during the third screening step. The criteria selected and listed in Table 2 are the most commonly considered in the reviewed studies (but note that they have here been subjected to some regrouping and adaptation). The criteria *geographic boundary* and *policy responsiveness,*

Table 2
Criteria to select sustainability indicators, and their appearance in different sets found in literature. For each selected (and sometimes modified) criterion, a description was made to guide in the indicator selection step.

Criteria	Description	Revi (1998)	Lundin et al. (1999)	Nathan and Reddy (2010)	Roy and Chan (2012)	Latruffe et al. (2016)	Mascarenhas et al. (2015)	EC (2001)	Lebacq et al. (2013)
Adaptability	The indicator is adaptable and applicable to a broad range of systems of different sizes and types. The indicator should be sufficiently universal for comparison across regions.	✓	✓		✓	✓	✓		✓
EU policy responsiveness	The indicator is capable of providing evidence that the development of the system is responsive to EU policies.	✓		✓	✓			✓	
Geographical scope	Indicators need to be allocated and matched to a specific geographic area; for this specific case study, Europe.		✓	✓	✓			✓	
Guiding	The indicator should provide information in time to act on it, and it should be able to guide future actions.	✓		✓	✓				
Participatory	The indicator should be accessible to users, and easy to understandfor decision making.	✓		✓	✓	✓	✓		✓
Practicability	The indicator should be based on measurable data available when needed.	✓	✓	✓	✓	✓	✓	✓	✓
Quality	The indicator should be based on accurate and robust data, consistent over time.	✓	✓	✓	✓		✓	✓	✓
Representativeness	The indicator should be appropriate to the context and system and be able to provide an early warning of potential problems.		✓	✓	✓	✓	✓	✓	✓

were, for this case study, limited to Europe. The description that was formulated for each selection criterion was aimed at guiding the indicator selection process.

Indicators were selected and considered for the assessment only if they were consistent with at least five of the eight criteria considered.

2.3.1. *Final refinement*

Finally, a last refinement and polishing step was performed that would allow the selected indicators to fully adapt to the context at hand. The units of measurement of the final set of the selected environmental and techno-economic indicators had to be attributed to a specific reference unit. This is a quantified description of the performance of the system and was in our case 1 kg of recovered product. In an LCA, this would be called the functional unit (FU), and according to a set of reviewed LCA studies, the selected FU is the most common and recommended reference unit to be considered for this kind of system (Amann et al., 2018). In addition, some techno-economic and social indicators had to be adapted to the considered system through slight rewording.

3. Results

From the review of all the documents, an initial list of 382 indicators was compiled (see list in SM 2). The list was narrowed down to 230 indicators (SM 2) by removing duplicates. This large set of indicators was further refined through the three screening steps to obtain a final list of 26 indicators. Table 3 presents an overview of the number of indicators suggested in the literature and those selected through the three screening steps: framework, actor priorities, and indicator criteria.

3.1. *Environmental indicators*

In the first screening, the 24 indicators that remained after removing a large number of duplicates were matched to material flows used or produced during the use of the considered technologies. After screening, only 13 remained.

Based on the results from the questionnaire, indicators under the areas of concern prioritised by the actors were selected (see results in section 5.2 of the SM1). The prioritised areas of concern were: *climate change, eutrophication potential, energy use, resource use*, and *ecotoxicity*. However, no indicator with *ecotoxicity* focus remained after the first screening, except with regard to the specific concern related to particulate matter (PM), due to ash and PM emissions during sludge treatment by bio-drying or incineration (see SM2).

All the environmental indicators selected in the second screening were retained after the third screening since they met the criteria of *practicability* and *quality* because the data required to assess the environmental impact using these indicators were considered available and easy to collect. Furthermore, these indicators were considered appropriate for judging whether the system is in line with EU directives (see section 2.1 in SM1 for the EU policies considered); hence, these indicators were *EU policy responsive*. In addition, these indicators were considered important for *guiding* future actions in further technical development.

Table 4 reports the final list of selected environmental indicators and the units suggested by the listed LCIA methodologies.

Table 3
Number of indicators after removing duplicates and after each step of the screening approach.

Indicators	Literature	Removing Duplicates	I Screening	II Screening	III Screening
Environmental	162	24	13	7	7
Techno-economic	51	37	19	11	7
Social	169	169	70	42	12
Total	***382***	***230***	***102***	***60***	***26***

Table 4
Environmental indicators selected for the assessment of the system delivering P recovery from dairy wastewater (DWW) for fertilizer use. The units of measurement are those suggested in different life cycle impact assessment (LCIA) methodologies, and they are related to the reference unit of 1 kg of recovered product.

Environmental indicators	Unit	LCIA methodologies
Cumulative energy demand	MJ	Eco-indicator 99
Global warming potential	kg CO2 eq	CML 2002
Freshwater eutrophication potential	kg P eq	CML 2002
Marine eutrophication potential	kg N eq	ReCiPe 2016 v1.1
Particulate matter formation	kg PM2.5	ReCiPe 2016 v1.1
Fossil depletion	kg oil eq	ReCiPe 2016 v1.1
Mineral depletion	kg Sb eq	CML 2002

Table 5
Techno-economic indicators selected for the assessment of the system delivering P recovered from dairy wastewater (DWW) for fertilizer use. The units of measurement are related to the reference unit of 1 kg of recovered product. The indicators are classified into three subcategories. Some indicators have been slightly modified compared to the original source so as to focus on the assessment of the considered system (see words in bold or with strike-through).

Subcategories	Techno-economic indicators	Unit
Financial	Annual operating labour costs	€/year
	Total production costs	€/year
	Gross profit	€/year
	Simple Rate of Return of Investment	%
Techno-economic cost	Payback time	t
Business indicators	**REFLOW system** producer prices	€
	REFLOW products production	**Kg/month**

3.2. Techno-economic indicators

In the first screening, the 37 indicators that remained after removing the duplicates were matched with the actors listed in the framework. After screening, only 19 remained.

Based on the results of the questionnaire, the areas of concern for P recovery from DWW prioritized by the actors were the *rate of return*, or rather the gains or losses of an investment, and *existing market*, which is the amount of ongoing trade of output, and *risk* due to possible variations in the return (see results in section 5.2 of the SM1). All the indicators under these areas of concern were selected.

The indicators retained after the third screening were those that meet most of the eight criteria and that are the most easily described with physical units. These indicators met the criteria of *practicability, guiding,* and *adaptable and representative.* Furthermore, they were also considered accessible to different users and easy to understand and use for decision-making, thereby meeting the criterion of being *participatory.*

Table 5 reports the final selected techno-economic indicators and their units. Unlike the environmental indicators that are technology-specific, the set of techno-economic indicators can be adapted and used for the assessment of different systems in early stages of development (TRL=3).

3.3. Social indicators

All the social indicators identified from the literature were retained for the first screening; no duplicates were removed. In the first screening, only 70 of 169 social indicators were matched with the EU policies and actors listed in the framework.

Based on the results of the questionnaire, and the participating actors' perspective, the assessment of consumer health, safety, and satisfaction of final products and capacity to engage local actors for market development were the most relevant areas of concern for assessing social impacts (more details about the results of the questionnaire are available in section 5.2 of the SM1).

A group of social indicators that denote health and safety was not included despite being considered relevant for the actors who participated in the questionnaire. The indicators classified under this area of concern cannot be used for the assessment of a system at TRL=3 because of their impracticability, unless we refer to the health and safety during the experiments in the laboratory. Table 6 reports the final social indicators selected.

Indicators under the area of concern *capacity to engage local actors for market development* were retained during the selection process, despite being absent from the top interests of the actors. We decided to consider the indicators classified under this area of concern because it is important to be aware of the involvement of local actors who can influence or be affected based on the different decisions taken during the development of the system at an early stage. Engaging local actors for market development is a strategic approach that promotes responsible and sustainable innovation. It acknowledges the importance of local knowledge, relationships, and context in the development and deployment of the new technologies.

The indicators retained after the third screening were those that met the criteria of *EU policy responsive*, and *participatory*.

4. Discussion

As previously noted, the examination of documents to identify sustainability indicators for the assessment of new technology or business models has been documented before, but its application has not been explored in the specific context of recycling P in the dairy industry.

Table 6
Social indicators selected for the assessment of the system delivering P recovered from dairy wastewater (DWW) for fertilizer use. The indicators are classified into five stakeholder categories and six subcategories. Some indicators have been slightly modified compared to the original source so as to focus on the assessment of the considered system (see words in bold or with strike-through).

Stakeholders	Subcategories	Social indicators
Workers	Smallholders including farmers	Participation **of** farmers' organization **in the design process** [Inclusiveness]
		Estimation of crop yield [Productivity]
		Estimation of the production per year [Productivity]
		Traceability and understanding of quality standards & price premiums (if they exist) [Trading Relationships]
Local community	Access to material resources	Strength of organizational risk assessment with regard to potential for material resource conflict
	Community Engagement	Diversity of community stakeholder groups that engage **during the development of the products**
Consumers	Transparency	Communication **and comprehensiveness** of the results of social, **techno-economic** and environmental life cycle impact assessment
		Assessment of feasibility of certification/label the **of system** for the product/site
Value chain actors	Wealth distribution	Definition of a fair price
Society	Technology development	Involvement in technology transfer program or projects
		Partnerships in research and development
		Investments in technology development/ technology transfer

Likewise, the consideration of theoretical or general indicator selection criteria is an established method which we have here applied in our particular technical context: P recovery for fertilizer production from DWW. To formalize and visualize a contextual framework as an initial indicator list filter is a novel approach, as such considerations of context are often more implicit than explicit in previous work.

One drawback of the screening method used here is an element of subjectivity which is inevitable when identifying and selecting sustainability indicators for specific scenarios. Fundamentally, the aim of work like ours is to express subjective human priorities for decision-making and environmental management that reflect the engineering, social and ecological realities in which new technology is situated. Our approach for integrating subjective priorities and contextual realities when selecting representative indicators for the considered system might, however, not work in all contexts. The framework and questionnaire can nevertheless serve as supportive tools to gain deeper insight into the technologies and actors' opinions. These tools enable the identification of problems as well as provide essential information for the assessment of different systems. These tools are used to understand the interaction between the processes of the system and the actors, whose knowledge and experience will guide the technical development of the system. The framework was developed for the specific sectors in the system to be assessed, however, it can likely be used for the assessment of different but similar systems. The framework can also be extended or adapted to suit other types of technologies or contexts; that might, however, require further information collection, for example, through interviews with experts in other sectors.

The selected sustainability indicators are in many cases specific for a TRL at an early stage. The environmental indicators were all specific for the assessment of a system focused on the dairy industry, wastewater treatment, P-recovery technologies, or fertiliser use. The techno-economic and social indicators, however, can be used for the sustainability assessment of systems that involve sectors other than those mentioned above. The screening framework, unlike the other two tools utilized for the second and third screening which are tailored for technologies at low TRL, can also be adapted to be used for mature technologies. The three elements of the framework - the actors, policies and material flows - pertinent to the assessment of mature technologies in the specific context must then be identified.

Although the selected indicators met the indicator criterion of geographical scope, this does not mean that they are all easily applicable to all European regions. The EU policies listed in the framework (see SM1 for more details) and used for the first screening, are regulations and directives. The regulations are legal acts that apply automatically and uniformly to all EU regions and are binding in all EU regions, without needing to be transposed into national law. The directives, however, must be incorporated into national legislation and therefore require measures by nations to incorporate them into national law, based on the local circumstances, in order to achieve the objectives set by the directive (European Commission, 2022). It is important to have sufficient information, such as European guidelines, to inform the use of these indicators in different regions of Europe. For example, the European Environmental Agency (EEA) regularly updates and disseminates guidelines for air quality monitoring. These guidelines encompass standardized measurement techniques, sampling protocols, and quality assurance procedures. Furthermore, these guidelines acknowledge the diversity of environmental conditions across Europe. They consider variations in climate, topography, and sources of pollution. For instance, regions with heavy industrial activity might have different baseline pollution levels compared to rural areas. The guidelines provide flexibility for member states to tailor their monitoring strategies while maintaining a common framework for comparison.

Interestingly, in the final list, indicators that consider local authorization aspects or the expected public acceptance of installation of the technologies and use of their products more specifically were absent, although these aspects are potentially relevant for the assessment in the present case. This became clear when the final list was compared with more specific lists that have been employed in situations that are similar but for various reasons not captured by the indicator identification process (Bertanza et al., 2015). The lack of these specific indicators in our final list is due to the fact that our final compilation was developed based on the indicators identified in literature, which do not consider the local authorization aspects or the expected public acceptance. Further efforts are required to operationalize the selected sustainability indicators. Consulting additional literature that specifically addresses local authorization requirements and public perception related to technology development is necessary. This will ensure more comprehensive evaluation accounts for the broader societal and regulatory contexts in which these technologies will be implemented.

To be able to use the selected sustainability indicators in practice, more work is needed beyond what has been done here. For example, potential gaps need to be evaluated. It can be argued that very small material flows perhaps not covered in the rough mapping could give rise to important issues, such as related to ecotoxicity, but some aspects are nevertheless hard to capture with current assessment methods and limits on the material flow data availability. Any decision support generated using the developed tools therefore needs to be complemented by additional considerations and a precautionary approach. The list of indicators developed here could provide decision support for further technical development, considering all three different sustainability dimensions (environmental, techno-economic, and social), in a multi-criteria analysis (MCA) setting. Appropriate aggregation procedures need to be selected or weighting for handling case-specific trade-offs. Alternatively, the indicators could be used in a life cycle sustainability assessment-type framework where LCA, a techno-economic assessment (TEA) and an S-LCA can be combined. The use of these indicators for actual assessments, however, require extensive time and resources, and is beyond the scope of this study.

5. Conclusions

This study generated a sustainability indicator list for the sustainability assessment of a conceptual technical system that recovers P from dairy wastewater for use as fertiliser in agriculture. In addition, it developed an approach for identifying and selecting sustainability indicators of more general interest. The study was made as a response to the need to define, before assessing the sustainability of the novel technology, a representative set of sustainability indicators.

An initial long list of 382 sustainability indicators was developed based on a non-systematic literature review, integrating previous reviews of various kinds. Owing to the large number of indicators identified, an approach to select representative indicators for the sustainability assessment of the considered system was developed. This approach was developed based on information from literature and interviews, and the application of this method was demonstrated in the paper. The approach comprised three main selection steps for which tools were developed within this work: a contextual framework based on expert interviews for the first step; a questionnaire on actors' priorities for the second step; and the identification of indicator selection criteria based on a literature review for the third step. The tools were designed so that environmental indicators are particularly suitable for systems very similar to the case represented here: phosphorus recovery from dairy wastewater for use as fertiliser in agriculture. The techno-economic and social indicators, however, have a specific focus on technologies at low TRL (specifically in this case TRL 3). Using the three tools, the initial very large set of indicators was narrowed down to a practicable number of 26.

This work shows that a set of sustainability indicators can be identified and selected trough the developed approach, using the specifically developed tools to guide the selection. The described approach for selecting a set of sustainability indicators is practical to implement and time- and resource-efficient, when no standard set of indicators exists.

Even when such sets of indicators do exist, the proposed approach and its selection tools can be useful for the selection of the most relevant sustainability indicators for a specific case.

Further research is needed to explore if these indicators are effective in assessing and comparing the technologies; as well as to include indicators that specifically address local authorization considerations, enhancing the comprehensiveness of the assessment process.

CRediT authorship contribution statement

Marta Behjat: Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Magdalena Svanström:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Gregory Peters:** Writing – review & editing, Supervision, Conceptualization. **Marta Perez-Soba:** Writing – review & editing, 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.

Data availability

No data was used for the research described in the article.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107646.

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